

**Low-Field and High-Field
Anisotropic Carrier Transport in SiC**

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Abstract

The global trend towards energy conservation has driven the significant advancements of semiconductor devices for power electronics and high-temperature electronics. While further innovation is necessary to realize more energy-efficient technologies for a carbon-neutral society, silicon (Si) electronics has matured and reached their inherent performance limits determined by the material properties of Si. Therefore, it remains a crucial challenge to achieve next-level breakthroughs in these fields beyond the framework of Si-based technology.

Silicon carbide (SiC) has been proposed as a next-generation semiconductor material to resolve this serious problem. With a high critical electric field (~ 2.5 MV/cm) and a wide bandgap (3.26 eV), SiC is a great candidate for low-loss and high-voltage power devices and high-temperature operational logic circuits, memories, and sensors. Over the past few decades, several technical issues of SiC have been overcome through dedicated efforts by researchers and engineers, leading to mass production and commercialization of 600–3300 V-class SiC power diodes and transistors. In addition, high-temperature devices based on SiC have been successfully demonstrated at temperatures exceeding the limit of Si devices. Despite the rapid revolution partially reaching social implementation, some critical physical properties in SiC remain unclear, which blocks the full realization of the material's potential of SiC in device applications. Among these, the carrier transport properties in SiC are particularly significant for the optimal design and accurate simulation of SiC devices.

Electrons and holes are transported by the electric field in a semiconductor with being influenced by a periodic potential and scattering sources such as impurities and lattice vibration. The electric field dependence of the drift velocity of carriers can be expressed using the slope in low-field (low-field mobility) and the saturated value in high-field region (high-field drift velocity). These material properties directly determine the devices' operation under any situation, such as on-state, switching, short-circuit, and avalanche breakdown, among others. The carrier transport properties in SiC exhibit anisotropy due to its hexagonal crystal structure, and that along the c -axis ($\langle 0001 \rangle$ direction) is the most important because the current flows along this direction in typical SiC power devices. However, reports on the low-field mobility and high-field velocity along the c -axis are exclusively limited because the commercially available SiC(0001) wafers do not include the c -axis in their in-plane, which makes them difficult to be measured by standard methods such as Hall effect measurements.

In this dissertation, the author systematically studied the transport phenomena of both electrons and holes under low and high electric field while considering its anisotropy by using SiC(11 $\bar{2}$ 0) wafers, which include the directions parallel and perpendicular to the c -axis

in their in-plane. The fundamental database of transport properties with various parameters including carrier type (electrons or holes), crystal direction, electric field strength, doping concentration, and temperature were presented, which are crucially important for understanding what happens in the devices for any situation. In addition, the origin of the anisotropic carrier transport in SiC was discussed based on the theoretical analysis of anisotropic effective mass using the band structure of SiC, which should be a significant insight into understanding physics of anisotropic semiconductor materials.

In Chapter 2, the low-field electron mobility was determined by Hall effect measurements on n-type SiC(11 $\bar{2}$ 0) epilayers over wide donor concentration ($N_D = 5 \times 10^{14}$ – 4×10^{18} cm $^{-3}$) and temperature (120–600 K) ranges. The electron mobility along the c -axis was found to be 10–20% higher than that perpendicular to the c -axis, and the highest mobility at room temperature ever measured for SiC (1210 cm 2 /Vs) was obtained. The anisotropic electron effective mass was focused on as the origin of anisotropic electron mobility, and theoretical calculation considering the energy distribution of electrons and the conduction band structure of SiC clarified that the anisotropy in electron mobility is quantitatively explained only by that in effective mass. The author also estimated the electron mobility along the c -axis by another approach using SiC(0001) wafers and discussed its validity.

In Chapter 3, the drift velocity of electrons was determined by conductance measurements on n-type SiC(11 $\bar{2}$ 0) epilayers under high electric fields up to 200 kV/cm. Velocity saturation was observed around 100 kV/cm, with saturated drift velocities of 1.7×10^7 cm/s for both directions parallel and perpendicular to the c -axis by careful consideration of transient current and self-heating. The relaxation of velocity anisotropy at higher electric field was qualitatively explained by the change in the energy distribution of electrons.

In Chapter 4, the low-field hole mobility was investigated by Hall effect measurements on p-type SiC(11 $\bar{2}$ 0) epilayers with various acceptor concentrations ($N_A = 8 \times 10^{15}$ – 7×10^{18} cm $^{-3}$) and temperatures (120–600 K). Unlike electron mobility, the hole mobility along the c -axis was 10% lower than that perpendicular to the c -axis, and empirical equations expressing the acceptor concentration and temperature dependences were determined. The anisotropy in effective mass along each direction considering the energy distribution of holes was calculated based on the valence band structure of SiC over the whole first Brillouin zone, and quantitatively explained the observed anisotropy in the hole mobility.

In Chapter 5, the hole drift velocity was measured by conductance methods on p-type SiC(11 $\bar{2}$ 0) epilayers over a wide range of electric field (1–200 kV/cm). Saturation of hole drift velocities was not observed even at 200 kV/cm, attributed to the low hole mobility in SiC. The preserved anisotropy in hole drift velocity ($\sim 10\%$) across the observed electric field range was consistent with the minimal dependence of the calculated anisotropy in effective mass on the energy distribution of holes.

In Chapter 6, the summary of this thesis and future prospects are given. The database and understanding of the carrier transport in SiC provided in the present study contribute the full realization of the SiC's great potential into power and high-temperature electronics.

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Chapter 1

Introduction

1.1 Background

The invention and developments of semiconductor technology have brought a lot of revolution to our lives in modern society. Since the first transistor came into the world at Bell Laboratories in 1947 [1], semiconductor devices have become increasingly essential and currently ubiquitous in our civilization, serving as indispensable components in logic circuits, memory devices, sensors, and optical devices, among others. The semiconductor industry is predominantly driven by silicon (Si)-based large-scale integrated circuits, where consistent improvements of devices beyond predicted performance limitations have been achieved through innumerable technological innovations. The widespread adoption of Si-based devices is primarily attributed to the relatively superior material properties, matured process technologies, and cost efficiency, making their territory well-established and not easily penetrated by other materials to this day.

Despite the remarkable progress and superiorities of Si-based electronics, certain challenges remain beyond their reach. In particular, further innovation in power electronics [2, 3] and high-temperature electronics [4, 5] is crucial for achieving more energy-efficient technologies for a carbon-neutral future. Power electronics involves converting electrical power forms (e.g., voltage, current, and frequency), serving as a core function of the utilization, transmission, and storage of electrical energy within the electrical grid. Si-based systems have played a dominant role in power electronics applications, with their technologies maturing significantly over decades of dedicated effort by researchers and engineers. As a result, the conversion efficiency is now approaching the theoretical limits determined by the inherent material properties of Si, and approximately 10% of electrical power is lost as Joule heat during each conversion process [6]. High-temperature electronics is required for effective utilization of underground natural resources and geothermal energy, where the ambient temperatures can exceed 300°C. However, Si-based devices are inherently incapable of operating at such high temperatures due to the material limitations of Si. Therefore, from the perspectives of both power electronics and high-temperature electronics, substantial

improvements are hardly expected anymore within the framework of Si-based technologies [7, 8].

To address these challenges in both applications, wide bandgap semiconductors – such as silicon carbide (SiC), gallium nitride (GaN), gallium oxide (Ga_2O_3), and diamond – have garnered significant attention as the next-generation materials. These semiconductors are known for their high critical electric fields for breakdown as well as wide bandgaps, as summarized in Table 1.1 [9–26], which suggests their potential to outperform the intrinsic limitations of Si devices. Among these materials, SiC stands out as a promising candidate for overcoming the barriers faced by Si-based devices due to the several remarkable characteristics and advantages in the growth and fabrication process.

1.2 Silicon Carbide (SiC)

SiC is a IV-IV compound semiconductor material consisting of equal numbers of Si and carbon (C) atoms. The strong chemical bonding between these atoms endows SiC with exceptional properties, such as high physical hardness, chemical inertness, high thermal conductivity, and distinctive electrical characteristics [11]. A wide variety of polytypes of SiC exist, distinguished by the stacking sequence of Si-C atomic pairs [27]. Among them, 4H-SiC has emerged as the most suitable polytype for electronic device applications due to its superior properties, including high critical electric field (2.5 MV/cm) [12], wide bandgap (3.26 eV) [28], and high electron mobility [29]. These characteristics make 4H-SiC ideal for high-performance and high-reliability electronic devices, particularly in applications requiring high-power and high-temperature operations. In addition, such a situation promoted the development and maturation of multiple techniques of 4H-SiC, including high-quality crystal growth, doping control, fabrication processes, and device optimization. From these points forward, this study focuses on 4H-SiC, and unless otherwise stated, references to “SiC” will denote 4H-SiC. In this section, the strong points of SiC in high-power and high-temperature electronics, and the history of research and development of SiC are explained.

1.2.1 Applications in Power Electronics

Power electronics is a technique used for converting electrical power forms according to the application, for example, for driving the motor by AC power to create the specific torque and speed of electric vehicles using the DC voltage of battery. A typical conversion circuit for converting DC to AC is illustrated in Fig. 1.1(a), as an example. The backbone of an electrical power conversion system consists of a transistor (as a switching device) and a diode (as a rectifier). Figure 1.1 (b) and (c) show schematic illustrations of the current–voltage (I – V) characteristics of these switching and rectifying devices, with the drawing of both ideal and real cases within the same figure. The power dissipation in these devices is determined by the product of voltage and current ($I \cdot V$), and smaller $I \cdot V$ values correspond

Table 1.1: Major material properties of Si [9, 10], SiC [11–14], GaN [15–20], Ga₂O₃ [21, 22], and diamond [23–26] (data given at room temperature).

Property	Si	4H-SiC	GaN	β -Ga ₂ O ₃	Diamond
Bandgap (eV)	1.12	3.26	3.39	4.5	5.5
Critical Electric Field (MV/cm) at $1 \times 10^{16} \text{ cm}^{-3}$	0.4	2.5 $//c$ 2.2 $\perp c$	2.5 $//c$	7–8*	10*
Electron Mobility (cm ² /Vs)	1400	1200 $//c,*$ 1000 $\perp c$	1480 $\perp c$	200	2400
Saturated Drift Velocity of Electrons ($\times 10^7 \text{ cm/s}$)	1.1	unknown $//c$ 2.2 $\perp c$	2.5 $\perp c$	unknown	1.5
Hole Mobility (cm ² /Vs)	480	unknown $//c$ 120 $\perp c$	30 $\perp c$	unknown	2100
Saturated Drift Velocity of Holes ($\times 10^7 \text{ cm/s}$)	0.8	unknown $//c$ unknown $\perp c$	0.7 $//c$	unknown	1.1
Relative Dielectric Constant	11.9	10.3 $//c$ 9.76 $\perp c$	9	10–12	5.7
Thermal Conductivity (W/cmK)	1.5	3.3–4.9	1–2	0.3	20

* Expected Values

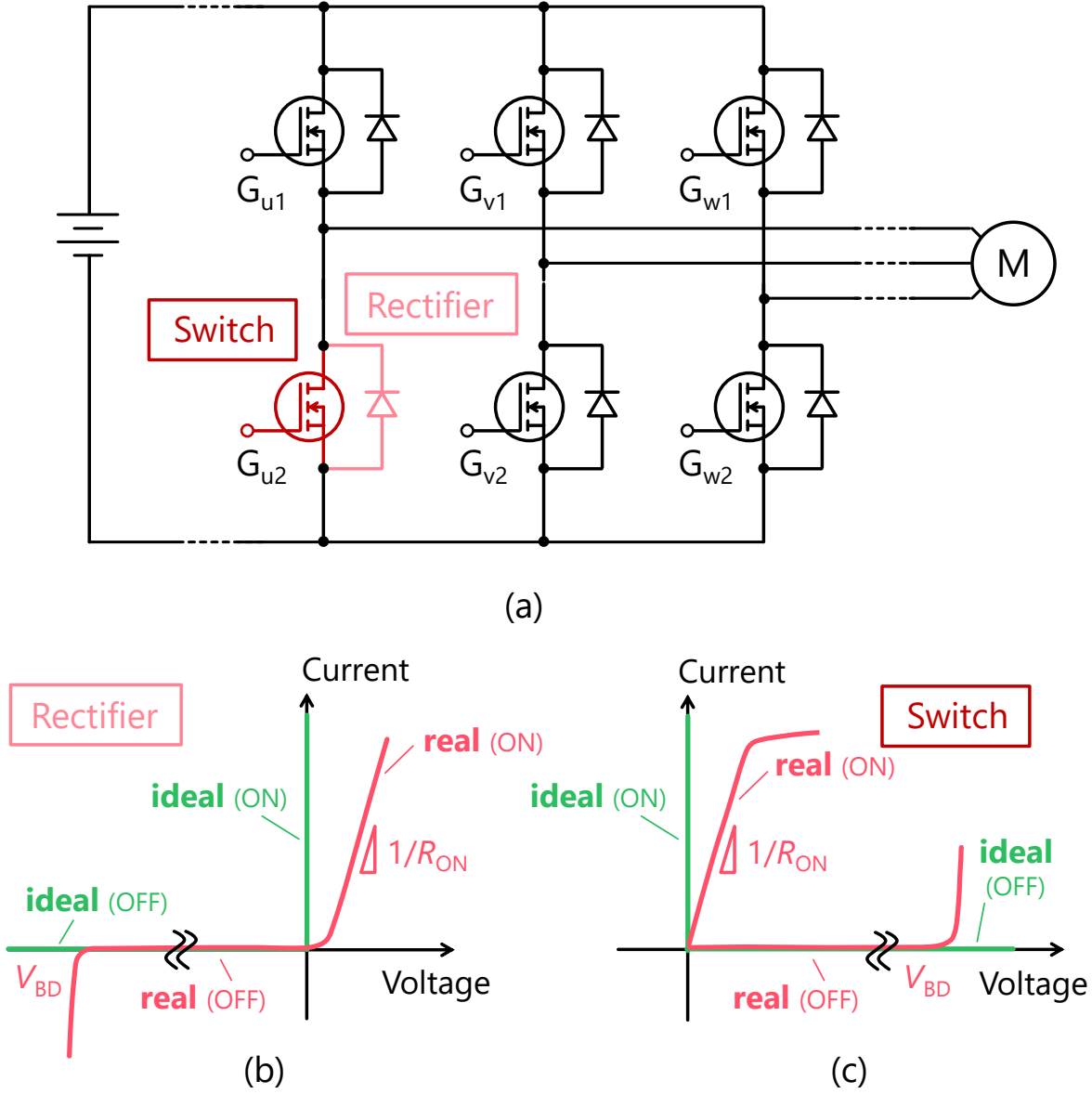


Figure 1.1: (a) Circuit diagram of a DC-AC inverter to drive a three-phase induction motor, which consists of six pairs of rectifier and switch. Current-voltage characteristics of (b) rectifying and (c) switching devices in ideal and real cases.

to better performance of power devices. Ideally, the $I \cdot V$ values are always zero since either current or voltage is zero under both ON- and OFF-state. However, real devices exhibit a non-zero forward voltage drop due to the on-resistance (R_{ON}) under the ON-state, and a non-zero current due to the breakdown voltage (V_{BD}) and leakage current under the OFF-state, leading to power dissipation. In addition, the real devices have switching delays, resulting in energy losses during the state transitions. Thus, to improve the performance of power devices and make them approach that of the ideal cases, a smaller R_{ON} , a higher V_{BD} , and a faster switching speed are required. From these points of view, SiC-based power devices offer considerable advantages over their Si-based counterparts.

Figure 1.2 schematically depicts the electric field distribution under reverse bias and carrier distributions under forward bias for (a) Si and (b) SiC devices, assuming a one-sided abrupt junction designed to have identical V_{BD} . For simplicity, n-type Schottky barrier diodes (SBDs) with non-punch-through structures are taken as examples. The electric field peaks at the junction in these devices, and the breakdown voltage is determined by integrating the triangular-shaped electric field distribution when the electric field at the junction reaches the critical electric field (E_{crit}). To achieve a higher breakdown voltage, one can increase the thickness of the blocking layer (W) and decrease the doping concentration (N_D). However, this approach raises the on-resistance, as it is approximately proportional to N_D/W . Thus, a fundamental trade-off relationship exists between R_{ON} and V_{BD} though, SiC power devices can mitigate this trade-off. The E_{crit} of SiC is nearly ten times higher than that of Si, enabling SiC devices to be designed with only one-tenth the blocking layer thickness and 100 times the doping concentration compared to Si devices with the same V_{BD} , and this leads to a drastic reduction in the R_{ON} . Figure 1.2(c) depicts the calculated trade-off relationships between R_{ON} and V_{BD} of Si and SiC unipolar devices, the so-called “unipolar limit” [30]. Notably, SiC devices can achieve almost 1/500th the on-resistance of their Si counterparts at equivalent V_{BD} , highlighting their superior performance.

The difference in the device structure, whether unipolar or bipolar, also has a significant impact on the device performance. The electric field and carrier distribution under reverse and forward bias are illustrated in Fig. 1.3, where (a) unipolar and (b) bipolar devices are designed to have the same V_{BD} using the same material. While the electric field distribution remains the same due to the identical E_{crit} and doping profile, the R_{ON} of bipolar devices can be significantly reduced owing to the conductivity modulation effect [31, 32]. In bipolar devices, both holes and electrons are injected into the lightly doped blocking layer, resulting in a much higher carrier concentration compared to the intentional doping, and consequently a lower on-resistance compared with unipolar devices. However, it should be emphasized that bipolar devices generally exhibit much larger switching loss arising from reverse recovery for diodes and tail current for insulated-gate bipolar transistors (IGBTs). Therefore, bipolar devices are typically used in situations, where reducing on-resistance is more critical than minimizing switching loss, such as higher voltage applications [33].

Figure 1.4 summarizes the major territories of rating voltage of unipolar and bipolar

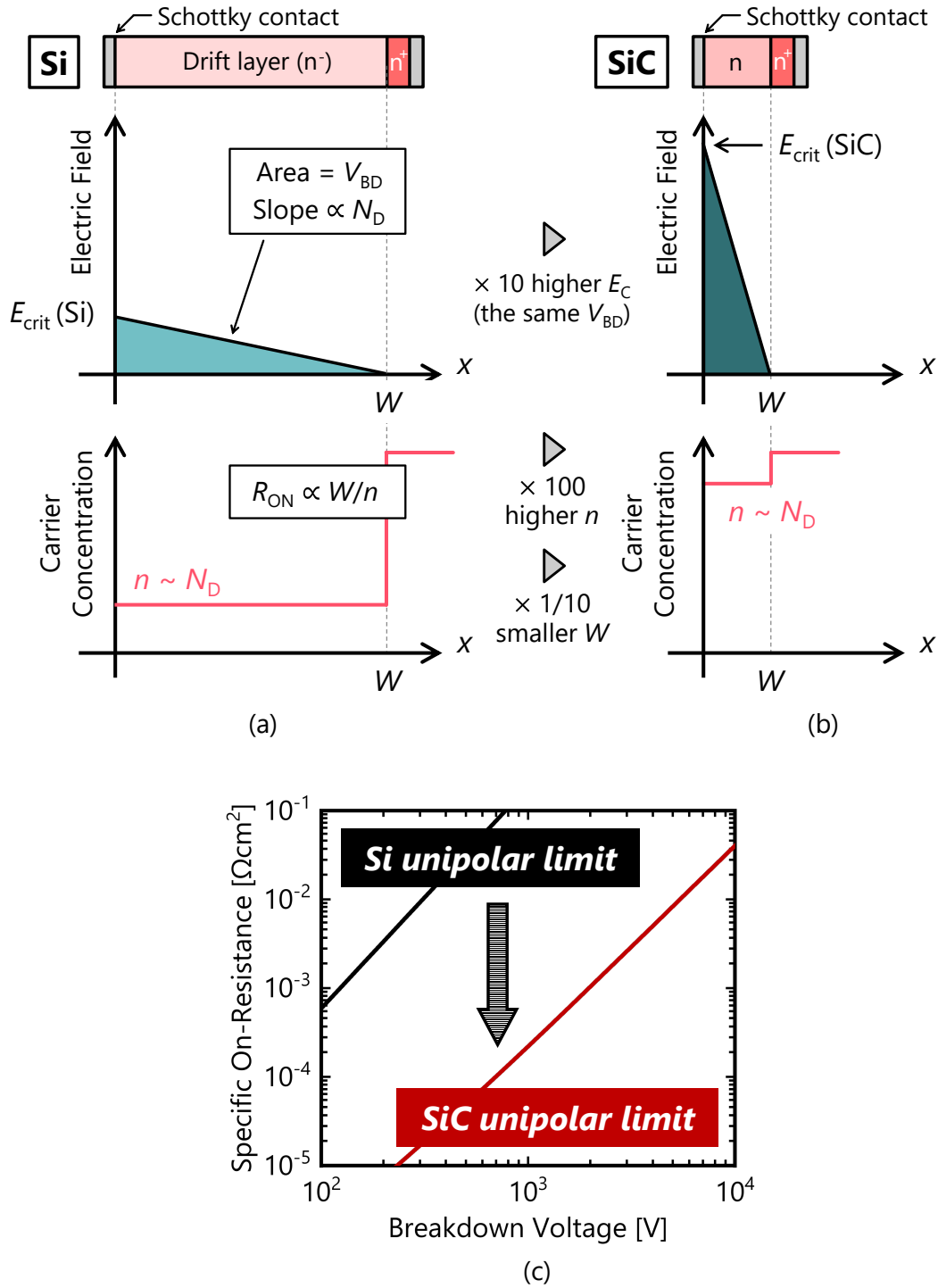


Figure 1.2: Comparison of electric field and carrier distributions in (a) Si and (b) SiC Schottky barrier diodes (SBDs) designed with the same blocking voltage. (c) Trade-off relationship between the specific on-resistance and breakdown voltage of Si and SiC unipolar devices [30].

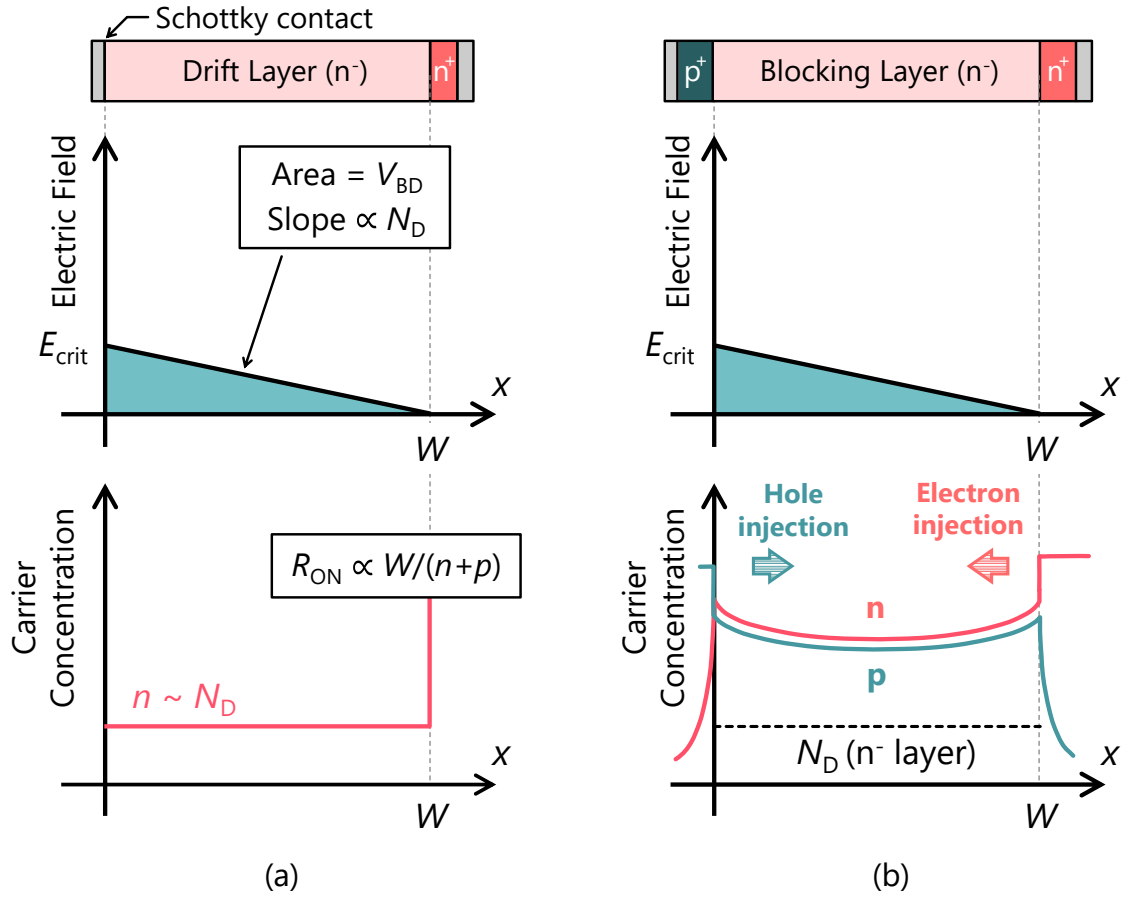


Figure 1.3: Comparison of electric field and carrier distributions in (a) unipolar and (b) bipolar devices designed with the same blocking voltage.

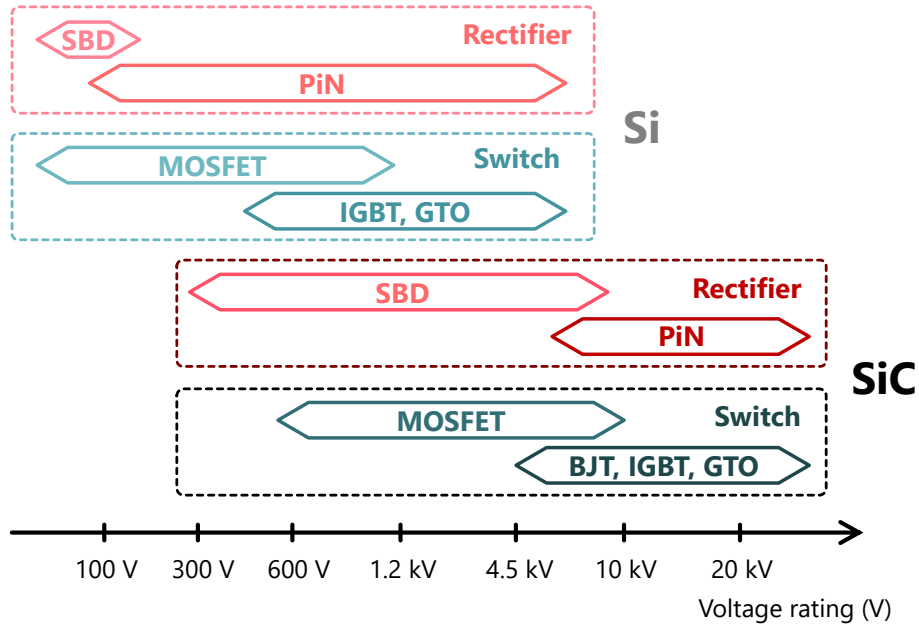


Figure 1.4: Major territories of unipolar and bipolar power devices for Si and SiC categorized based on their rated blocking voltage [34].

power devices for Si and SiC [34]. Bipolar devices such as PiN diodes, bipolar junction transistors (BJTs), IGBTs, and gate-turn-off (GTO) thyristors take possession of higher voltage regions than unipolar devices like SBDs and metal-oxide-semiconductor field-effect transistors (MOSFETs) for each material. The territory of SiC devices is roughly shifted toward higher voltage compared with that of Si devices, and it is particularly noteworthy that the voltage range of SiC unipolar devices approximately corresponds to those of Si bipolar devices. This means that SiC unipolar devices can achieve reduced switching losses while maintaining the same blocking voltage and on-resistance as Si bipolar devices. In addition, SiC bipolar devices unlock the maximum blocking voltage beyond Si devices, which is also important for ultra-high voltage applications, such as power transmission and factory automation.

The advantages described above are common to wide bandgap semiconductors, but SiC is particularly more attractive at the present stage due to its advanced growth and device fabrication technologies, as well as its superior material properties. The bottlenecks for other wide bandgap semiconductors are as follows. While GaN is also a promising material, which has nearly identical bandgap and critical electric field strength to SiC, it is encountering difficulties in selective doping techniques (especially p-type) [35] and large-diameter bulk growth. In addition, the direct band structure of GaN results in a short carrier lifetime, which prevents the realization of GaN bipolar power devices with significantly reduced R_{ON} . Although Ga_2O_3 and diamond exhibit even wider bandgaps and higher critical electric field strengths than SiC, they suffer from reliability issues in MOS devices because wider bandgaps lead to smaller band offsets against the gate oxide materials. Moreover, there still remain challenges in doping control; p-type doping in Ga_2O_3 and n-type doping in diamond have yet to be fully established. In addition, the low thermal conductivity of Ga_2O_3 also limits its potential for high-power operations. In contrast, SiC is superior in these aspects; matured technologies including wide-range doping control of p- and n-type by either impurity doping during epitaxial growth or ion implantation, and availability of large-diameter wafers (8 inch at the present stage) [36]. Furthermore, it also benefits from its material properties such as a long carrier lifetime due to its indirect band structure, sufficiently large band offsets, and a high thermal conductivity.

1.2.2 Applications in High-Temperature Electronics

The primary motivation for developing high-temperature electronics lies in their potential applications for monitoring and controlling systems in extreme environments, such as deep-well drilling for underground resources, turbine engines in airplanes, and space explorers, where the surrounding temperatures are beyond 300°C [8]. In general, it becomes more difficult for semiconductor devices to operate reliably at higher temperatures. This is primarily due to the significant rise in leakage currents through pn junctions – key components of device structures and isolation between devices – which become unacceptably high under

such conditions, ultimately leading to device operation failure and isolation issues. Leakage current through a pn junction consists of generation current and diffusion current, with the latter being proportional to the square of the intrinsic carrier concentration (n_i). The intrinsic carrier concentration is determined by the temperature (T) and the bandgap of material (E_g) as described in the following equation [9]:

$$n_i = \sqrt{N_C N_V} \exp\left(-\frac{E_g}{2k_B T}\right), \quad (1.1)$$

where N_C and N_V are the effective concentrations of states in the conduction and valence bands, respectively, while k_B is the Boltzmann constant. For the case of Si, n_i becomes comparable to the intentional doping concentration when the ambient temperature exceeds approximately 200°C due to its relatively small bandgap ($E_g = 1.12$ eV), which means the limit of operational temperature of Si-based devices. Even with silicon-on-insulator (SOI) substrates, which employ trench etching to achieve device isolation with minimizing the area of pn junction, the maximum operation temperature is still limited to around 300°C [37, 38]. In contrast, the wider bandgap of SiC ($E_g = 3.26$ eV) results in an extremely low n_i compared to Si: approximately 10^{10} cm^{-3} for Si and 10^{-9} cm^{-3} for SiC at 30°C, 10^{16} cm^{-3} for Si and 10^6 cm^{-3} for SiC at 300°C. This fundamental property enables SiC-based devices to operate at much higher temperatures, making them highly promising for high-temperature electronics applications that exceed the limitations of silicon. In addition, it should be supplemented that the wide bandgap of SiC provides the potential to operate under hostile environments including radiation exposure as well as high temperatures [39, 40].

1.2.3 Progress in the Decades

Over the past 40 years, extensive research covering from crystal growth to device fabrication has been conducted to realize the immense potential of SiC into devices [36, 41–43]. In 1978, a critical challenge in SiC crystal growth – the lack of a stoichiometric SiC liquid phase, making melt growth of SiC impossible [44] – was resolved by development of the seeded sublimation method (modified Lely method) [45, 46]. This innovation paved the way for research and development in SiC bulk crystal growth, ultimately leading to high-quality and large-diameter SiC crystals [47, 48]. In 1987, the technique of step-controlled epitaxy, which utilizes surface steps existing on the off-axis substrate, was proposed [49, 50]. This breakthrough enabled homoepitaxial growth of high-quality SiC while preventing the inclusion of other polytypes, leading to an indication of SiC to be adopted for power electronics [51]. Doping control of both n-type and p-type conductivity was successfully achieved during both epitaxial growth [52, 53] and ion implantation [54, 55], providing greater flexibility of device design. From a perspective of development of SiC devices, 1 kV-class SiC SBD was demonstrated in 1994 [56], which triggered extensive research work on SiC power diodes [57–59]. Significant improvements in device structure and fabrication processes aimed at achieving high-voltage and high-current capabilities have led to a substantial

reduction in switching losses compared with Si PiN diodes. Regarding SiC-based transistors, SiC junction field effect transistors (JFETs), SiC BJTs, and SiC MOSFETs have been proposed [60–62]. In particular, innovative improvements in the SiC MOS interface quality [63–67] and fabrication process enabled development of relatively high-performance SiC MOSFETs [68–72], and SiC MOSFETs have emerged as the most promising switching devices, with their R_{ON} reduced to one-twentieth of that of Si devices at the current stage. Thanks to the advancement outlined above, 8-inch SiC substrates and 600–3300 V-class SiC SBDs and SiC MOSFETs have been commercialized, and they have been adopted in inverters for electric vehicles and railcar systems [73–75]. In addition, rapid progress is being made in the development of SiC bipolar devices such as PiN diodes, IGBTs, BJTs, and GTO thyristors [76–79]. As for high-temperature applications, SiC-based devices operating at high temperatures above 300°C have been demonstrated from several groups; such as SiC MOSFETs [80, 81], SiC BJTs [82, 83], and SiC JFETs [84, 85].

1.3 Key Issues — Unclarified Material Properties in SiC

Despite extensive research and development driven by the superiorities of SiC that have led to the commercialization of SiC devices, the understanding of the fundamental material properties is still not sufficient, which blocks the full realization of the material’s potential of SiC in the device application. Among these, the carrier transport properties in SiC remain unclear while they are crucially significant for the optimal design and accurate simulation of SiC devices.

1.3.1 Low-Field Mobility and High-Field Drift Velocity

Electrons and holes in semiconductor materials are accelerated by the electric field (E) in the semiconductor as shown in Fig. 1.5(a), and subsequently scattered by impurities, defects, and phonons, resulting in an averaged drift velocity (v_d) by repeating acceleration and scattering. As depicted in Fig. 1.5(b), the averaged drift velocity is known to be proportional to the electric field under low-field and approaches a certain value at high-field situations in general semiconductor materials due to the stronger interaction with optical phonons [9, 86, 87]. Therefore, the important material properties that express the drift velocity of carriers are the slope in the low-field region (low-field mobility) and the saturated value in the high-field region (high-field saturated velocity). In the low-field region, the drift velocity of electrons and holes ($v_{e,\text{drift}}$ and $v_{h,\text{drift}}$) can be given by

$$v_{e,\text{drift}} = -\mu_e E, \quad v_{h,\text{drift}} = \mu_h E, \quad (1.2)$$

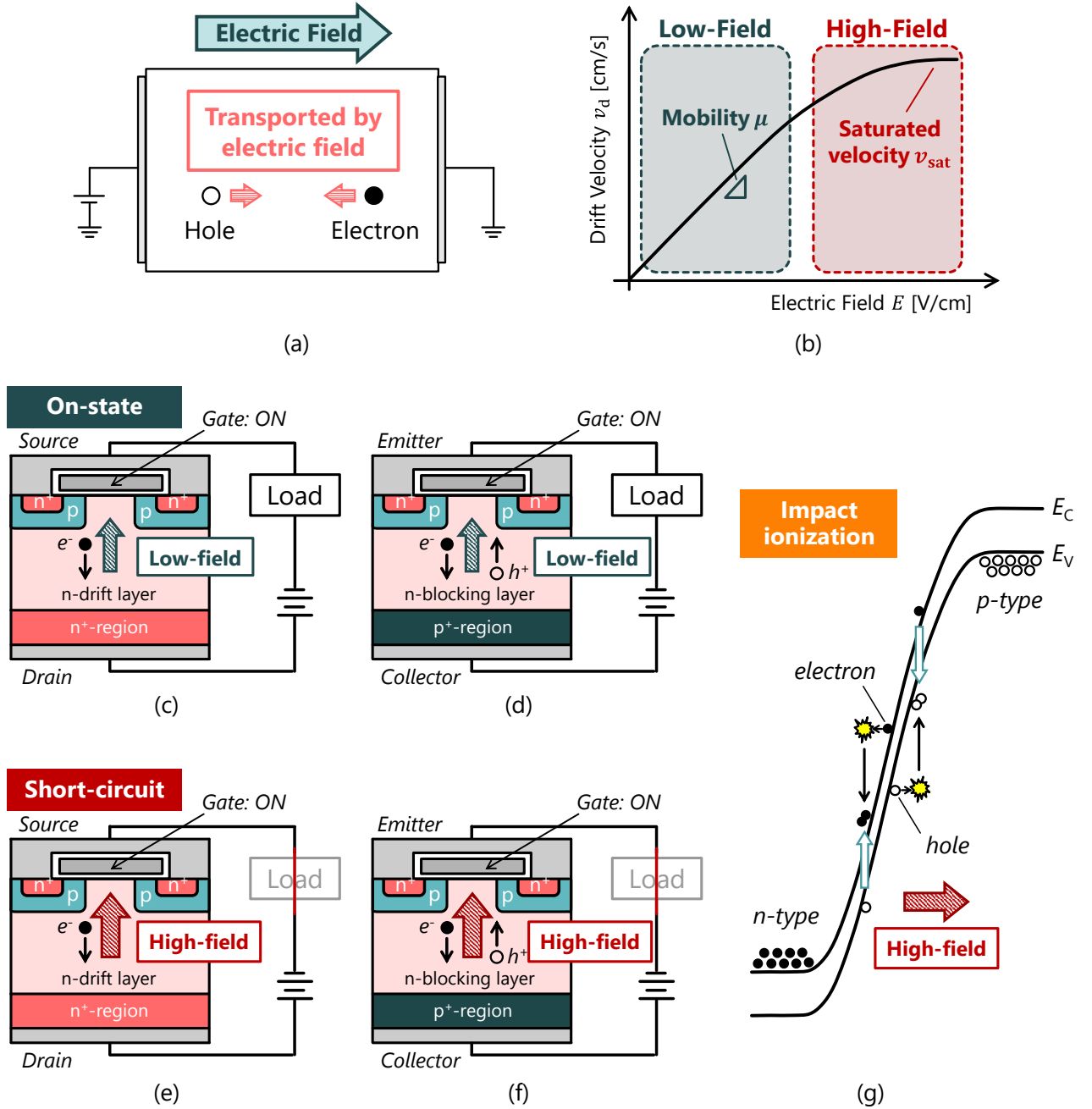


Figure 1.5: (a) Schematic of carriers transported by the electric field in a semiconductor material and (b) typical relationship between the drift velocity of carriers and electric field. (c–f) Schematic illustration of MOSFETs and IGBTs during on-state operation and short circuits events. (g) Energy band diagram of a pn junction when avalanche breakdown occurs.

where μ_e and μ_h are the low-field mobilities of electrons and holes, respectively. On the other hand, under high electric field, they are expressed as follows;

$$v_{e,\text{drift}} = -v_{e,\text{sat}}, \quad v_{h,\text{drift}} = v_{h,\text{sat}}, \quad (1.3)$$

where $v_{e,\text{sat}}$ and $v_{h,\text{sat}}$ are the saturated drift velocities of electrons and holes. In this paper, the absolute values of drift velocity will be used for the simple discussion to avoid confusing accompanied by the difference in sign between electrons and holes. Note that the transport properties of some materials deviate from the general case shown in Fig. 1.5(b) due to peculiar phenomena attributed to their band structure, such as Gunn effect in GaAs [88].

The low-field mobility and high-field velocity of carriers are fundamental material properties that describe how easily carriers are transported within the materials, essentially, the material's ability of electrical conduction. Therefore, these properties are crucially important to understanding the device's performance under various conditions including static operation, switching transients, short-circuit ruggedness, and avalanche breakdown. Specific operating modes are also illustrated in Fig. 1.5, which includes (c–f) the schematic representations of power MOSFETs and IGBTs, on behalf of unipolar and bipolar devices, under on-state and short-circuit conditions, and (g) the band diagram of a pn junction when impact ionization occurs. During on-state operation, low electric field regions appear in both unipolar and bipolar devices, and electrons in unipolar devices and electrons and holes in bipolar devices are transported by low electric fields. Thus, the low-field mobility directly determines R_{ON} of the devices. Besides, when there is an accidental short circuit of load, a high voltage is applied directly to the device and carriers are accelerated in the high-field region as shown in Fig. 1.5(e) and (f), which eventually causes irreversible breakdown of devices due to significant Joule heating and high-voltage stress [89]. Hence, the high-field drift velocity plays a critical role in determining the short-circuit withstand time, which is a key parameter for device reliability. In addition, high-field carrier acceleration occurs in other cases, such as during impact ionization leading to avalanche breakdown as depicted in Fig. 1.5(g), reverse recovery in turned-off bipolar devices [31], or carrier transport in the short-channel MOS devices [90]. In summary, the carrier transport properties, including low-field mobility and high-field velocity, are essential for analyzing and optimizing device performance through understanding the spatial distributions of carrier concentration, current density, potential, temperature, i.e., what happens in the devices.

1.3.2 Anisotropy in Carrier Transport

Over the long history of SiC research, the transport properties of electrons and holes in SiC have been extensively studied, since it became a significant research area of interest around 30 years ago when relatively high-quality SiC crystals were successfully obtained [91–95]. However, almost all of these studies overlook a critical point: the anisotropy of carrier transport in SiC. The hexagonal crystal structure of SiC shown in Fig. 1.6(a) induces anisotropic

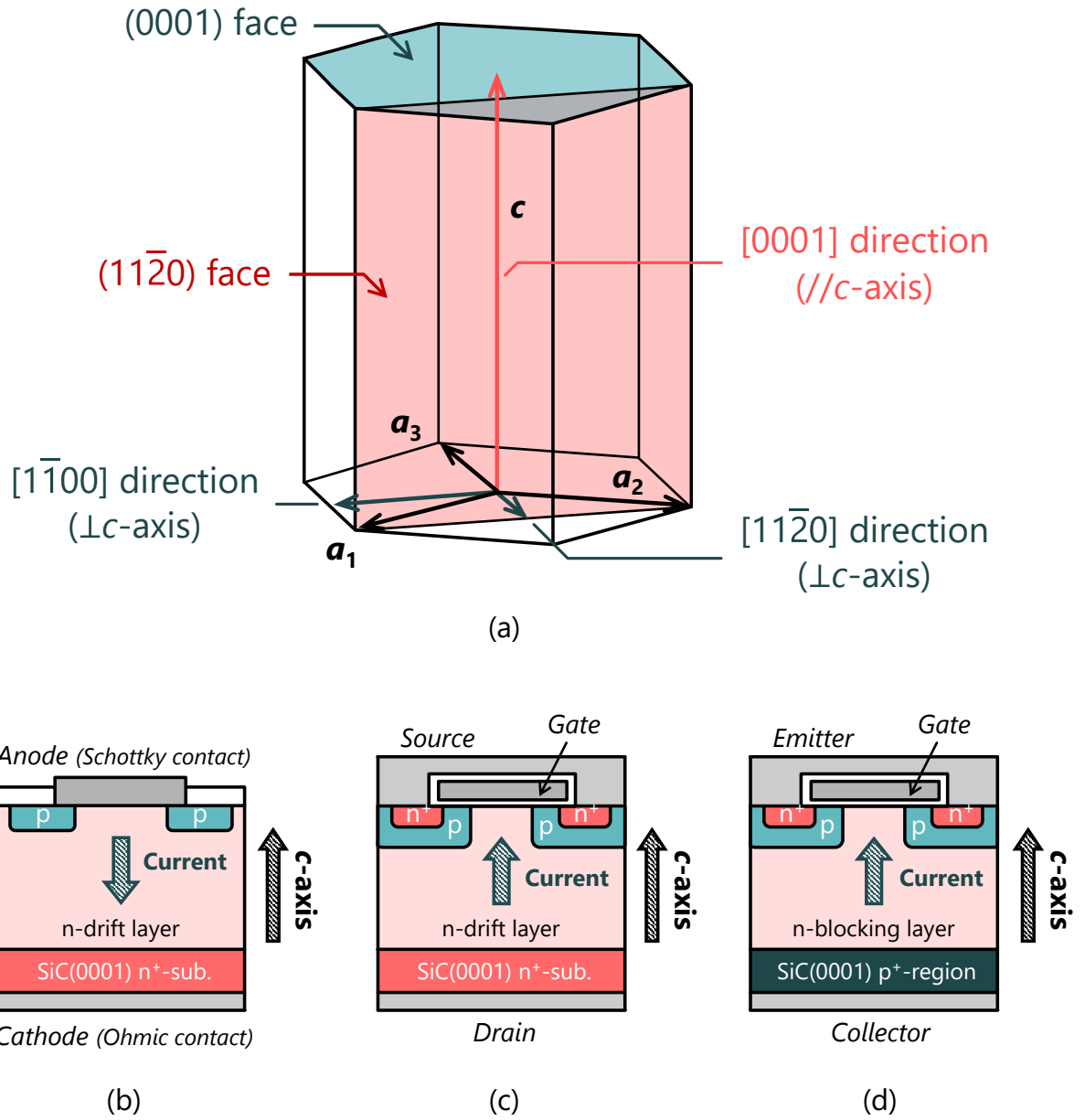


Figure 1.6: (a) Primitive cell and fundamental translation vectors of SiC. (b–d) Schematic illustrations of typical SiC vertical power devices; SiC SBD, SiC MOSFET, and SiC IGBT, where the current flows along the c -axis.

physical properties such as the effective mass [96–98], dielectric constant [99, 100], impact ionization coefficient [12, 101, 102], and thermal conductivity [103]. Similarly, carrier transport properties in SiC are also anisotropic, with differences between that parallel and perpendicular to the c -axis [93, 104–107]. Among these directions, the low-field mobility and high-field velocity along the $\langle 0001 \rangle$ (c -axis) are the most important for power device application. This importance stems from the fact that typical SiC power devices are exclusively fabricated on SiC(0001) wafers using a vertical configuration. In such devices, the anode, source, and emitter are placed on the top sides while the cathode, drain, and collector are on the bottom sides as shown in Fig. 1.6(b–d), meaning carriers primarily flow along the vertical direction, i.e., the parallel direction to the c -axis. However, previous reports mainly focused on the low-field mobility perpendicular to the c -axis of electrons [29, 108–110] and holes [111–114], and there exist only a few reports on the high-field velocity of carriers even for any direction [14, 115, 116], leaving carrier transport along the c -axis and its anisotropy largely underexplored. This incomplete status of research can be attributed to the following factors: (a) Commercially available wafers are predominantly SiC(0001) wafers, which do not include the c -axis in their in-plane directions, (b) Hall effect measurement, the standard method for mobility determination, only provides the low-field mobility of the in-plane direction of samples. These situations have limited insights into the carrier transport along the c -axis, and in order to determine the carrier transport properties parallel to the c -axis in SiC, the two approaches below can be considered:

1. Using SiC(0001) wafers: The mobility or drift velocity along the c -axis can be determined as the vertical transport properties of the samples. However, while test samples can be easily prepared due to the availability of SiC(0001) wafers, accurate measurement and analysis methods for this direction are yet to be established.
2. Using SiC(11 $\bar{2}$ 0) or (1 $\bar{1}$ 00) wafers: The mobility or drift velocity along the c -axis can be measured as the transport properties of the in-plane direction of samples using standard methods like Hall effect or conductance measurements. This approach offers the additional advantage that these wafers include both directions parallel and perpendicular to the c -axis. By carefully orienting the measurement structures, the transport properties in both directions can be accurately determined, and the anisotropy can be experimentally obtained.

The second approach, utilizing SiC(11 $\bar{2}$ 0) wafers, appears to be particularly promising for understanding the anisotropic carrier transport in SiC, potentially providing valuable information for optimizing SiC device performance.

1.4 Purpose and Outline of This Thesis

Based on the background discussed above, the objective of this study is to experimentally determine the anisotropic transport properties of both electrons and holes in SiC over a wide

electric field range using SiC(11 $\bar{2}$ 0) wafers. In addition, the study aims to clarify the origin of the anisotropic low-field mobility and high-field velocity by leveraging theoretical calculation based on the conduction and valence band structure of SiC. The research is divided into four parts according to the carrier type and electric field strength; low-field electron mobility (Chapter 2), high-field electron velocity (Chapter 3), low-field hole mobility (Chapter 4), and high-field hole velocity (Chapter 5).

In Chapter 2, the author investigates the low-field electron mobility along the c -axis by conducting Hall effect measurements on n-type SiC(11 $\bar{2}$ 0) epilayers over wide ranges of donor concentration and temperature. The anisotropy of low-field electron mobility is determined, and its origin is discussed focusing on the anisotropic electron effective mass. For the quantitative discussion, theoretical calculation is performed, taking into account the energy distribution of electrons and the conduction band structure of SiC. Moreover, the author attempts to estimate the electron mobility along the c -axis by another approach using SiC(0001) wafers and evaluates its accuracy and validity.

In Chapter 3, the high-field electron velocity is determined by conductance measurements on n-type SiC(11 $\bar{2}$ 0) epilayers with various electric field strengths up to 200 kV/cm. The study begins with the selection of measurement method suitable for the drift velocity determination in SiC, followed by the design consideration of a bridge structure and a high-voltage short-pulse source for the high-field measurement. The saturated drift velocities are accurately determined by carefully accounting for the effect of transient current from parasitic capacitors and self-heating of structures. Furthermore, the electric field dependence of anisotropy in electron drift velocity is also discussed, with a focus on changes in the energy distribution of electrons under high electric fields.

In Chapter 4, the low-field hole mobility is investigated through Hall effect measurements on p-type SiC(11 $\bar{2}$ 0) epilayers with widely varied acceptor concentrations and temperatures. The temperature and doping concentration dependences of hole mobility are discussed by comparing them with those of electron mobility. Theoretical analyses are performed to discuss the origin of anisotropy, considering the energy distribution of holes and the valence band structure of SiC over the whole first Brillouin zone. The contribution of the anisotropy in hole effective mass to the observed anisotropy in hole mobility is discussed based on the theoretical calculation.

In Chapter 5, the author focuses on the high-field hole velocity, which is determined via conductance measurements using p-type SiC(11 $\bar{2}$ 0) epilayers over a wide range of electric field with a maximum value of 200 kV/cm. The difference in the electric field dependence of drift velocities between electrons and holes is discussed based on the different mobilities and effective masses. Furthermore, the electric field dependence of anisotropy in hole drift velocity is also discussed, with particular attention to changes in the energy distribution of holes by high electric fields.

Finally, the author summarizes this dissertation and presents an outlook for future research in Chapter 6.

References

- [1] W. Shockley, *IEEE Trans. Electron Devices* **23**, 597 (1976).
- [2] W. E. Newell, *IEEE Trans. Ind. Appl.* **IA-10**, 7 (1974).
- [3] J. G. Kassakian, D. J. Perreault, G. C. Verghese, and M. F. Schlecht, *Principles of Power Electronics* (Cambridge University Press, 2nd edition, 2023).
- [4] H. Morkoç, S. Strite, G. B. Gao, M. E. Lin, B. Sverdlov, and M. Burns, *J. Appl. Phys.* **76**, 1363 (1994).
- [5] P. L. Dreike, D. M. Fleetwood, D. B. King, D. C. Sprauer, and T. E. Zipperian, *IEEE Trans. Compon. Packag. Manuf. Technol. A* **17**, 594 (1994).
- [6] J. Lutz, H. Schlangenotto, U. Scheuermann, and R. De Doncker, *Semiconductor Power Devices* (Springer Cham, 2nd edition, 2018).
- [7] M. Bhatnagar and B. J. Baliga, *IEEE Trans. Electron Devices* **40**, 645 (1993).
- [8] P. G. Neudeck, R. S. Okojie, and L. Y. Chen, *Proc. IEEE* **90**, 1065 (2002).
- [9] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (John Wiley & Sons, 2006).
- [10] C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *Solid State Electron.* **20**, 77 (1977).
- [11] T. Kimoto and J. A. Cooper, *Fundamentals of Silicon Carbide Technology* (John Wiley & Sons, 2014).
- [12] H. Niwa, J. Suda, and T. Kimoto, *IEEE Trans. Electron Devices* **62**, 3326 (2015).
- [13] D. Stefanakis, X. Chi, T. Maeda, M. Kaneko, and T. Kimoto, *IEEE Trans. Electron Devices* **67**, 3740 (2020).
- [14] I. A. Khan and J. A. Cooper, *IEEE Trans. Electron Devices* **47**, 269 (2000).
- [15] A. Lidow, M. d. Rooij, J. Strydom, D. Reusch, and J. Glaser, *GaN Transistors for Efficient Power Conversion* (John Wiley & Sons, 3rd edition, 2019).
- [16] T. Maeda, T. Narita, S. Yamada, T. Kachi, T. Kimoto, M. Horita, and J. Suda, *J. Appl. Phys.* **129**, 185702 (2021).
- [17] S. Kaneki, T. Konno, T. Kimura, K. Kanegae, J. Suda, and H. Fujikura, *Appl. Phys. Lett.* **124**, 012105 (2024).

- [18] J. M. Barker, D. K. Ferry, D. D. Koleske, and R. J. Shul, *J. Appl. Phys.* **97**, 063705 (2005).
- [19] M. Horita, S. Takashima, R. Tanaka, H. Matsuyama, K. Ueno, M. Edo, T. Takahashi, M. Shimizu, and J. Suda, *Jpn. J. Appl. Phys.* **56**, 031001 (2017).
- [20] D. Ji, B. Ercan, and S. Chowdhury, *IEEE Electron Device Lett.* **41**, 23 (2020).
- [21] M. Higashiwaki and M. H. Wong, *Annu. Rev. Mater. Res.* **54**, 175 (2024).
- [22] Z. Galazka, R. Uecker, K. Irmscher, M. Albrecht, D. Klimm, M. Pietsch, M. Brützmann, R. Bertram, S. Ganschow, and R. Fornari, *Cryst. Res. Technol.* **45**, 1229 (2010).
- [23] G. A. J. Amaratunga, *Science* **297**, 1657 (2002).
- [24] F. Nava, C. Canali, M. Artuso, E. Gatti, P. F. Manfredi, and S. F. Kozlov, *IEEE Trans. Nucl. Sci.* **26**, 308 (1979).
- [25] S. Bhagavantam and D. A. A. S. Narayana Rao, *Nature* **161**, 729 (1948).
- [26] T. R. Anthony and W. F. Banholzer, *Diam. Relat. Mater.* **1**, 717 (1992).
- [27] A. R. Verma and P. Krishna, *Polymorphism and Polytypism in Crystals* (John Wiley & Sons, 1966).
- [28] W. J. Choyke and R. P. Devaty, Optical properties of SiC: 1997–2002, *Silicon Carbide: Recent Major Advances* (eds. W. J. Choyke, H. Matsunami, and G. Pensl), (Springer Berlin Heidelberg, 2004), p. 413.
- [29] J. Pernot, W. Zawadzki, S. Contreras, J. L. Robert, E. Neyret, and L. Di Cioccio, *J. Appl. Phys.* **90**, 1869 (2001).
- [30] T. Kimoto, *Jpn. J. Appl. Phys.* **58**, 018002 (2019).
- [31] B. J. Baliga, *Fundamentals of Power Semiconductor Devices* (Springer, 2nd edition, 2019).
- [32] T. Kimoto and Y. Yonezawa, *Mater. Sci. Semicond. Process.* **78**, 43 (2018).
- [33] D. T. Morissette and J. A. Cooper, *IEEE Trans. Electron Devices* **49**, 1657 (2002).
- [34] T. Kimoto, *Jpn. J. Appl. Phys.* **54**, 040103 (2015).
- [35] H. Sakurai, M. Omori, S. Yamada, Y. Furukawa, H. Suzuki, T. Narita, K. Kataoka, M. Horita, M. Bockowski, J. Suda, and T. Kachi, *Appl. Phys. Lett.* **115**, 142104 (2019).
- [36] T. Kimoto, *Proc. Jpn. Acad. Ser. B* **98**, 161 (2022).

- [37] D. Flandre, *Mater. Sci. Eng. B Solid State Mater. Adv. Technol.* **29**, 7 (1995).
- [38] M. A. Huque, S. K. Islam, L. M. Tolbert, and B. J. Blalock, *IEEE Trans. Power Electron.* **27**, 4153 (2012).
- [39] S. S. Suvanam, S. Kuroki, L. Lanni, R. Hadayati, T. Ohshima, T. Makino, A. Hallen, and C.-M. Zetterling, *IEEE Trans. Nucl. Sci.* **64**, 852 (2017).
- [40] F. La Via, D. Alquier, F. Giannazzo, T. Kimoto, P. Neudeck, H. Ou, A. Roncaglia, S. E. Sadow, and S. Tudisco, *Micromachines* **14**, 1200 (2023).
- [41] P. Friedrichs, *Phys. Status Solidi B Basic Res.* **245**, 1232 (2008).
- [42] X. She, A. Q. Huang, O. Lucia, and B. Ozpineci, *IEEE Trans. Ind. Electron.* **64**, 8193 (2017).
- [43] H. Tsuchida, I. Kamata, T. Miyazawa, M. Ito, X. Zhang, and M. Nagano, *Mater. Sci. Semicond. Process.* **78**, 2 (2018).
- [44] R. W. Olesinski and G. J. Abbaschian, *Bulletin of Alloy Phase Diagrams* **5**, 486 (1984).
- [45] Y. M. Tairov and V. F. Tsvetkov, *J. Cryst. Growth* **43**, 209 (1978).
- [46] Y. M. Tairov and V. F. Tsvetkov, *J. Cryst. Growth* **52**, 146 (1981).
- [47] T. Kimoto, *Prog. Cryst. Growth Charact. Mater.* **62**, 329 (2016).
- [48] D. Nakamura, I. Gunjishima, S. Yamaguchi, T. Ito, A. Okamoto, H. Kondo, S. Onda, and K. Takatori, *Nature* **430**, 1009 (2004).
- [49] N. Kuroda, K. Shibahara, W. Yoo, S. Nishino, and H. Matsunami, *Ext. Abstr. 19th Conf. on Solid State Devices and Materials* (1987), p. 227.
- [50] H. S. Kong, J. T. Glass, and R. F. Davis, *J. Appl. Phys.* **64**, 2672 (1988).
- [51] B. J. Baliga, *IEEE Electron Device Lett.* **10**, 455 (1989).
- [52] H. Matsunami and T. Kimoto, *Mater. Sci. Eng. R Rep.* **20**, 125 (1997).
- [53] A. A. Burk, *Chem. Vap. Depos.* **12**, 465 (2006).
- [54] T. Kimoto, N. Inoue, and H. Matsunami, *Phys. Status Solidi A* **162**, 263 (1997).
- [55] T. Troffer, M. Schadt, T. Frank, H. Itoh, G. Pensl, J. Heindl, H. P. Strunk, and M. Maier, *Phys. Status Solidi A* **162**, 277 (1997).
- [56] A. Itoh, T. Kimoto, and H. Matsunami, *IEEE Electron Device Lett.* **16**, 280 (1995).

- [57] J. A. Cooper and A. Agarwal, *Proc. IEEE* **90**, 956 (2002).
- [58] F. Dahlquist, C. M. Zetterling, M. Östling, and K. Rottner, *Mater. Sci. Forum* **264–268**, 1061 (1998).
- [59] R. Singh, J. A. Cooper, M. R. Melloch, T. P. Chow, and J. W. Palmour, *IEEE Trans. Electron Devices* **49**, 665 (2002).
- [60] P. Friedrichs, H. Mitlehner, R. Kaltschmidt, U. Weinert, W. Bartsch, C. Hecht, K. O. Dohnke, B. Weis, and D. Stephani, *Mater. Sci. Forum* **338–342**, 1243 (2000).
- [61] J. W. Palmour, J. A. Edmond, H. S. Kong, and C. H. Carter, Jr, *Physica B Condens. Matter* **185**, 461 (1993).
- [62] S.-H. Ryu, A. K. Agarwal, R. Singh, and J. W. Palmour, *IEEE Electron Device Lett.* **22**, 124 (2001).
- [63] S. Dimitrijević, H.-F. Li, H. B. Harrison, and D. Sweatman, *IEEE Electron Device Lett.* **18**, 175 (1997).
- [64] L. A. Lipkin, M. K. Das, and J. W. Palmour, *Mater. Sci. Forum* **389–393**, 985 (2002).
- [65] S. Asaba, T. Schimizu, Y. Nakabayashi, S. Fukatsu, T. Ito, and R. Iijima, *Mater. Sci. Forum* **924**, 457 (2018).
- [66] T. Kobayashi, T. Okuda, K. Tachiki, K. Ito, Y.-I. Matsushita, and T. Kimoto, *Appl. Phys. Express* **13**, 091003 (2020).
- [67] K. Tachiki, M. Kaneko, and T. Kimoto, *Appl. Phys. Express* **14**, 031001 (2021).
- [68] J. Tan, J. A. Cooper, and M. R. Melloch, *IEEE Electron Device Lett.* **19**, 487 (1998).
- [69] T. Nakamura, Y. Nakano, M. Aketa, R. Nakamura, S. Mitani, H. Sakairi, and Y. Yokotsuji, *2011 International Electron Devices Meeting (IEDM)* (2011), p. 26.5.1.
- [70] A. Ichimura, Y. Ebihara, S. Mitani, M. Noborio, Y. Takeuchi, S. Mizuno, T. Yamamoto, and K. Tsuruta, *Mater. Sci. Forum* **924**, 707 (2018).
- [71] T. Masuda, Y. Saito, T. Kumazawa, T. Hatayama, and S. Harada, *2018 IEEE International Electron Devices Meeting (IEDM)* (2018), p. 8.1.1.
- [72] K. Kawahara, S. Hino, K. Sadamatsu, Y. Nakao, Y. Yamashiro, Y. Yamamoto, T. Iwamatsu, S. Nakata, S. Tomohisa, and S. Yamakawa, *2017 29th International Symposium on Power Semiconductor Devices and IC's (ISPSD)* (2017), p. 41.
- [73] T. Nakamura, M. Miura, N. Kawamoto, Y. Nakano, T. Otsuka, K. Okumura, and A. Kamisawa, *Phys. Status Solidi A* **206**, 2403 (2009).

- [74] S.-H. Ryu, C. Jonas, B. Heath, J. Richmond, A. Agarwal, and J. Palmour, *Mater. Res. Soc. Symp. Proc.* **911**, 1304 (2011).
- [75] K. Hamada, S. Hino, N. Miura, H. Watanabe, S. Nakata, E. Suekawa, Y. Ebiike, M. Imaizumi, I. Umezaki, and S. Yamakawa, *Jpn. J. Appl. Phys.* **54**, 04DP07 (2015).
- [76] N. Kaji, H. Niwa, J. Suda, and T. Kimoto, *IEEE Trans. Electron Devices* **62**, 374 (2015).
- [77] H. Miyake, T. Okuda, H. Niwa, T. Kimoto, and J. Suda, *IEEE Electron Device Lett.* **33**, 1598 (2012).
- [78] Y. Yonezawa, K. Nakayama, R. Kosugi, S. Harada, K. Koseki, K. Sakamoto, T. Kimoto, and H. Okumura, *2018 IEEE International Electron Devices Meeting (IEDM)* (2018), p. 19.3.1.
- [79] L. Cheng, J. W. Palmour, A. K. Agarwal, S. T. Allen, E. V. Brunt, G. Y. Wang, V. Pala, W. J. Sung, A. Q. Huang, M. J. O’Loughlin, A. A. Burk, D. E. Grider, and C. Scozzie, *Mater. Sci. Forum* **778–780**, 1089 (2014).
- [80] S.-H. Ryu, K. T. Kornegay, J. A. Cooper, and M. R. Melloch, *IEEE Trans. Electron Devices* **45**, 45 (1998).
- [81] N. Kuhns, L. Caley, A. Rahman, S. Ahmed, J. Di, H. A. Mantooth, A. M. Francis, and J. Holmes, *IEEE Trans. Device Mater. Reliab.* **16**, 105 (2016).
- [82] J.-Y. Lee, S. Singh, and J. A. Cooper, *IEEE Trans. Electron Devices* **55**, 1946 (2008).
- [83] L. Lanni, R. Ghandi, B. G. Malm, C.-M. Zetterling, and M. Ostling, *IEEE Trans. Electron Devices* **59**, 1076 (2012).
- [84] P. G. Neudeck, D. J. Spry, L. Chen, N. F. Prokop, and M. J. Krasowski, *IEEE Electron Device Lett.* **38**, 1082 (2017).
- [85] M. Kaneko, M. Nakajima, Q. Jin, and T. Kimoto, *IEEE Electron Device Lett.* **43**, 997 (2022).
- [86] P. Y. Yu and M. Cardona, *Fundamentals of semiconductors: Physics and materials properties* (Springer, 4th edition, 2010).
- [87] C. Hamaguchi, *Basic Semiconductor Physics* (Springer, 2nd edition, 2010).
- [88] J. B. Gunn, *Solid State Commun.* **1**, 88 (1963).
- [89] G. Romano, A. Fayyaz, M. Riccio, L. Maresca, G. Breglio, A. Castellazzi, and A. Irace, *IEEE J. Emerg. Sel. Top. Power Electron.* **4**, 978 (2016).

- [90] Y. Taur and T. H. Ning, *Fundamentals of modern VLSI devices* (Cambridge University Press, 3rd edition, 2021).
- [91] G. Pensl and W. J. Choyke, *Physica B: Physics of Condens. Matter* **185**, 264 (1993).
- [92] A. Itoh, H. Akita, T. Kimoto, and H. Matsunami, *Appl. Phys. Lett.* **65**, 1400 (1994).
- [93] W. J. Schaffer, G. H. Negley, K. G. Irvine, and J. W. Palmour, *Mater. Res. Soc. Symp. Proc.* **339**, 595 (1994).
- [94] T. Kimoto, A. Itoh, and H. Matsunami, *Phys. Status Solidi B* **202**, 247 (1997).
- [95] A. A. Burk, M. J. O’Loughlin, R. R. Siergiej, A. K. Agarwal, S. Sriram, R. C. Clarke, M. F. MacMillan, V. Balakrishna, and C. D. Brandt, *Solid State Electron.* **43**, 1459 (1999).
- [96] W. M. Chen, N. T. Son, E. Janzén, D. M. Hofmann, and B. K. Meyer, *Phys. Status Solidi A* **162**, 79 (1997).
- [97] D. Volm, B. K. Meyer, D. M. Hofmann, W. M. Chen, N. T. Son, C. Persson, U. Lindefelt, O. Kordina, E. Sörman, A. O. Konstantinov, B. Monemar, and E. Janzén, *Phys. Rev. B* **53**, 15409 (1996).
- [98] N. T. Son, C. Persson, U. Lindefelt, W. M. Chen, B. K. Meyer, D. M. Hofmann, and E. Janzén, *Cyclotron resonance studies of effective masses and band structure in SiC, Silicon Carbide – Recent Major Advances* (eds. W. J. Choyke, H. Matsunami, and G. Pensl), (Springer, 2004), p. 437.
- [99] L. Patrick and W. J. Choyke, *Phys. Rev.* **2**, 2255 (1970).
- [100] S. Ninomiya and S. Adachi, *Jpn. J. Appl. Phys.* **33**, 2479 (1994).
- [101] A. O. Konstantinov, Q. Wahab, N. Nordell, and U. Lindefelt, *Appl. Phys. Lett.* **71**, 90 (1997).
- [102] T. Hatakeyama, T. Watanabe, T. Shinohe, K. Kojima, K. Arai, and N. Sano, *Appl. Phys. Lett.* **85**, 1380 (2004).
- [103] X. Qian, P. Jiang, and R. Yang, *Mater. Today Phys.* **3**, 70 (2017).
- [104] T. Hatakeyama, T. Watanabe, M. Kushibe, K. Kojima, S. Imai, T. Suzuki, T. Shinohe, T. Tanaka, and K. Arai, *Mater. Sci. Forum* **433–436**, 443 (2003).
- [105] M. Schadt, G. Pensl, R. P. Devaty, W. J. Choyke, R. Stein, and D. Stephani, *Appl. Phys. Lett.* **65**, 3120 (1994).
- [106] H. Iwata, K. M. Itoh, and G. Pensl, *J. Appl. Phys.* **88**, 1956 (2000).

- [107] G. Bosch, *J. Phys. Chem. Solids* **27**, 795 (1966).
- [108] H. Iwata and K. M. Itoh, *J. Appl. Phys.* **89**, 6228 (2001).
- [109] S. Kagamihara, H. Matsuura, T. Hatakeyama, T. Watanabe, M. Kushibe, T. Shinohe, and K. Arai, *J. Appl. Phys.* **96**, 5601 (2004).
- [110] H. Harima, S. Nakashima, and T. Uemura, *J. Appl. Phys.* **78**, 1996 (1995).
- [111] A. Koizumi, J. Suda, and T. Kimoto, *J. Appl. Phys.* **106**, 013716 (2009).
- [112] H. Tanaka, S. Asada, T. Kimoto, and J. Suda, *J. Appl. Phys.* **123**, 245704 (2018).
- [113] J. Pernot, S. Contreras, and J. Camassel, *J. Appl. Phys.* **98**, 023706 (2005).
- [114] A. Parisini and R. Nipoti, *J. Appl. Phys.* **114**, 243703 (2013).
- [115] V. I. Sankin and A. A. Lepneva, *Semiconductors* **33**, 547 (1999).
- [116] W. v. Muench and E. Pettenpaul, *J. Appl. Phys.* **48**, 4823 (1977).

Chapter 2

Low-Field Electron Mobility

2.1 Introduction

The low-field electron mobility along the c -axis is the most important to determine the on-resistance of SiC(0001) vertical power devices. However, previous research has been focused on that perpendicular to the c -axis [1–4], and that parallel to the c -axis has been reported at limited conditions with relatively higher donor concentration [5–9] as explained in Chapter 1, and consequently leading to poor understanding of its anisotropy. In this chapter, the electron mobility along the c -axis was determined by two approaches. First, the author attempted to estimate the electron mobility along the c -axis by analyzing the electrical characteristics of SiC(0001) vertical Schottky diodes (SBDs). As the second approach, Hall effect measurements on SiC(11 $\bar{2}$ 0) samples were performed and the anisotropy in electron mobility was discussed based on theoretical calculation focusing on the anisotropy in electron effective mass.

2.2 Estimation of Electron Mobility by Using Schottky Barrier Diodes

Determining the vertical mobility (i.e., the mobility along the c -axis in SiC(0001) wafers) is not easy in general because it cannot be measured using the Hall effect measurement in principle, which is the most widely employed method for mobility characterization. This limitation arises from the fundamental mismatch between the current flow direction in Hall effect measurements (in-plane direction) and that in power device operation (vertical direction). One possible approach is to utilize SiC(11 $\bar{2}$ 0) or (1 $\bar{1}$ 00) wafers, which include the c -axis within their in-plane orientation, as the samples for Hall effect measurement. However, such special wafers are not readily available in the market for certain semiconductor materials including SiC due to challenges in crystal growth (while Hall effect measurements using SiC(11 $\bar{2}$ 0) wafers were also done in this study as explained in Section 2.3). An al-

ternative method for accurately determining the vertical mobility offers several advantages: the wafers with a special crystal face are not necessary and the complexity associated with the Hall scattering factor is avoided. On the other hand, while some papers have reported the vertical mobility obtained by using vertical Schottky barrier diodes (SBDs) [10–13], there are still issues in the analysis, such as neglecting current spreading and ignoring the contribution of series resistance components. Based on the above, the authors sought to improve this method to determine the vertical mobility with the analyses using SiC(0001) vertical SBDs with various device parameters and discussed the accuracy and validity, as the first step to investigate the carrier transport properties parallel to the c -axis.

2.2.1 Approach of Electron Mobility Estimation

Electron mobility in an n-type semiconductor is given using the electron concentration (n), the resistivity (ρ), and the elementary charge (e) by

$$\mu = \frac{1}{en\rho}. \quad (2.1)$$

Therefore, the electron mobility can be obtained by experimentally measuring the electron concentration and resistivity. In this section, both the electron concentration and the resistivity were determined from the electrical characteristics of SiC(0001) SBDs schematically illustrated in Fig. 2.1(a), and then the electron mobility parallel to the c -axis was estimated. For improving the accuracy of analysis, the thicknesses of epilayer and substrate were varied in wide ranges, as summarized in Table 2.1. The detailed procedure and experiments are explained in the following section.

2.2.1.1 Estimation Method of Electron Concentration

Accurate determination of the electron concentration in an n-type semiconductor is difficult in general without using Hall effect measurements. While it can be estimated from the donor concentration (N_D) and temperature (T), the analysis is complicated because the ionization ratio depends on these parameters. However, in the case when the donor concentration is low enough, the donors are almost completely ionized, which means one can determine the electron concentration from the net donor concentration. Figure 2.2(a) shows the ionization ratio of N donors in n-type SiC at room temperature. The result was calculated by solving the following charge neutrality equation considering hexagonal and cubic sites [14].

$$n + N_A = \frac{N_D/2}{1 + g_D \exp\left(\frac{-(E_C - E_F) + \Delta E_{D,h}}{k_B T}\right)} + \frac{N_D/2}{1 + g_D \exp\left(\frac{-(E_C - E_F) + \Delta E_{D,k}}{k_B T}\right)},$$

$$\Delta E_{D,i} = \Delta E_{D,i,0} - \alpha_D (N_D)^{1/3} \quad (i = h, k), \quad (2.2)$$

$$\Delta E_{D,h,0} = 61 \text{ meV}, \quad \Delta E_{D,k,0} = 126 \text{ meV}, \quad g_D = 2, \quad \alpha_D = 3 \times 10^{-8} \text{ eVcm}.$$

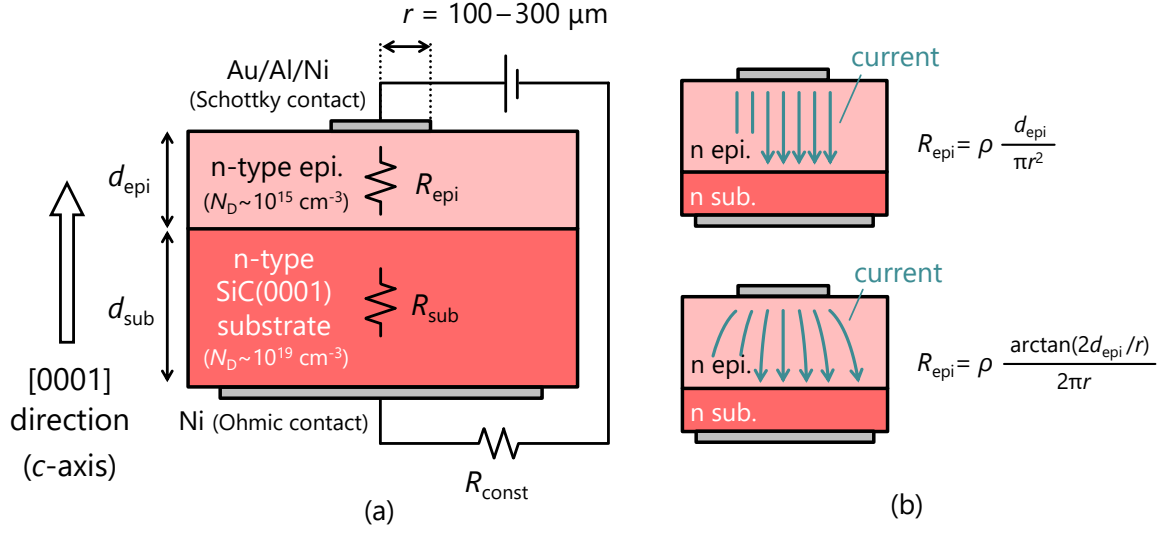


Figure 2.1: (a) Schematic illustration of the vertical Ni/n-type SiC(0001) SBD fabricated in the present study to determine the electron mobility in the n-type epilayer along the vertical direction, i.e., parallel to the c -axis, based on I - V and C - V measurements with various device parameters. Series resistance components of the SBD are also depicted, where R_{epi} and R_{sub} are the resistances of the n-type epilayer and substrate, and R_{const} is the total resistance of ohmic contact, probing, and the measurement system. (b) Schematic illustration of the current flow in a vertical SBD without and with consideration of current spreading in the epilayer, accompanied by the corresponding equations for R_{epi} . (Reproduced from R. Ishikawa *et. al.*, *Solid State Phenomena* **360**, 205 (2024).)

Table 2.1: Polishing amounts of the front and back sides, and remaining thicknesses of the epilayer and substrate for each sample. The thicknesses were varied using CMP techniques to enable a more precise analysis of the mobility.

Sample No.	Polishing Amount [μm]		Thickness after Polishing [μm]	
	Front side (Epilayer)	Back side (Substrate)	Epilayer	Substrate
S-1	0	0	45	370
S-2	10	0	35	370
S-3	23	0	22	370
S-4	30	0	15	370
S-5	40	0	5	370
S-6	30	70	15	300
S-7	30	150	15	220

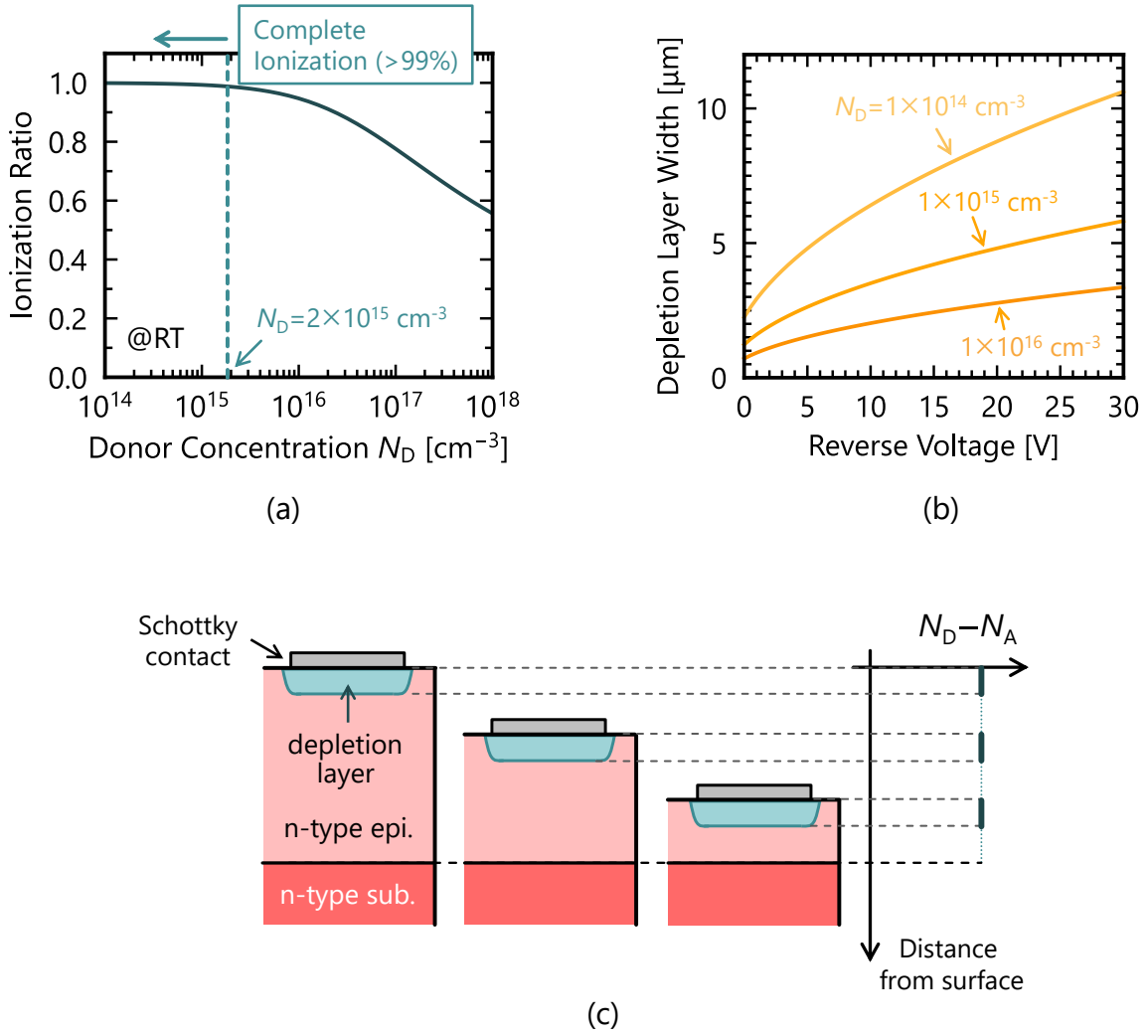


Figure 2.2: (a) Ionization ratio of nitrogen donors in SiC as a function of the donor concentration (N_D). (b) Depletion layer width versus the reverse voltage applied to Ni/n-type SiC SBDs with various N_D . (c) Schematic diagram of the present concept to determine the depth profile of the net donor concentration over a 45-μm-thick epilayer by combining polishing and C - V measurements.

Here, N_A represents the compensating acceptor concentration, E_C denotes the conduction band minimum, E_F is the Fermi level, k_B is the Boltzmann constant, $\Delta E_{D,h}$ and $\Delta E_{D,k}$ are the ionization energies of N donors at the hexagonal and cubic sites, respectively. Figure 2.2(a) suggests that the ionization ratio increases with decreasing the donor concentration, with donors being nearly fully ionized for $N_D \leq 2 \times 10^{15} \text{ cm}^{-3}$, that is, the electron concentration is almost identical to the net donor concentration ($n \simeq N_D - N_A$). Then, the author adopted a lightly doped n-type epitaxial layer ($N_D \sim 1 \times 10^{15} \text{ cm}^{-3}$) as the subject of this study, in which case one can determine n from the net donor concentration.

The net donor concentration can be determined from a capacitance–voltage (C – V) measurement of SBD since the net donor concentration at the depletion layer edge of the Schottky junction can be expressed as follows [15],

$$N_D - N_A \big|_{x=w} = 2 \left[q \varepsilon_s A^2 \frac{d(1/C^2)}{dV} \right]^{-1}, \quad w = \frac{\varepsilon_s A}{C}, \quad (2.3)$$

where x is the distance from the Schottky contact, w is the depletion layer width, ε_s is the dielectric constant of semiconductor ($10.32\varepsilon_0$ in SiC along the c -axis), and A is the area of the Schottky contact. The depth profile of net donor concentration can be obtained from the analysis based on C – V measurements and Eq. (2.3). Here, the depth range of the analysis above is limited to the region near the Schottky contact, while the present approach using Eq. (2.1) is based on the premise that the electron concentration is uniform over the measurement region. Figure 2.2(b) shows the depletion layer width versus the reverse voltage applied on Ni/n-type SiC SBDs. The depletion layer width becomes larger for lower N_D , and it is about $10 \mu\text{m}$ even when $N_D = 1 \times 10^{14} \text{ cm}^{-3}$ and the applied voltage is 30 V. This result suggests that one can obtain the net donor concentration only near the surface of sample ($\sim 10 \mu\text{m}$) by a single C – V measurement, and this is not enough compared with the epitaxial layer thickness of the prepared sample in our study ($d_{\text{epi}} \sim 45 \mu\text{m}$). Then, the author varied the thickness of epilayer by polishing samples and determined the net donor concentration over a wide depth range by performing C – V measurements on SBDs fabricated each sample with different d_{epi} . The schematic of the present concept is shown in Fig. 2.2(c). It is worth noting that designing d_{epi} to be small ($< 10 \mu\text{m}$) is preferable in the perspective to confirm a uniform profile of electron concentration in the epilayer though, d_{epi} should be thick enough for the following analysis to ensure that the resistance of the epilayer is greater than that of other components.

2.2.1.2 Estimation Method of Resistivity

The resistivity of epilayer (ρ) can be estimated from the series resistance (R) of the vertical SiC SBDs. The simplest method to derive ρ from the total series resistance is to use the equation below:

$$R = \rho \frac{d_{\text{epi}}}{\pi r^2}, \quad (2.4)$$

where it is assumed that R is equal to the resistance of the cylindrical region of the epilayer with radius r and height d_{epi} . However, there are two issues with the analysis based on Eq. (2.4). The first one is that R should be the total of the epilayer resistance (R_{epi}), the substrate resistance (R_{sub}), and the other resistance components including probing and measurement system (R_{const}), as illustrated in Fig. 2.1(a). These components must be carefully separated for an accurate analysis because it leads to an overestimation of ρ . The second issue is that Eq. (2.4) assumes the current flows solely along the vertical direction without spreading, whereas, in reality, the current spreads out in the epilayer as illustrated in Fig. 2.1(b). Taking into account both the components of the series resistance and the current spreading, R is expressed by the following equation [15–17].

$$\begin{aligned} R(r, d_{\text{epi}}, d_{\text{sub}}) &= R_{\text{epi}}(r, d_{\text{epi}}) + R_{\text{sub}}(r, d_{\text{sub}}) + R_{\text{const}} \\ &= \rho \frac{\arctan(2d_{\text{epi}}/r)}{2\pi r} + R_{\text{sub}}(r, d_{\text{sub}}) + R_{\text{const}}. \end{aligned} \quad (2.5)$$

Here, R_{sub} was assumed to be independent on the epilayer thickness and to have a linear relationship with d_{sub} ($R_{\text{sub}} \propto d_{\text{sub}}$) for a simple analysis. The resistivity was estimated using the following procedure based on Eq. (2.5). After extracting the substrate resistance from SBDs with varying d_{sub} , a fitting was performed on the total series resistance of SBDs with different r and d_{epi} , where ρ and R_{const} were obtained as fitting parameters. It should be noted that this analysis assumes that the current flows uniformly at the Schottky interfaces as discussed in the follow section.

2.2.2 Sample Preparation and Measurements

A SiC(0001) substrate with an n-type epilayer ($N_{\text{D}} = 1 \times 10^{15} \text{ cm}^{-3}$) was prepared, and the thicknesses of epilayer and substrate were varied by chemical-mechanical polishing (CMP), as summarized in Table 2.1. After forming an ohmic contact on the bottom side of samples with Ni (100 nm) followed by annealing (950°C, 2 min, vacuum), Au (150 nm)/Al (310 nm)/Ni (130 nm)/SiC SBDs were fabricated on the top side of these samples, as illustrated in Fig. 2.1(a). Electrode patterning was performed with a lithography and a lift-off process and the radius of Schottky contact was varied in 100–300 μm . Both Al and Au metals were deposited to ensure current uniformity at the Ni/SiC Schottky interface, to make the electrodes thick enough and to protect them from natural oxidation, respectively. Using the SBDs with various device parameters (r , d_{epi} , and d_{sub}) prepared by this procedure, the authors performed current–voltage (I – V) and C – V measurements for each device.

2.2.3 Results and Analyses

2.2.3.1 Estimated Result of Electron Concentration

The net donor concentration was determined from C – V measurements on each device with different d_{epi} , and as an example, the obtained result for sample S-1 ($d_{\text{epi}} = 45 \text{ }\mu\text{m}$) is

shown in Fig. 2.3(a). Figure 2.3(b) represents the summarized depth profile obtained from various devices, where the net donor concentration was found to remain uniform along the depth direction throughout the entire epilayer. By averaging these results, the electron concentration was determined to be $n \simeq N_D - N_A \simeq 9.7 \times 10^{14} \text{ cm}^{-3}$.

2.2.3.2 Estimated Result of Resistivity

Forward I - V characteristics for SBDs fabricated on sample S-1 with different r values are plotted in Fig. 2.4. The current decreases as r becomes smaller, indicating larger series resistances of SBDs. Linear extrapolation was performed in the current range of 30–80 mA for each plot and the series resistances were extracted from the slopes, as shown by solid lines in Fig. 2.4. The same analyses were conducted on four SBDs with each device parameters, and the results are discussed as follow. Figure 2.5(a) shows the series resistance of SBDs ($d_{\text{epi}} = 15 \text{ } \mu\text{m}$ and $r = 300 \text{ } \mu\text{m}$) as a function of d_{sub} . The substrate resistance of samples without polishing the substrate side ($d_{\text{sub}} = 370 \text{ } \mu\text{m}$) was extracted by linear extrapolation, as shown in Fig. 2.5(a), and the results are summarized in Fig. 2.5(b) as a function of r . Smaller R_{sub} for larger r is reasonable because the area where the current flows becomes larger in the substrates. The obtained R_{sub} was subtracted from the total series resistance, and the results are plotted by symbols in Fig. 2.6. Next, a fitting based on Eq. (2.5) was performed, resulting in the fitting parameters to be $\rho \simeq 6.1 \text{ } \Omega\text{cm}$ and $R_{\text{const}} \simeq 8.4 \text{ } \Omega$. The fitting results for $R - R_{\text{sub}}$ vs. r relationship are depicted by the dashed lines in Fig. 2.6, which reproduce the experimental results well.

It should be supplemented that for an accurate analysis, the current uniformity in the Schottky contact should be carefully considered because r is an important parameter for the resistivity analysis. In cases with thinner metal electrode compared to r as in the present case, the current may not spread sufficiently within the metal and instead concentrate beneath the probe point. This could make the effective area of current smaller than the actual contact area, leading to an inaccurate analysis. Then, I - V characteristics under two different conditions were compared: (i) with one and (ii) two probe needles placed on the Schottky electrode, as shown in Fig. 2.7. The obtained results showed almost no dependence on the number of needles, ensuring that the current at the interface is uniform even with one needle, and setup with a needle was adopted for the present analysis.

2.2.4 Discussion

The validity of the analysis method of the resistivity used in the present study is discussed in the former part of this section. Figure 2.8 shows the comparison of the resistivity determined by three different methods: (a) ignoring both the substrate resistance R_{sub} and current spreading, (b) considering R_{sub} and ignoring current spreading, (c) considering both R_{sub} and current spreading (the present method). As can be seen, the result of (c) is more independent of r and d_{epi} , which means the method (c) is more valid compared with others

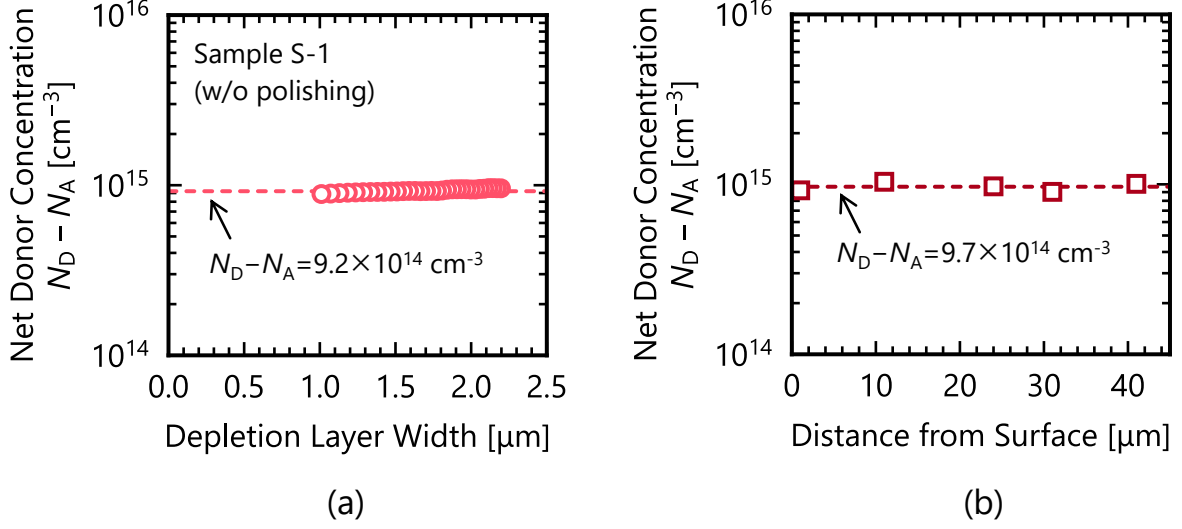


Figure 2.3: (a) Depth profile of the net donor concentration $N_D - N_A$ determined by a C - V measurement on a Ni/SiC SBD ($d_{\text{epi}} = 45 \mu\text{m}$, $r = 300 \mu\text{m}$). (b) Depth profile of $N_D - N_A$ from the epilayer surface obtained from the SBDs with different d_{epi} . (Reproduced from R. Ishikawa *et. al.*, *Solid State Phenomena* **360**, 205 (2024).)

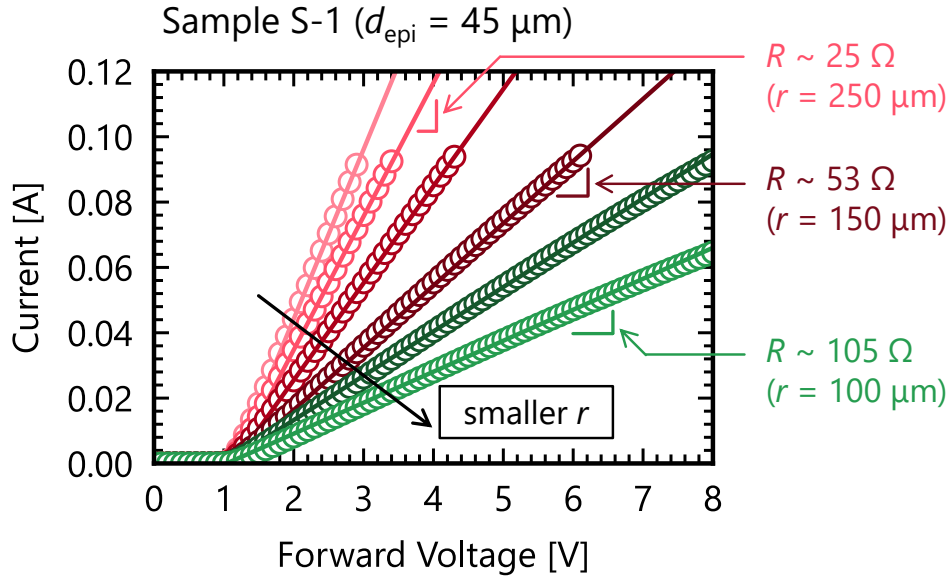


Figure 2.4: Forward I - V characteristics of Ni/n-type SiC SBDs ($d_{\text{epi}} = 45 \mu\text{m}$) with various radii of Schottky contact (r). Different colors represent the results with different r . The total series resistance (R) was determined from the slope of each result. (Reproduced from R. Ishikawa *et. al.*, *Solid State Phenomena* **360**, 205 (2024).)

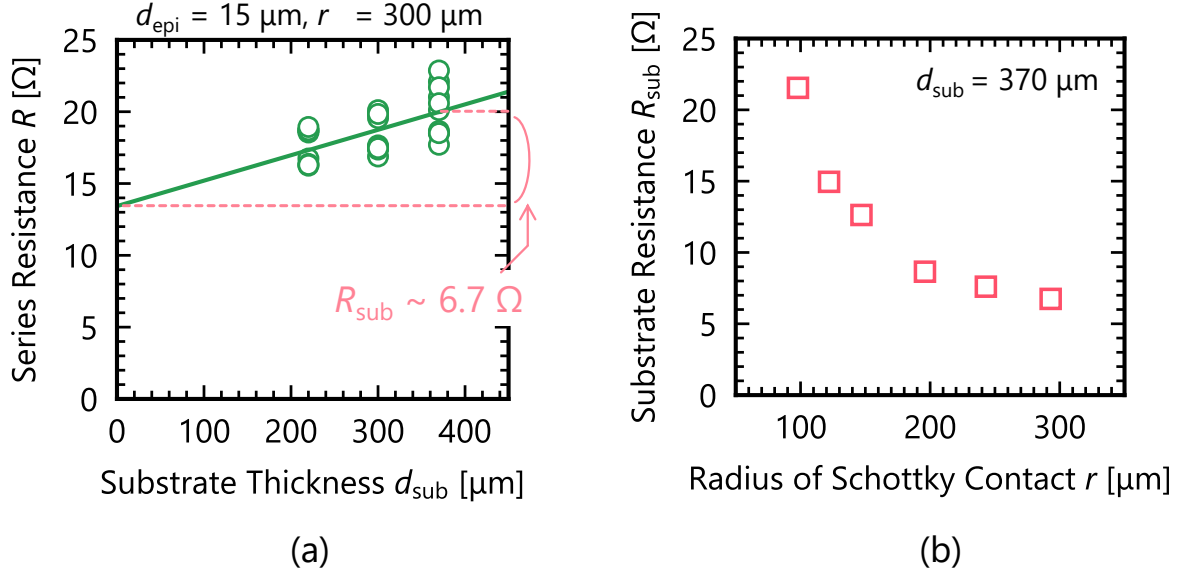


Figure 2.5: (a) Series resistance of SBDs (R) as a function of substrate thickness (d_{sub}) for an epilayer thickness $d_{\text{epi}} = 15 \mu\text{m}$ and a Schottky radius $r = 300 \mu\text{m}$. The substrate resistance (R_{sub}) was extracted based on a linear approximation. (b) Obtained R_{sub} as a function of r ($d_{\text{sub}} = 370 \mu\text{m}$). (Reproduced from R. Ishikawa *et. al.*, *Solid State Phenomena* **360**, 205 (2024).)

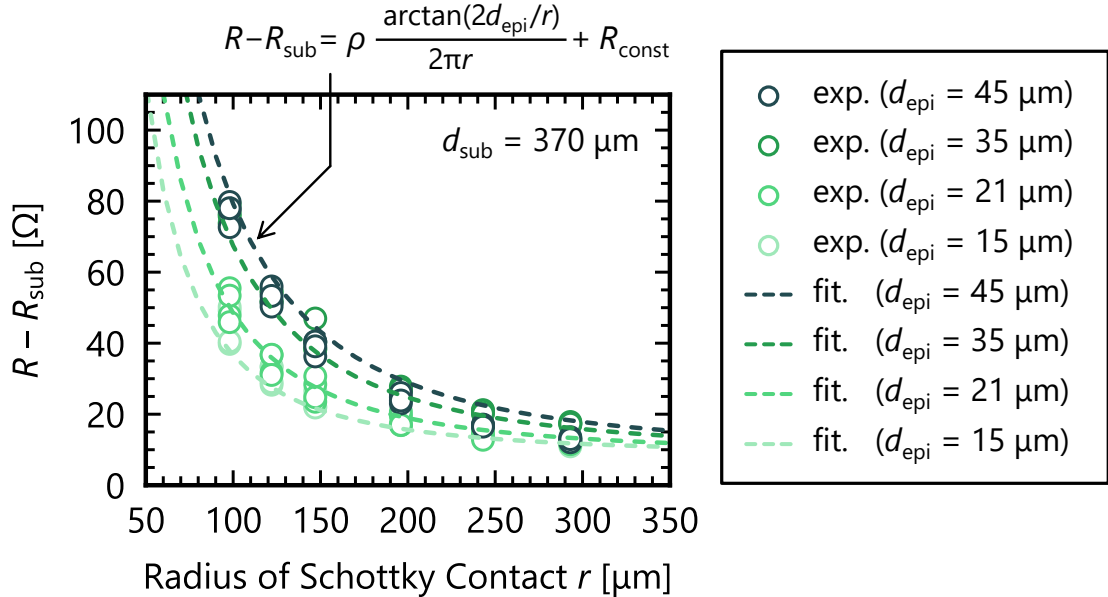


Figure 2.6: $R - R_{\text{sub}}$ versus Schottky contact radius (r) obtained from SBDs with various epilayer thicknesses (d_{epi}). Dashed lines in the figure show the fitting results based on Eq. (2.5), where the fitting parameters were obtained as $\rho \simeq 6.1 \Omega\text{cm}$ and $R_{\text{const}} \simeq 8.4 \Omega$. (Reproduced from R. Ishikawa *et. al.*, *Solid State Phenomena* **360**, 205 (2024).)

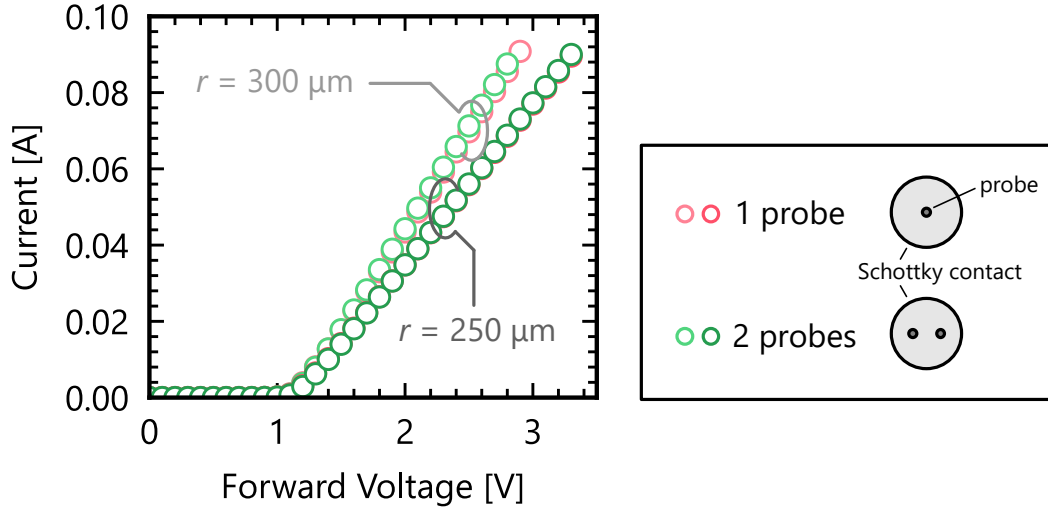


Figure 2.7: Comparison of I - V characteristics of SiC SBD in cases where one and two probe needles are placed on the Schottky contact. The number of probe needles makes little difference in the measurement results.

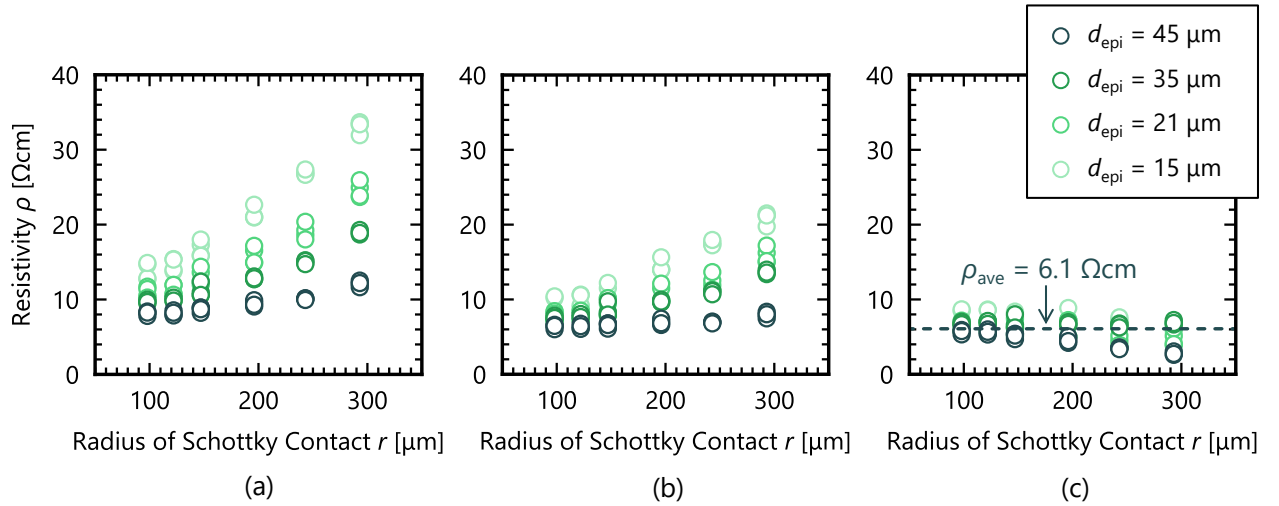


Figure 2.8: Resistivity (ρ) of the n-type epilayer versus the electrode radius (r) obtained by three different analyses, (a) ignoring both the substrate resistance R_{sub} and current spreading, (b) considering R_{sub} and ignoring current spreading, (c) considering both R_{sub} and current spreading. (Reproduced from R. Ishikawa *et al.*, *Solid State Phenomena* **360**, 205 (2024).)

because the resistivity should be independent of these parameters. The tendency that the variation of the resistivity increases for larger r and smaller d_{epi} can be explained by that R_{epi} is smaller and more easily affected by the resistance of other components.

Finally, $\mu_{//}$ was determined from the obtained n and ρ to be $\mu_{//} \sim 1070 \text{ cm}^2/\text{Vs}$ with an accuracy of $\pm 290 \text{ cm}^2/\text{Vs}$. Although $\mu_{//}$ obtained in this study still exhibits a large uncertainty, the average value is slightly higher than the Hall mobility perpendicular to the c -axis in lightly-doped samples ($1020 \text{ cm}^2/\text{Vs}$) reported previously [14]. Taking into account that the Hall mobility is influenced by the Hall scattering factor (> 1), and by which the Hall mobility is slightly overestimated in comparison with the drift mobility, it is suggested that $\mu_{//}$ is higher than $\mu_{\perp}$ and this anisotropy is consistent with the result of a previous study [5]. The validity of the absolute value of obtained $\mu_{//}$ will be discussed after showing the result of Hall effect measurements in Section 2.3.

2.3 Electron Mobility Determined by Hall Effect Measurement

Determining the mobility along the c -axis using SiC(0001) wafers remains challenging, even with improvements in measurement techniques and analysis as discussed in the previous section. As an alternative approach, the author performed Hall effect measurements on SiC(11 $\bar{2}$ 0) samples, which can potentially provide a systematic database of electron mobility across various doping concentrations and temperatures. Additionally, this approach allows to determine the anisotropy in electron mobility, i.e., the difference in the electron mobilities parallel and perpendicular to the c -axis with the same condition including the doping concentration and temperature. However, while there have been some reports on the electron mobility parallel to the c -axis by similar approaches [5–7], the donor concentration and temperature dependences have not been thoroughly investigated, leading to poor understanding of electron transport properties in SiC including their anisotropy. Therefore, the objective of this section is to characterize the electron mobilities along both directions parallel and perpendicular to the c -axis.

2.3.1 Determination Method of Anisotropic Mobility

Determination method of anisotropic mobility in SiC using SiC(11 $\bar{2}$ 0) samples is described in this section. The explanation begins with the principle of Hall effect measurements and continues with the concept to investigate the mobility anisotropy.

2.3.1.1 Principle of Hall Effect Measurements

In Hall effect measurements, carrier concentration and resistivity can be obtained by combining the electrical characterization with the application of a magnetic field, which leads

to the determination of carrier mobility [15]. Figure 2.9 shows the schematic setup of Hall effect measurement (for an n-type semiconductor), where the sample has a width (w) and thickness (t). When current flows along the y -direction and a magnetic field (B) is applied along the x -direction, the traveling electrons experience a Lorentz force, which deflects them along the z -direction, generating the Hall voltage V_H along the z -direction. The electron concentration (n) can be determined from V_H , as they are related to each other by the following questions:

$$V_H = \frac{\gamma_H BI}{ent} \quad \therefore n = \frac{\gamma_H BI}{eV_H t}, \quad (2.6)$$

where γ_H is the Hall scattering factor and I is the current. Additionally, the voltage drop V_ρ of the region with a length L , measured without applying the magnetic field, gives the resistivity (ρ) as follows:

$$V_\rho = \rho I \frac{L}{Wt} \quad \therefore \rho = \frac{V_\rho Wt}{IL}. \quad (2.7)$$

The mobility (μ) can be determined using n and ρ obtained in the above equations,

$$\mu = \frac{1}{en\rho} = \frac{LV_H}{\gamma_H BWV_\rho}. \quad (2.8)$$

Typically, the Hall scattering factor is assumed to be unity in Hall effect measurements although it can be different from unity depending on the carrier scattering mechanism. In this dissertation, the mobility obtained based on the assumption ($\gamma_H = 1$) is referred to as “Hall electron mobility” (μ_H) to distinguish it from the “drift electron mobility” (μ), which represents the true mobility of electrons. Similarly, the term “Hall electron concentration” (n_H), assuming $\gamma_H = 1$, is used to differentiate it from the actual “electron concentration” (n). The relationships between μ_H and μ , and n_H and n are given by:

$$\mu_H = \gamma_H \mu, \quad n_H = n / \gamma_H. \quad (2.9)$$

2.3.1.2 Van der Pauw structure and Hall Bar Structure

The van der Pauw structure shown in Fig. 2.10(a) is often employed to obtain the mobility or carrier concentration in Hall effect measurements. However, the measurements with this structure only provide an average mobility of the in-plane direction because the current flows in multiple directions (along both the 1–2 and 1–4 directions). This characteristic makes the van der Pauw structure unsuitable for analyzing anisotropic in-plane mobilities, as is the case with SiC(11 $\bar{2}$ 0) samples, where the mobility varies depending on the direction. In contrast, a Hall bar structure illustrated in Fig. 2.10(b) allows for the measurement of mobility along a specific direction because the current is constrained to flow in only one direction (along the 5-6 direction in the figure). In this setup, V_H is measured across electrodes 1 and 2, or 3 and 4, while V_ρ is measured by electrodes 1 and 4, or 2 and 3. For the reason above, Hall bar structures were adopted for the present study, which enables the investigation of anisotropic mobility by carefully designing structures to control the current’s direction and extract the mobility along desired axes. This approach is particularly important for materials like SiC, where the mobility anisotropy must be accurately characterized.

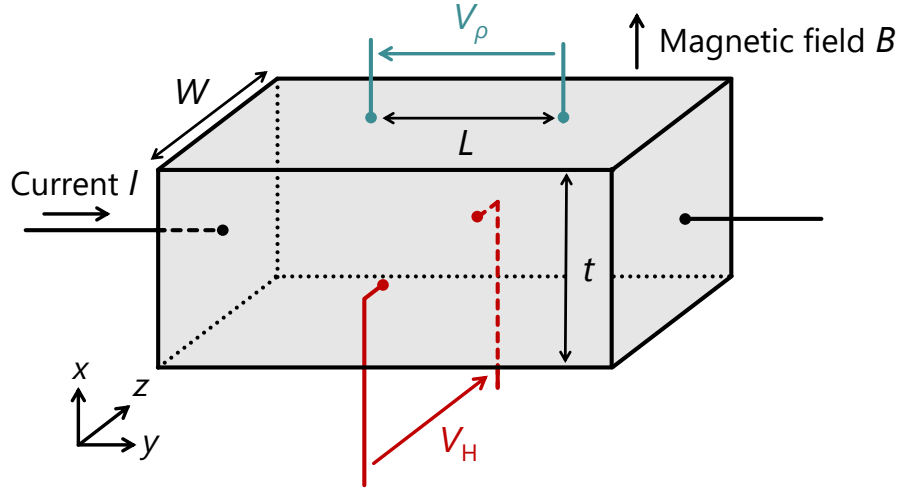


Figure 2.9: Schematic diagram of the principle of Hall effect measurement. One can obtain the resistivity from the voltage drop V_ρ and the carrier concentration from the Hall voltage V_H , and can determine the mobility from these measurements.

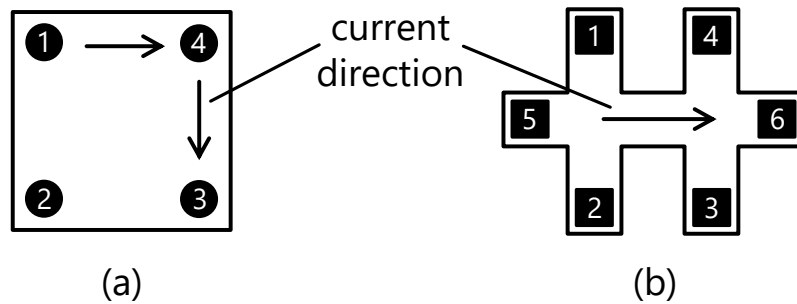


Figure 2.10: Two common structures for Hall effect measurement: (a) van der Pauw structure and (b) Hall bar structure. The latter structure is appropriate when the mobility is anisotropic because it enables the determination of mobility along a particular direction by restricting the current flow in one direction.

2.3.2 Design and Fabrication of Hall Bar Structures

2.3.2.1 Design of Hall Bar Structure

The author designed the Hall bar structure with specific considerations to ensure accurate mobility measurements. The schematic of the designed Hall bar structure is depicted in Fig. 2.11, which includes the following key definition of dimensions: the length and width of the main bar region where V_H and V_ρ are measured (L_1 and W), a length between the electrode 5 or 6 to the main bar region (L_2), and a width of the connection part between the electrode 1–4 and the bar region (L_3). First, L_2 should be larger than W ($L_2 > W$) to ensure that electrons flowing from the electrode 5 or 6 are sufficiently deflected before reaching the connection parts near the electrodes 1–4, allowing accurate measurements of V_H . Second, L_3 should be designed to be as small as possible because small L_3 prevents two-dimensional (not straight) current flow near the connection part with the electrodes 1–4, which could otherwise lead to inaccuracies in V_H and V_ρ . Finally, the resistance between the electrodes 1–4 and the bar region should be minimized to facilitate precise measurements of electric potential and to make contact check easier. Based on these considerations, the structure parameters were chosen as follows: $L_1 = 200 \mu\text{m}$, $L_2 = 180 \mu\text{m}$, $L_3 = 20 \mu\text{m}$, and $W = 80 \mu\text{m}$ as shown in Fig. 2.11(a), and the connection regions with the terminals 1–4 to the bridge were designed to $200 \mu\text{m}$ -wide and heavily-doped regions were formed by phosphorus (P) ion implantation, as illustrated in Fig. 2.11(b), to further improve measurement accuracy.

2.3.2.2 Fabrication Process of Hall Bar Structure

Hall bar structures were fabricated on SiC(11 $\bar{2}$ 0) n-type epitaxial layers, which were electrically isolated from the n-type substrates by intermediate p-type epitaxial layers as shown in Fig. 2.12(a) and (b). These epitaxial layers were prepared by the chemical vapor deposition (CVD) process with nitrogen (N) and aluminum (Al) atoms introduced to achieve n- and p-type doping during the growth. Two types of Hall bar structures were arranged side by side on the same sample, one was oriented along the [0001] direction to measure the Hall electron mobility parallel to the c -axis ($\mu_{H, //}$), and the other was oriented along the [1 $\bar{1}$ 00] direction for that perpendicular to the c -axis ($\mu_{H, \perp}$). These Hall bar structures were fabricated on nine kinds of samples with different donor concentrations of the n-type epilayers from $5 \times 10^{14} \text{ cm}^{-3}$ to $4 \times 10^{18} \text{ cm}^{-3}$. In addition, lateral SBDs were also fabricated on the same samples to determine the net donor concentration. The detailed fabrication process is explained using Fig. 2.13 and Fig. 2.14 as follows:

1. Epitaxial Growth

- (a) Continuous growth of n-/p-type layers on SiC(11 $\bar{2}$ 0) substrate by the CVD process.

2. Ion Implantation

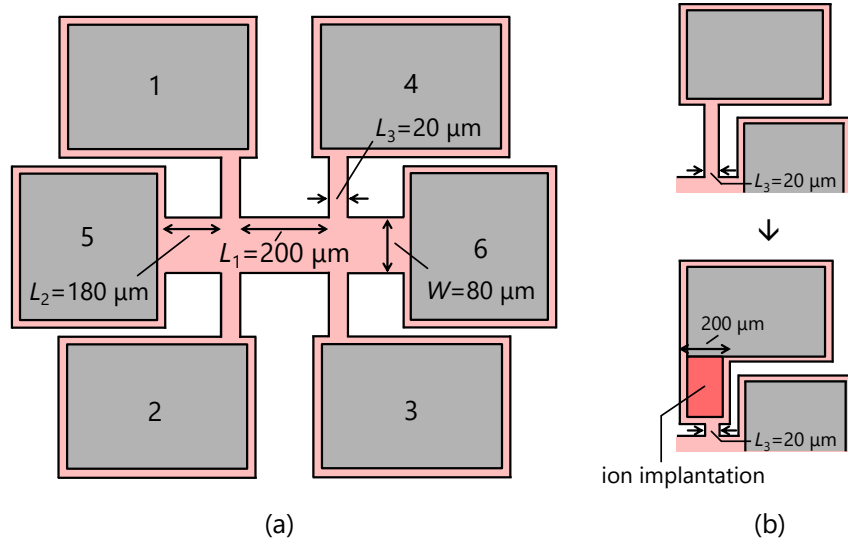


Figure 2.11: (a) Schematic illustration and main dimensions of the designed Hall bar structure for measuring electron mobilities, and (b) detailed structure of the connection part of electrodes 1–4 and bar region.

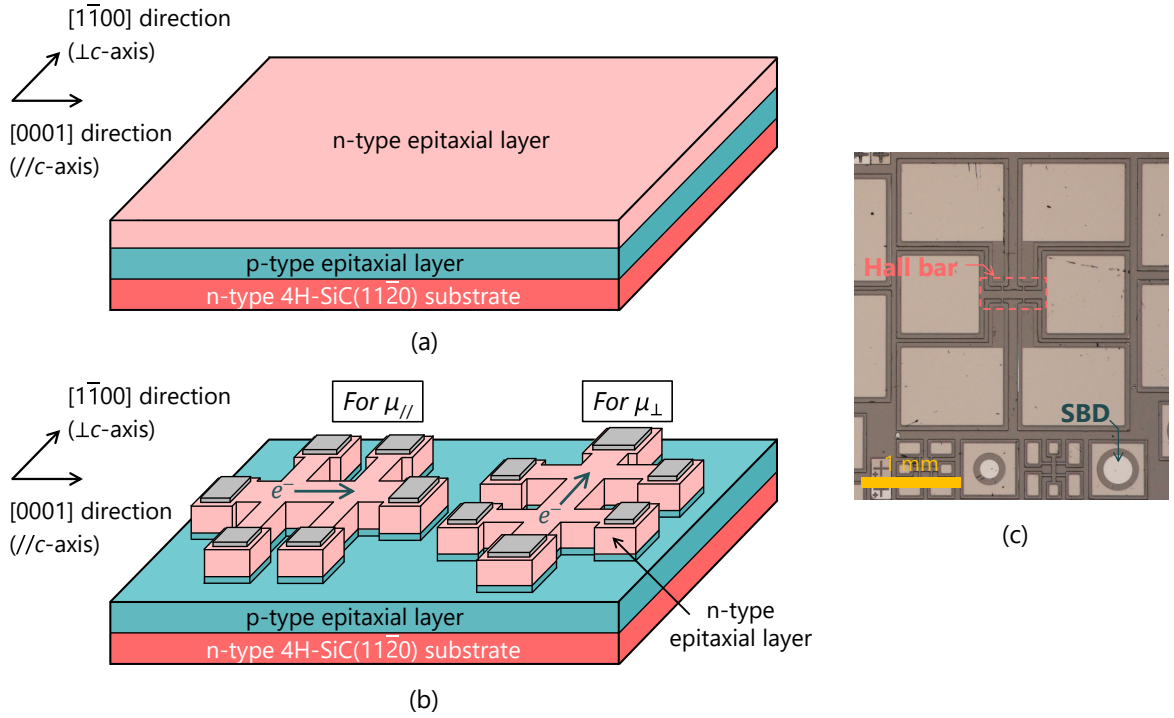


Figure 2.12: (a) n-type epitaxial layer grown on an n-type SiC(11 $\bar{2}$ 0) substrate with an intermediate p-type epitaxial layer. (b) Hall bar structures along the [0001] and [1 $\bar{1}$ 00] directions for measuring the Hall electron mobility along the c -axis ($\mu_{H,\parallel}$) and that perpendicular to the c -axis ($\mu_{H,\perp}$) fabricated on the sample. (© IOP Publishing. Reproduced with permission from R. Ishikawa *et al.*, *Appl. Phys. Express* **14**, 061005 (2021). All rights reserved.) (c) Optical microscope image of fabricated structures including a Hall bar structure for measuring electron mobility and lateral Schottky barrier diodes (top view).

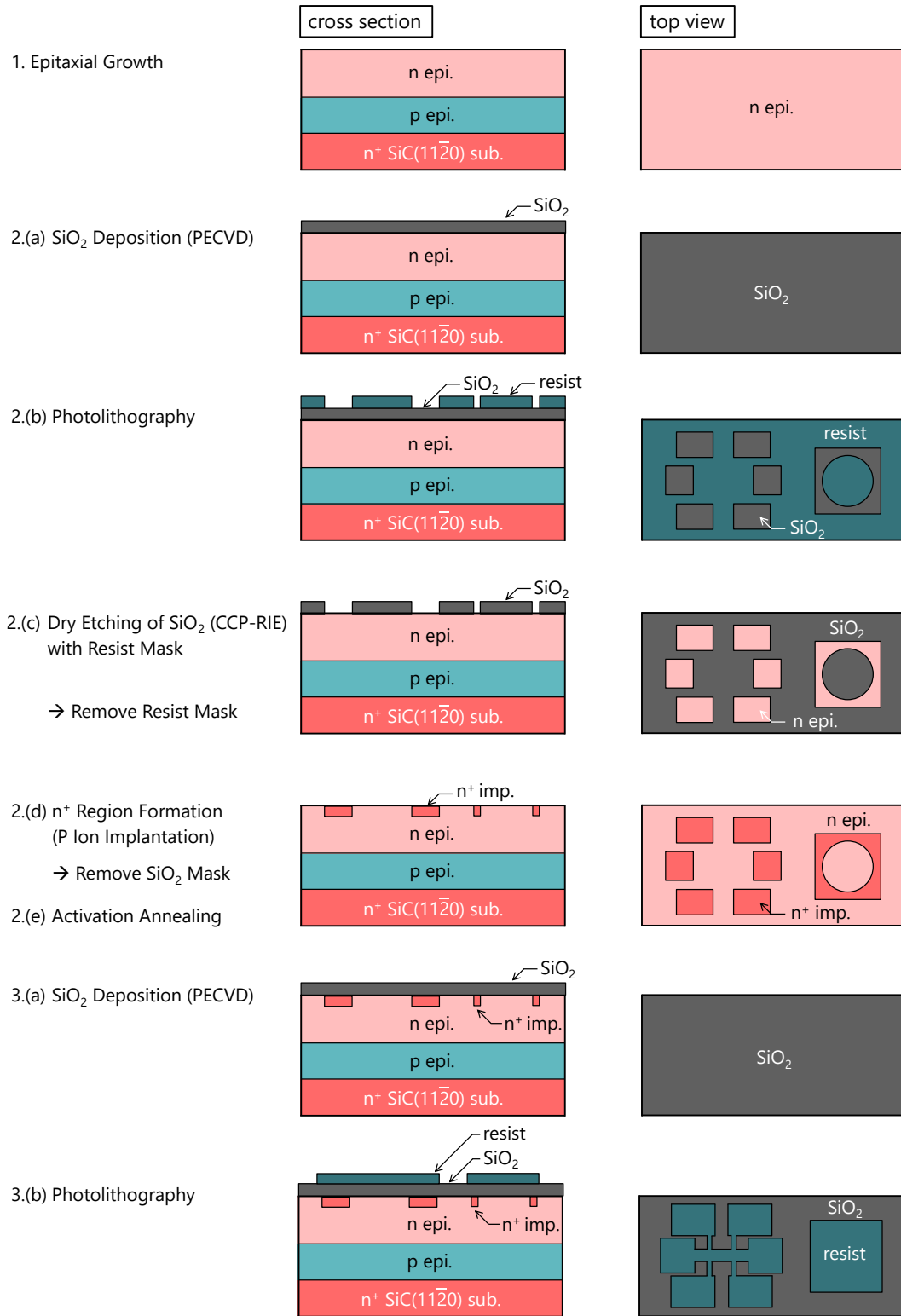


Figure 2.13: Fabrication process flow of Hall bar structure for measuring electron mobility and lateral Schottky barrier diode for C - V measurement (1/2).

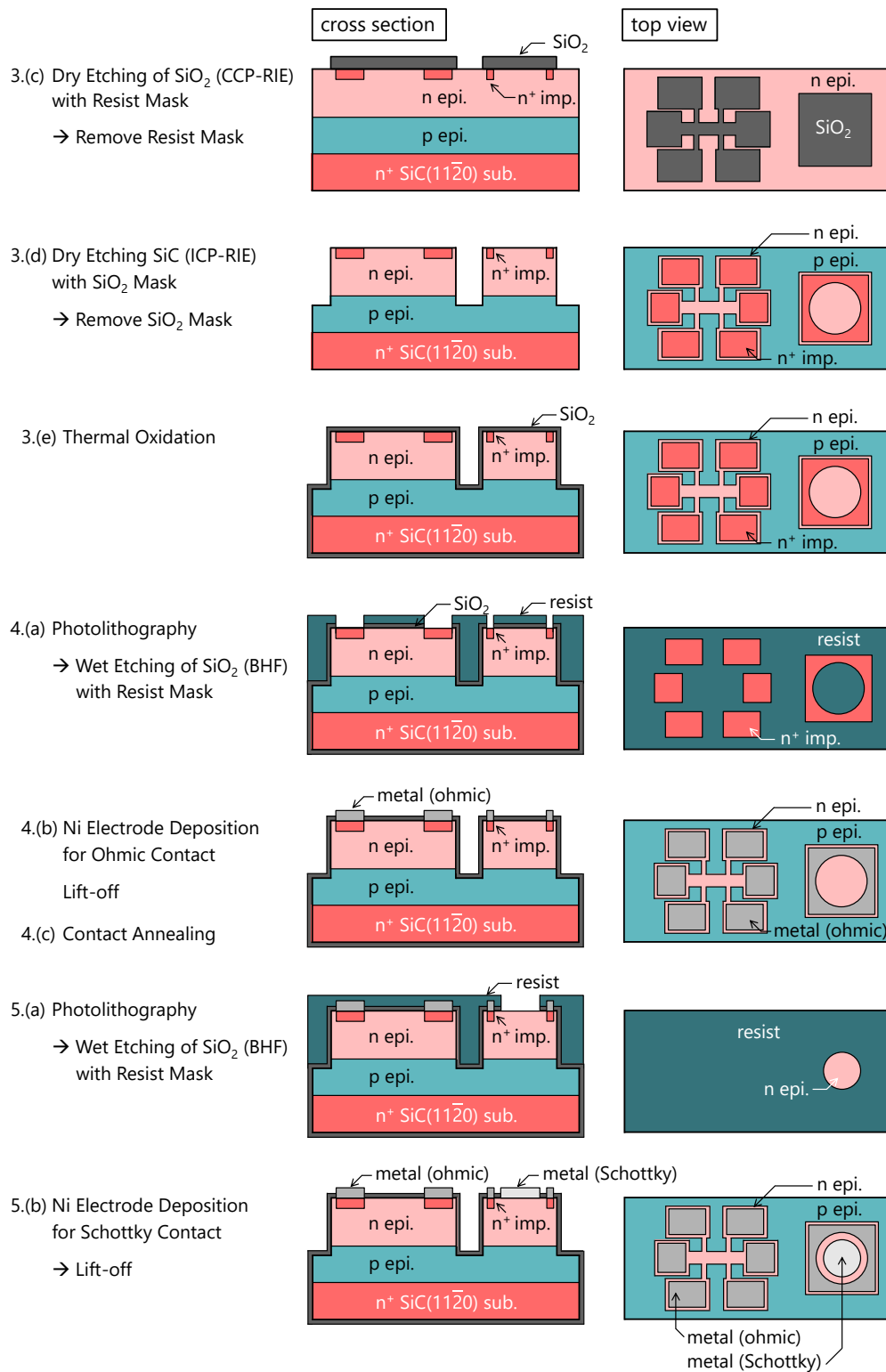


Figure 2.14: Fabrication process flow of Hall bar structure for measuring electron mobility and lateral Schottky barrier diode for C - V measurement (2/2).

- (a) Deposition of SiO_2 ($\sim 2.4 \mu\text{m}$) by plasma-enhanced chemical vapor deposition (PECVD) with TEOS/ O_2 flow.
- (b) Formation of a resist pattern by photolithography.
- (c) Dry etching of SiO_2 using a resist mask by capacitive-coupled plasma reactive ion etching (CCP-RIE) with CF_4/H_2 flow, and resist removal using a piranha solution.
- (d) Formation of the n^+ region by P ion implantation (concentration: $1 \times 10^{20} \text{ cm}^{-3}$, thickness: 300 nm), followed by the removal of residual SiO_2 with a HF solution.
- (e) Activation annealing with a carbon cap (1750°C , 20 min, under Ar flow) [18].

3. Mesa Isolation

- (a) Deposition of SiO_2 ($\sim 3.0 \mu\text{m}$) by PECVD with TEOS/ O_2 flow.
- (b) Formation of a resist pattern by photolithography.
- (c) Dry etching of SiO_2 using a resist mask by CCP-RIE with CF_4/H_2 flow, followed by resist removal using a piranha solution.
- (d) Dry etching of SiC with SiO_2 as a mask by inductively-coupled plasma reactive ion etching (ICP-RIE) with $\text{SF}_6/\text{O}_2/\text{Ar}$ flow under the following condition: [$\text{SF}_6/\text{O}_2/\text{Ar}$: 10/20/100 sccm, ICP/Bias power: 500/100 W, pressure: 2 Pa, etching rate: $0.7 \mu\text{m}$], and the removal of remaining SiO_2 with a HF solution.
- (e) Thermal oxidation (1150°C , 40 min) and removal of generated SiO_2 film ($\sim 60 \text{ nm}$) with a HF solution to eliminate etching damage, followed by another thermal oxidation (1150°C , 10 min) to form a SiO_2 passivation film ($\sim 30 \text{ nm}$).

4. Ohmic Metal Formation

- (a) Formation of a resist pattern by photolithography, followed by localized removal of the SiO_2 passivation film using buffered HF (BHF) with a resist mask.
- (b) Ni electrode deposition ($\sim 150 \text{ nm}$) and lift-off process.
- (c) Contact annealing (950°C , 2 min, vacuum).

5. Schottky Metal Formation

- (a) Formation of a resist pattern by photolithography, followed by localized removal of the SiO_2 passivation film using BHF with a resist mask.
- (b) Ni electrode deposition ($\sim 150 \text{ nm}$) and lift-off process.

An optical microscope image of the fabricated Hall bar structure and lateral SBD is shown in Fig. 2.12(c).

Hall effect measurements were performed on these fabricated structures with a magnetic field strength of 0.5 T in the temperature range from 140 K to 600 K, and the Hall electron concentration, resistivity, and Hall electron mobility were determined for both directions parallel and perpendicular to the c -axis. The current values for the measurements were chosen properly for each donor concentration and temperature so that the measurement voltages are not affected by the noise of measurement system and self-heating, where

typical values are 10 μA for $N_D = 5 \times 10^{14} \text{ cm}^{-3}$ and 6 mA for $N_D = 4 \times 10^{18} \text{ cm}^{-3}$ at room temperature. In addition, the net donor concentration was determined from C - V measurements on the lateral SBDs.

2.3.3 Electron Mobility versus Donor Concentration and Temperature

2.3.3.1 Donor Concentration Dependence of Electron Mobility

Figure 2.15(a) shows the donor concentration dependences of the Hall electron mobilities parallel and perpendicular to the c -axis ($\mu_{H, //}$ and $\mu_{H, \perp}$) obtained at room temperature. Notably, the present study determined $\mu_{H, //}$ over a wide donor concentration range, from $5 \times 10^{14} \text{ cm}^{-3}$ to $4 \times 10^{18} \text{ cm}^{-3}$, whereas previous reports provide values of $\mu_{H, //}$ for only two, relatively high donor concentrations of $1 \times 10^{17} \text{ cm}^{-3}$ and $6 \times 10^{18} \text{ cm}^{-3}$ [5, 8]. A significant finding is a high $\mu_{H, //}$ of $1210 \text{ cm}^2/\text{Vs}$ was obtained for N_D of $2 \times 10^{15} \text{ cm}^{-3}$ at 300 K, and this value represents the highest electron mobility ever measured for SiC at room temperature, even when considering other polytypes like 3C- and 6H-SiC [1–5, 11, 19–27]. Additionally, $\mu_{H, //}$ was 1.1–1.2 times higher than $\mu_{H, \perp}$ at room temperature, which has a positive impact on power device applications since the current flows along the c -axis in typical SiC power devices fabricated on SiC(0001) wafers. Note that $\mu_{H, \perp}$ determined in this study is almost the same as that reported using SiC(0001) samples previously [14], suggesting that the present measurements are reasonable and the defect concentration in the SiC(11 $\bar{2}$ 0) epilayers is sufficiently low to avoid defects impacting the mobility. The results that $\mu_{H, //}$ and $\mu_{H, \perp}$ increase with decreasing N_D and approach certain values can be explained by the underlying carrier scattering mechanism. At lower N_D , the effect of impurity scattering diminishes and that of phonon scattering becomes dominant, resulting in a constant value of mobility. Conversely, at higher N_D , impurity scattering becomes more pronounced, which lowers the mobility.

Here, it should be noted that the donor concentration was determined by combining the net donor concentration obtained from C - V measurements on lateral SBDs and the atom concentrations of donor- and acceptor-type impurities obtained from secondary ion mass spectrometry (SIMS) analysis. The results of these measurements and analyses are depicted in Fig. 2.16(a) and (b), and the obtained results are summarized in Table 2.2, where the net donor concentrations show good agreement with the N atom concentration. The acceptor-type impurities concentrations were assumed to be $2 \times 10^{14} \text{ cm}^{-3}$ for the samples with $N_D \geq 5 \times 10^{15} \text{ cm}^{-3}$ and $5 \times 10^{13} \text{ cm}^{-3}$ with $N_D \leq 2 \times 10^{15} \text{ cm}^{-3}$, and the donor concentration was calculated by adding the acceptor-type impurities concentrations ($[\text{Al}] + [\text{B}]$) to the net donor concentration, i.e., $N_D \simeq (N_D - N_A) + [\text{Al}] + [\text{B}]$.

The donor concentration dependences of $\mu_{H, //}$ and $\mu_{H, \perp}$ at several temperatures from 300 K to 600 K are shown in Fig. 2.15(b) and (c). The obtained dependences were fitted using the following formula, which is a Caughey-Thomas-based empirical equation [28] expressing

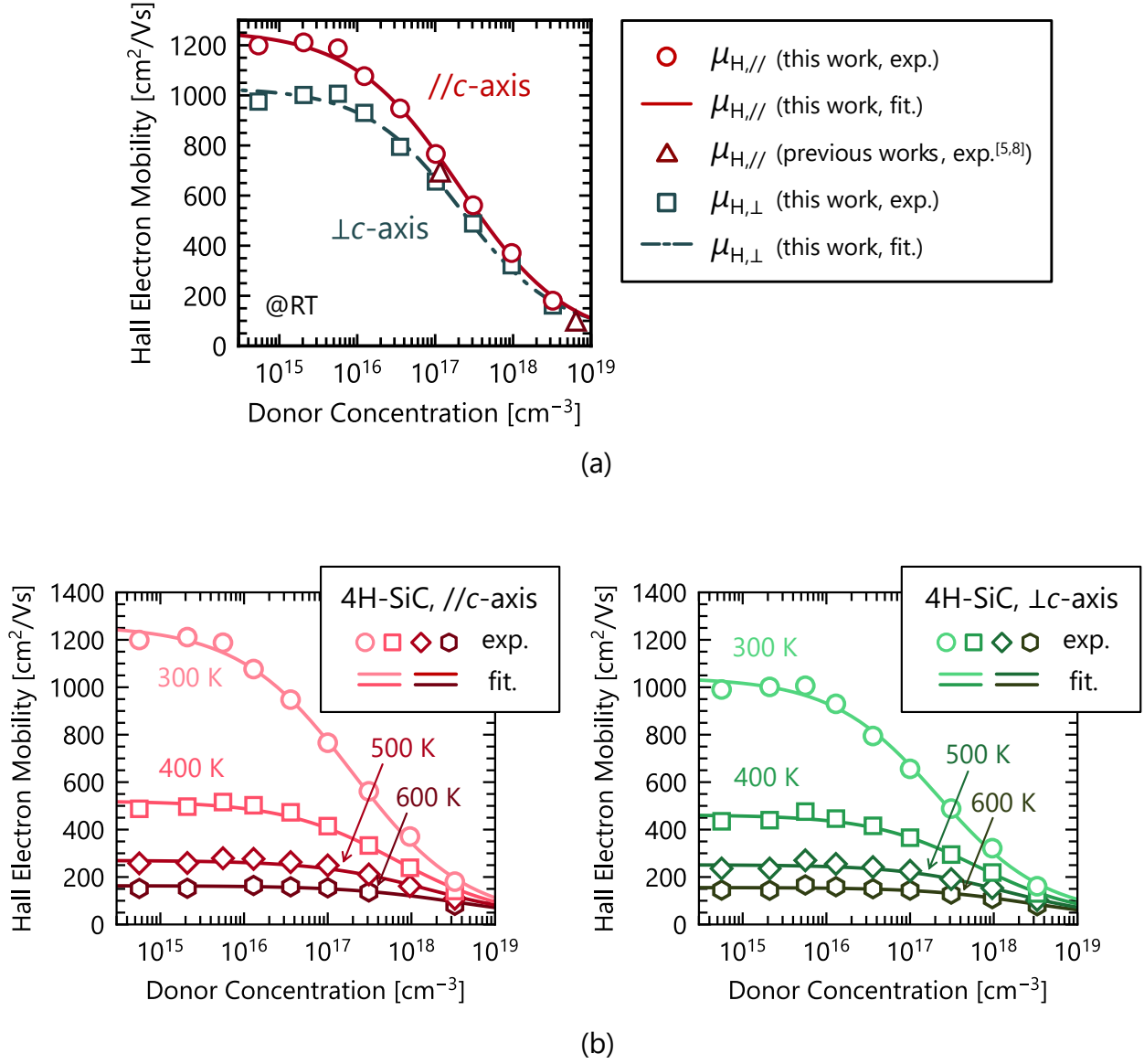


Figure 2.15: Donor concentration dependences of the Hall electron mobility parallel and perpendicular to the c -axis ($\mu_{H, \perp}$ and $\mu_{H, //}$) at (a) room temperature and (b) several temperatures from 300 K to 600 K. The red and green lines depict the fitting results expressed by Eqs. (2.11) and (2.12). (Reproduced from R. Ishikawa *et. al.*, *Phys. Status Solidi B* **260**, 2300275 (2023), with the permission of Wiley.)

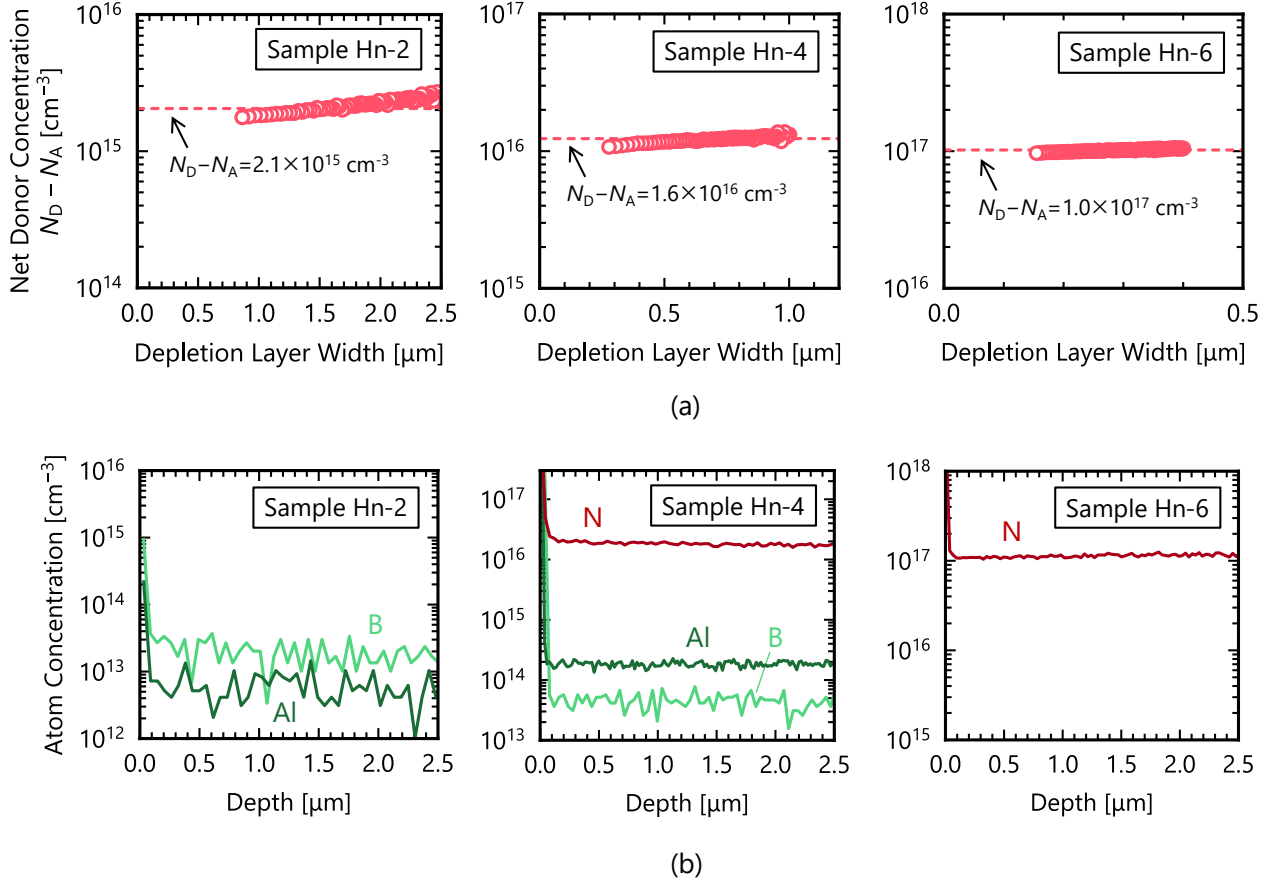


Figure 2.16: Depth profiles of (a) the net donor concentration determined by C - V measurements of lateral Schottky barrier diodes and (b) the N, B, and Al atom concentrations obtained by SIMS analyses. The averaged values of them are summarized in Table 2.2.

Table 2.2: Summary of the net donor concentrations ($N_D - N_A$) obtained from C - V measurements, and the donor- and acceptor-type impurity concentrations ($[N]$ and $[B] + [Al]$) determined by SIMS analyses.

Sample No.	Designed N_D	$N_D - N_A$ (C - V)	$[N]$ (SIMS)	$[B] + [Al]$ (SIMS)
Hn-1	$8 \times 10^{14} \text{ cm}^{-3}$	$5.4 \times 10^{14} \text{ cm}^{-3}$	—	$< 1 \times 10^{14} \text{ cm}^{-3}$
Hn-2	$2 \times 10^{15} \text{ cm}^{-3}$	$2.3 \times 10^{15} \text{ cm}^{-3}$	—	$< 1 \times 10^{14} \text{ cm}^{-3}$
Hn-3	$5 \times 10^{15} \text{ cm}^{-3}$	$5.6 \times 10^{15} \text{ cm}^{-3}$	$\sim 5 \times 10^{15} \text{ cm}^{-3}$	$\sim 2 \times 10^{14} \text{ cm}^{-3}$
Hn-4	$1 \times 10^{16} \text{ cm}^{-3}$	$1.2 \times 10^{16} \text{ cm}^{-3}$	$\sim 1 \times 10^{16} \text{ cm}^{-3}$	$\sim 2 \times 10^{14} \text{ cm}^{-3}$
Hn-5	$3 \times 10^{16} \text{ cm}^{-3}$	$3.6 \times 10^{16} \text{ cm}^{-3}$	$\sim 3 \times 10^{16} \text{ cm}^{-3}$	—
Hn-6	$1 \times 10^{17} \text{ cm}^{-3}$	$1.1 \times 10^{17} \text{ cm}^{-3}$	$1.2 \times 10^{17} \text{ cm}^{-3}$	—
Hn-7	$3 \times 10^{17} \text{ cm}^{-3}$	$3.6 \times 10^{17} \text{ cm}^{-3}$	$3.8 \times 10^{17} \text{ cm}^{-3}$	—
Hn-8	$1 \times 10^{18} \text{ cm}^{-3}$	$9.6 \times 10^{17} \text{ cm}^{-3}$	$9.3 \times 10^{17} \text{ cm}^{-3}$	—
Hn-9	$5 \times 10^{18} \text{ cm}^{-3}$	$3.2 \times 10^{18} \text{ cm}^{-3}$	$4.0 \times 10^{18} \text{ cm}^{-3}$	—

both donor concentration and temperature dependences:

$$\mu = \frac{(\mu_{\max} - \mu_{\min}) \cdot (T/300 \text{ K})^{\delta_1}}{1 + (N_D/N_{\text{ref}})^{\alpha} \cdot (T/300 \text{ K})^{\delta_2}} + \mu_{\min} \cdot (T/300 \text{ K})^{\delta_3}, \quad (2.10)$$

where $\mu_{\max}$, $\mu_{\min}$, N_{ref} , α , δ_1 , δ_2 , and δ_3 are fitting parameters. The fitting procedure is separated into two steps. $\mu_{\max}$, $\mu_{\min}$, N_{ref} , and α were determined from the donor concentration dependence of the mobilities at 300 K at first, and then δ_1 , δ_2 , and δ_3 were determined to reproduce the temperature dependences of them. The obtained fitting equations for $\mu_{H, //}$ and $\mu_{H, \perp}$ based on the systematic experimental data from 300 K to 600 K are obtained as below;

$$\mu_{H, //} = \frac{(1260 - 20) \cdot (T/300 \text{ K})^{-3.2}}{1 + (N_D/2.0 \times 10^{17} \text{ cm}^{-3})^{0.64} \cdot (T/300 \text{ K})^{-2.7}} + 20 \cdot (T/300 \text{ K})^{0.3} \text{ cm}^2/\text{Vs}, \quad (2.11)$$

$$\mu_{H, \perp} = \frac{(1040 - 40) \cdot (T/300 \text{ K})^{-2.9}}{1 + (N_D/2.2 \times 10^{17} \text{ cm}^{-3})^{0.68} \cdot (T/300 \text{ K})^{-2.5}} + 40 \cdot (T/300 \text{ K})^{-0.7} \text{ cm}^2/\text{Vs}. \quad (2.12)$$

As depicted by solid lines in Fig. 2.15, the fitting results reproduce the experimental results well. These equations are significant for the simulation or designing of any SiC device.

2.3.3.2 Temperature Dependence of Electron Mobility

The temperature dependences of Hall electron mobilities along the both directions from 300 K to 600 K are shown in Fig. 2.17 for each N_D sample. The Hall electron mobility decreases with elevating temperature for all the N_D samples, which is due to the enhanced effect of phonon scattering. The relationship between the electron mobility (μ) and the temperature (T) is often discussed using an equation $\mu \propto T^{-\beta}$, where β depends on the scattering mechanism. As depicted in Fig. 2.17, the μ - T relationship shows an approximately linear trend in the log-log plot from 300 K to 600 K, allowing β values to be determined for both directions and each donor concentration via linear extrapolation. It can be observed that the β values decrease with increasing N_D , which can be roughly explained by the doping-dependent scattering mechanism. For the lightly-doped samples, the dominant scattering process is phonon scattering because of the low concentration of impurities, and the mobility determined by phonon scattering (μ_{ph}) exhibits a negative correlation with the temperature [29, 30]. With increasing the donor concentration, the effect of the ionized impurity scattering becomes more significant, which decreases β because the mobility determined by the ionized impurity scattering (μ_{im}) has a positive correlation with the temperature, opposite to that by phonon scattering. The total mobility (μ) is approximately given by the following Matthiessen's rule [31];

$$\frac{1}{\mu} \simeq \frac{1}{\mu_{\text{im}}} + \frac{1}{\mu_{\text{ph}}}. \quad (2.13)$$

As a result, the slope in $\log \mu$ - $\log T$ plot from 300 K to 600 K becomes gentler for higher donor concentrations, which means the reduction in β values as schematically illustrated in

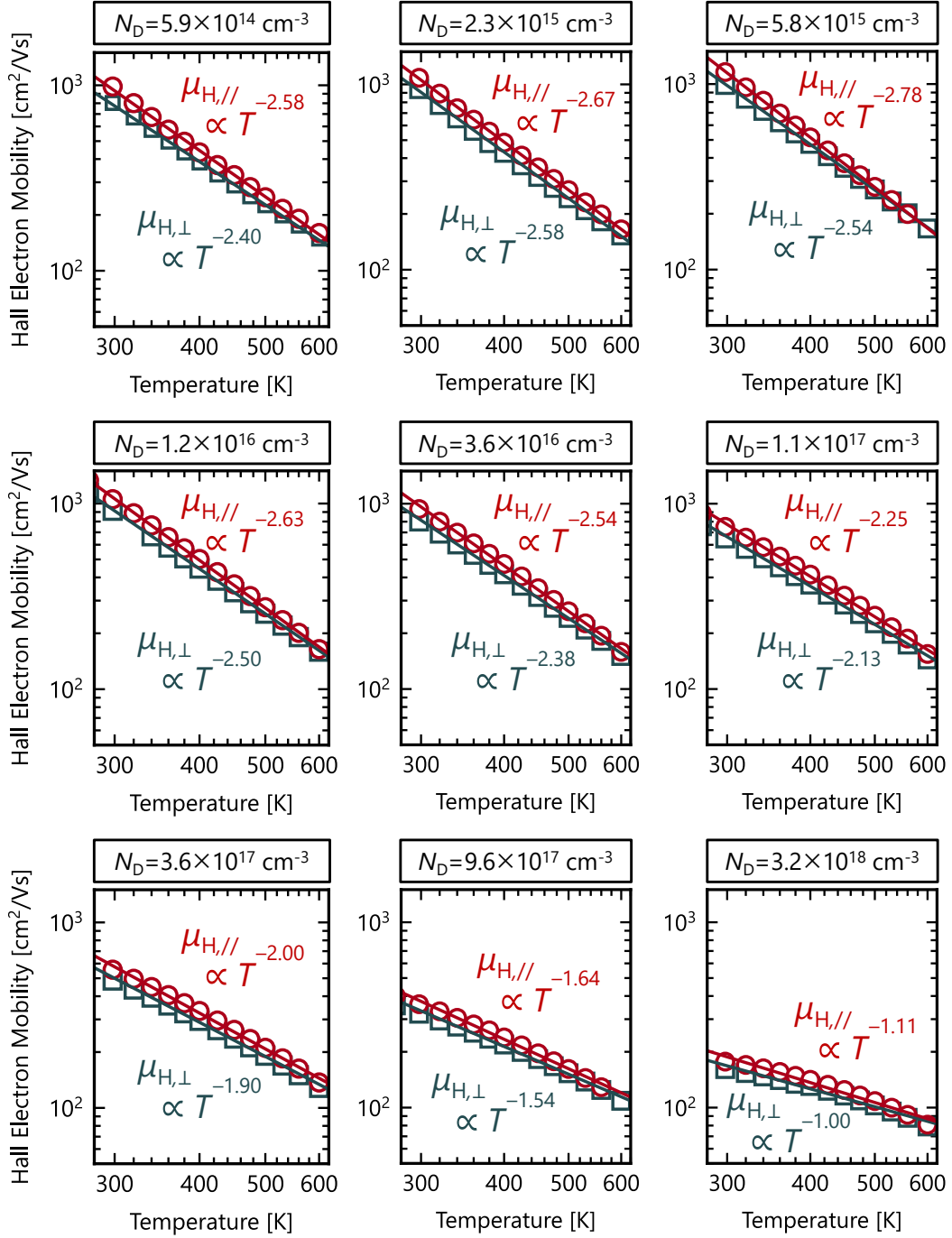


Figure 2.17: Temperature dependences of the Hall electron mobilities along the directions parallel and perpendicular to the c -axis (red and green symbols) for different donor concentrations (N_D). Solid lines show the fitting results based on $\mu \propto T^{-\beta}$, which indicates the decreases of β with increasing N_D . (© IOP Publishing. Partially reproduced with permission from R. Ishikawa *et. al.*, *Appl. Phys. Express* **14**, 061005 (2021). All rights reserved.)

Figure 2.18(a). The obtained β parallel and perpendicular to the c -axis ($\beta_{//}$ and $\beta_{\perp}$) are summarized in Fig. 2.18(b) as a function of N_D . $\beta_{\perp}$ determined based on the theoretical calculation of $\mu_{H,\perp}$ [1] is also plotted and shows good agreement with the results of this study. The fact that $\beta_{//}$ is somewhat larger than $\beta_{\perp}$ is attributed to the difference in the temperature dependence of electron effective mass, which will be further discussed in Section 2.4.

2.3.3.3 Discussion

Device performance must be accurately predicted considering the anisotropic mobility, and one of the key characteristics that should be updated is “unipolar limit” (the specific on-resistance of the drift layer in unipolar power devices) of SiC. The on-resistance of the drift ($R_{ON,drift}$) layer is given by the following equation using the thickness of drift layer (W),

$$R_{ON,drift} = \frac{W}{en\mu}. \quad (2.14)$$

Since $\mu_{//}$ should be used for the calculation of on-resistance because current flows along the c -axis in SiC(0001) vertical power devices, previous predictions, which used $\mu_{\perp}$ due to the limited studies on $\mu_{//}$, were not entirely accurate. Then, the author updated the SiC unipolar limit using $\mu_{H,//}$ determined in this study instead of $\mu_{H,\perp}$, and the calculated result is shown in Fig. 2.19 and expressed as follows:

$$R_{ON,drift} = 5.4 \times 10^{-11} V_{BD}^{2.22} \Omega \text{cm}^2 \quad (V_B : \text{V unit}). \quad (2.15)$$

Here, V_{BD} is the blocking voltage of device, and for this calculation, a non-punch-through structure and the N_D -dependent critical electric field were considered. As shown in Fig. 2.19, the performance limit of SiC unipolar devices was calculated correctly with $\mu_{H,//}$, which reveals that the on-resistance is 20% smaller than the conventional one calculated using $\mu_{H,\perp}$.

2.3.4 Hall Scattering Factor and Drift Mobility

The Hall electron mobility obtained through Hall effect measurements differs from the drift mobility due to the influence of the Hall scattering factor, as expressed by Eq. (2.9). Thus, in order to obtain the drift mobility, the determination of Hall scattering factor is required, which is generally complicated because it depends both on donor concentration and temperature. In this section, with the aim of conversion of Hall electron mobility to drift electron mobility in SiC, an estimation of the Hall scattering factor of electrons was attempted. From the Hall electron concentration experimentally obtained by Hall effect measurements and the calculated values of electron concentration, the Hall scattering factor was estimated using the relationship given by Eq. (2.9).

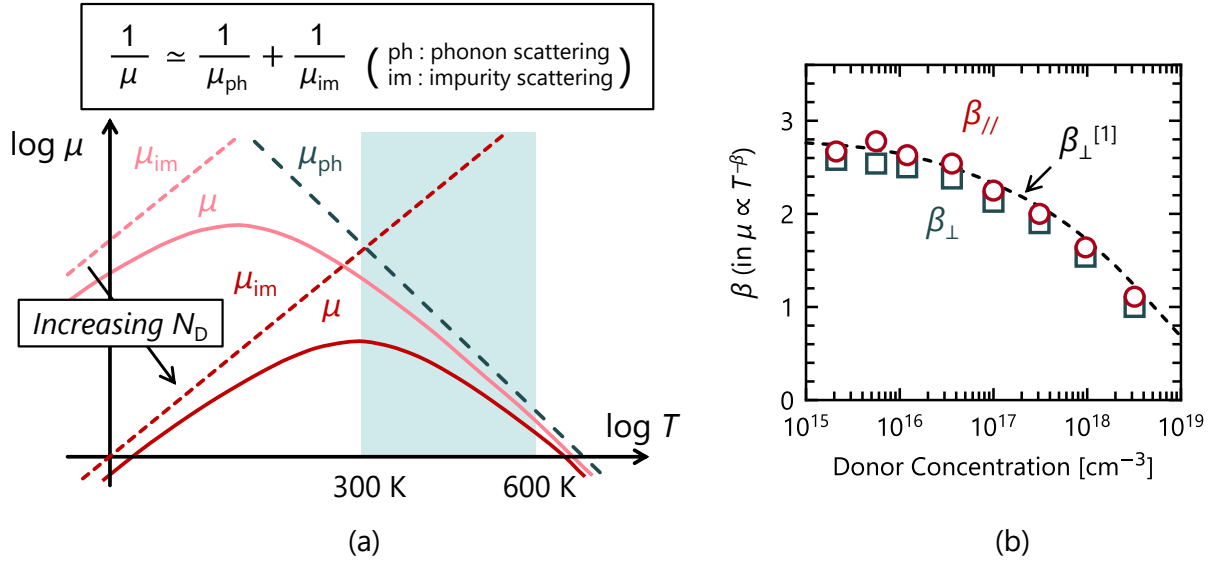


Figure 2.18: (a) Schematic diagram of the mobility–temperature (μ – T) relationship in log–log plot. While the mobility determined by phonon scattering (μ_{ph}) is little influenced by the donor concentration (N_D), that by impurity scattering (μ_{im}) decreases with increasing N_D , resulting in a smaller β in the temperature range from 300 K to 600 K for the heavily-doped sample. (b) N_D dependence of β for $\mu_{H,\parallel}$ and $\mu_{H,\perp}$ ($\beta_{\parallel}$ and $\beta_{\perp}$). $\beta_{\perp}$ calculated based on the scattering mechanism in SiC reported by a previous study [1] is also depicted by a dashed line.

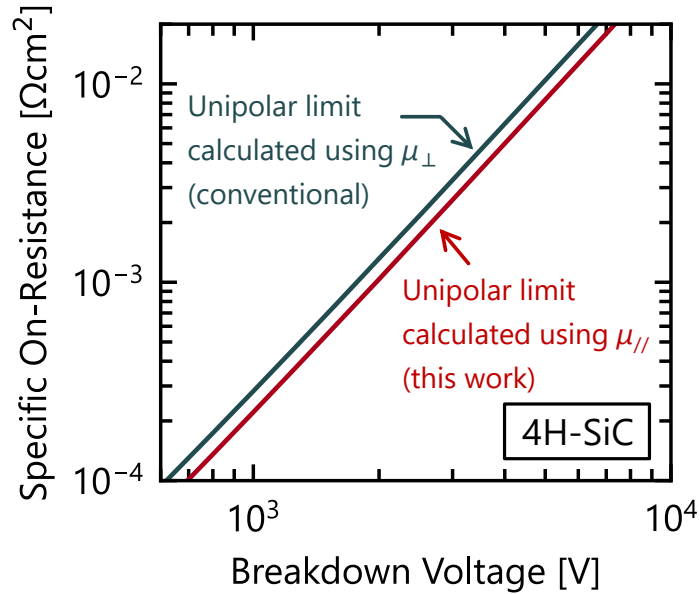


Figure 2.19: Unipolar limit of SiC updated using the electron mobility along the c -axis obtained in this study instead of using that perpendicular to the c -axis.

2.3.4.1 Hall Scattering Factor

Hall electron concentration can be obtained using Eq. (2.6), where the thickness t plays a crucial role in accurate determination of n_H . For the determination of t , the author first measured the thickness of n-type epilayer by scanning electron microscope (SEM) observation as shown in Fig. 2.20, which provides a visual contrast between layers with different conduction types, enabling to identify the boundary between the n-type and p-type layers. The measured thicknesses are summarized in Table 2.3. Since the analysis of Hall effect measurement assumes a uniform electron concentration throughout the thickness t , it is necessary to account for the depletion layer at the pn junction between n-type and p-type epitaxial layers, where no electrons exist. Then, the author determined the actual t by subtracting a calculated depletion layer thickness from the n-type epitaxial layer thickness measured by SEM. For the calculation, the acceptor concentration of $3 \times 10^{16} \text{ cm}^{-3}$ (designed value) was used for p-layers, and the depletion layer widths were estimated to be about $1.1 \text{ } \mu\text{m}$ for $N_D = 2 \times 10^{15} \text{ cm}^{-3}$ and 10 nm for $N_D = 1 \times 10^{18} \text{ cm}^{-3}$. Arrhenius plots of the obtained Hall electron concentrations determined using t calculated by the above procedure are shown by symbols in Fig. 2.21(a). The Hall electron concentration increases with increasing temperature and approaches a constant value, indicating the saturation temperature range of donors.

The electron concentration n was calculated using the charge neutrality equation (Eq. (2.2)) using the values of N_D and N_A obtained from C - V measurements and SIMS analyses. Here, the acceptor concentrations were assumed to be $2 \times 10^{14} \text{ cm}^{-3}$ for the samples with $N_D \geq 5 \times 10^{15} \text{ cm}^{-3}$ and $5 \times 10^{13} \text{ cm}^{-3}$ with $N_D \leq 2 \times 10^{15} \text{ cm}^{-3}$ from the SIMS analyses of acceptor-type atom concentration ($[B] + [Al]$), and the calculated results are depicted by dashed lines in Fig. 2.21, which show relatively good agreement with experimentally measured n_H .

Finally, the Hall scattering factor for electrons was extracted from the difference between n_H and n , and the obtained results are plotted in Fig. 2.21(b) as a function of temperature. The Hall scattering factor was observed to increase with increasing both donor concentration and temperature, and these tendencies can be roughly understood by the change in scattering mechanism. At higher donor concentrations, the ionized impurity scattering becomes the dominant mechanism, which provides a relatively large scattering factor ($\gamma_H \simeq 1.9$, when only considering ionized impurity scattering). Besides, with elevating temperature, the dominant phonon scattering shifts from acoustic phonon scattering ($\gamma_H \simeq 1.2$) to intervalley phonon scattering ($\gamma_H \simeq 1.4$) and optical phonon scattering ($\gamma_H \simeq 1.8$). Note that the scattering factors described above are calculated values based on the relaxation time (τ) reported previously for the direction perpendicular to the c -axis [1] using an equation $\gamma_H = \langle \tau^2 \rangle / \langle \tau \rangle^2$.

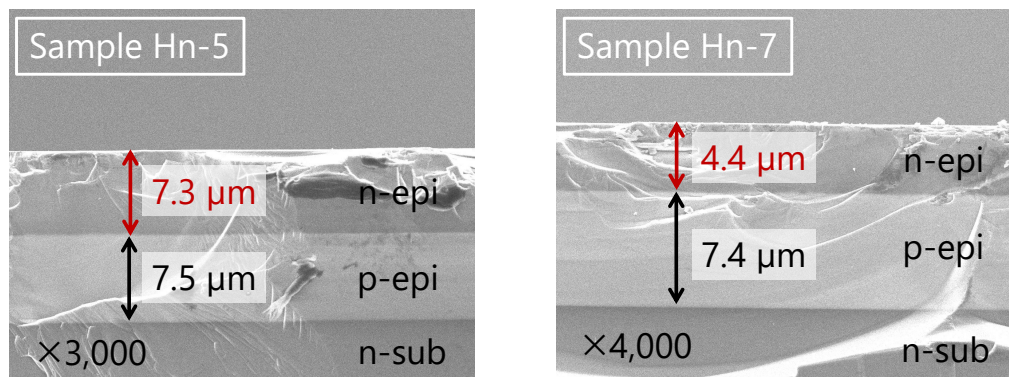


Figure 2.20: SEM images of the samples (cross-section) before the fabrication of Hall bar structures. The thicknesses of n-type epilayers were determined from the contrast in the images.

Table 2.3: Summary of the thicknesses of top n-type epilayers determined by SEM observation.

Sample No.	N_D	Designed Thickness	Actual Thickness (SEM)
Hn-1	$8 \times 10^{14} \text{ cm}^{-3}$	12 μm	11.6 μm
Hn-2	$2 \times 10^{15} \text{ cm}^{-3}$	12 μm	10.9 μm
Hn-3	$5 \times 10^{15} \text{ cm}^{-3}$	10 μm	9.0 μm
Hn-4	$1 \times 10^{16} \text{ cm}^{-3}$	8 μm	7.1 μm
Hn-5	$3 \times 10^{16} \text{ cm}^{-3}$	8 μm	7.3 μm
Hn-6	$1 \times 10^{17} \text{ cm}^{-3}$	5 μm	4.5 μm
Hn-7	$3 \times 10^{17} \text{ cm}^{-3}$	5 μm	4.4 μm
Hn-8	$1 \times 10^{18} \text{ cm}^{-3}$	5 μm	5.0 μm
Hn-9	$5 \times 10^{18} \text{ cm}^{-3}$	5 μm	5.4 μm

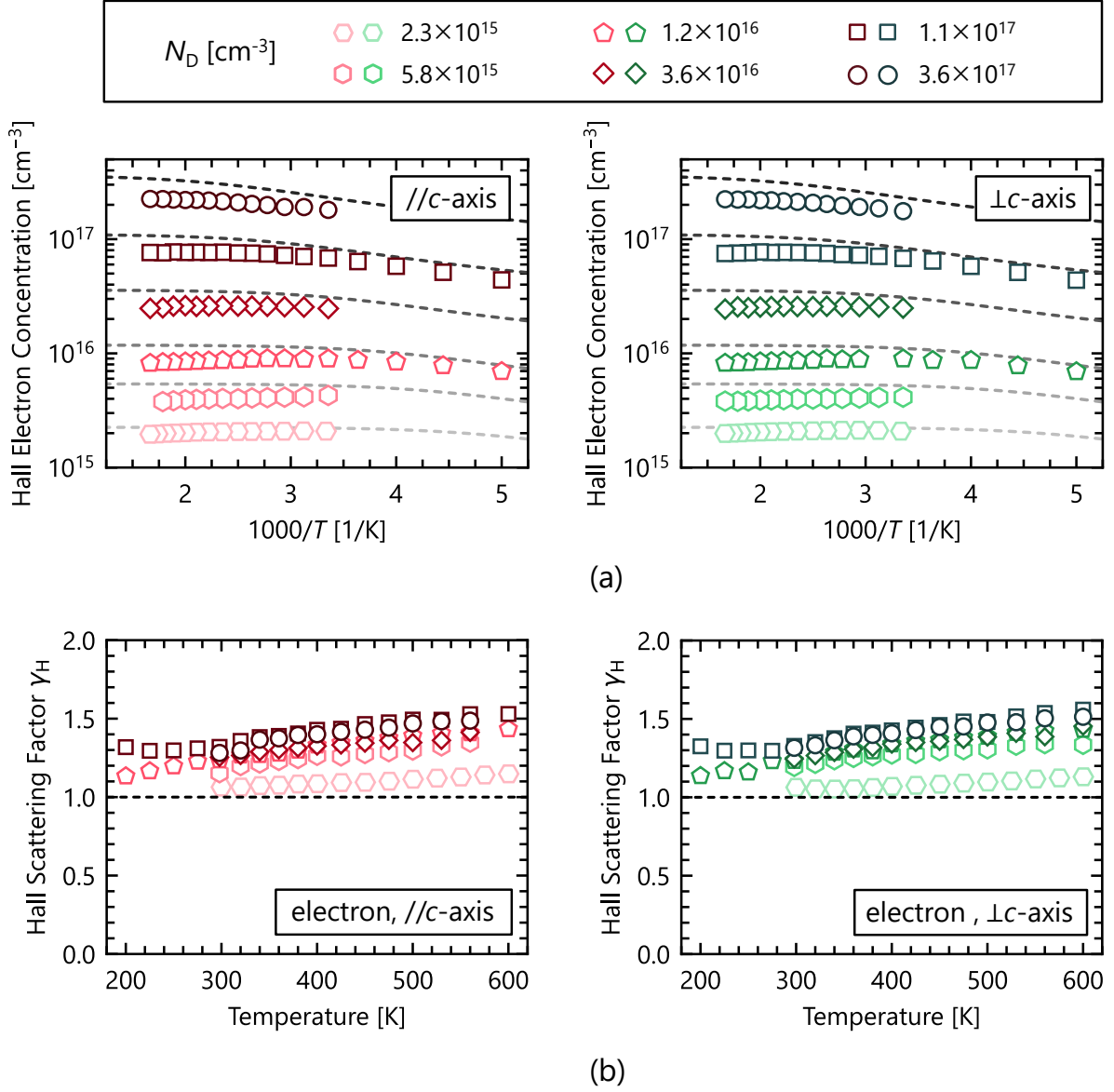


Figure 2.21: (a) Arrhenius plots of the Hall electron concentrations determined using Hall bar structures parallel and perpendicular to the c -axis for different donor concentrations. The dashed lines depict the calculated electron concentration from the charge neutrality equation. (b) Hall scattering factors for electrons obtained from the present analyses as functions of temperature.

2.3.4.2 Drift Mobility

The Hall electron mobility was converted into the drift electron mobility using the obtained Hall scattering factors, and the results for the directions parallel and perpendicular to the c -axis at room temperature are shown in Fig. 2.22. The lines in Fig. 2.22 show the fitting results based on Eq. (2.10) for $T = 300$ K, and fitting equations are as follows:

$$\mu_{//} = \frac{(1190 - 10) \cdot (T/300 \text{ K})^{-3.4}}{1 + (N_D/1.0 \times 10^{17} \text{ cm}^{-3})^{0.54} \cdot (T/300 \text{ K})^{-2.2}} + 10 \cdot (T/300 \text{ K})^{0.8} \text{ cm}^2/\text{Vs}, \quad (2.16)$$

$$\mu_{\perp} = \frac{(980 - 30) \cdot (T/300 \text{ K})^{-3.2}}{1 + (N_D/1.2 \times 10^{17} \text{ cm}^{-3})^{0.55} \cdot (T/300 \text{ K})^{-1.6}} + 30 \cdot (T/300 \text{ K})^{-0.2} \text{ cm}^2/\text{Vs}. \quad (2.17)$$

In addition, the drift mobility parallel to the c -axis estimated by vertical SBDs discussed in Section 2.2 is also plotted in Fig. 2.22, where the averaged value matches well with the drift mobility for lightly doped samples obtained by the present analyses. This agreement suggests that the methods using vertical SBDs and Hall effect measurements are both reasonable and the results are accurate.

2.4 Theoretical Analysis on Origin of Mobility Anisotropy

In this section, the electron mobility anisotropy is experimentally determined, and the origin of mobility anisotropy is discussed based on the theoretical calculation of effective mass anisotropy.

2.4.1 Determination of Electron Mobility Anisotropy

The ratio of drift mobility ($\mu_{//}/\mu_{\perp}$) was determined from the ratio of resistivity ($\rho_{\perp}/\rho_{//}$) instead of that of Hall electron mobility ($\mu_{H, //}/\mu_{H, \perp}$) in order to eliminate the effect of Hall scattering factor. This is because the resistivity ratio and Hall mobility ratio are given by the following equations:

$$\frac{\rho_{\perp}}{\rho_{//}} = \frac{\mu_{//}}{\mu_{\perp}}, \quad \frac{\mu_{H, //}}{\mu_{H, \perp}} = \frac{\gamma_{H, //}}{\gamma_{H, \perp}} \frac{\mu_{//}}{\mu_{\perp}}, \quad (2.18)$$

where $\gamma_{H, //}$ and $\gamma_{H, \perp}$ are the Hall scattering factors in the parallel and perpendicular directions to the c -axis, respectively. The obtained drift mobility ratio of electrons is shown in Fig. 2.23. The mobility ratio is about 1.1–1.3 at 140 K, while it decreases to about 1.0–1.1 at 600 K, indicating that the drift mobility becomes more isotropic at higher temperatures. Here, the drift mobility μ is given by:

$$\mu = \frac{e\langle\tau\rangle}{m^*}, \quad (2.19)$$

where $\langle\tau\rangle$ is the averaged momentum relaxation time of electrons and m^* is the electron effective mass. To understand the origin of the mobility anisotropy, the author focused on

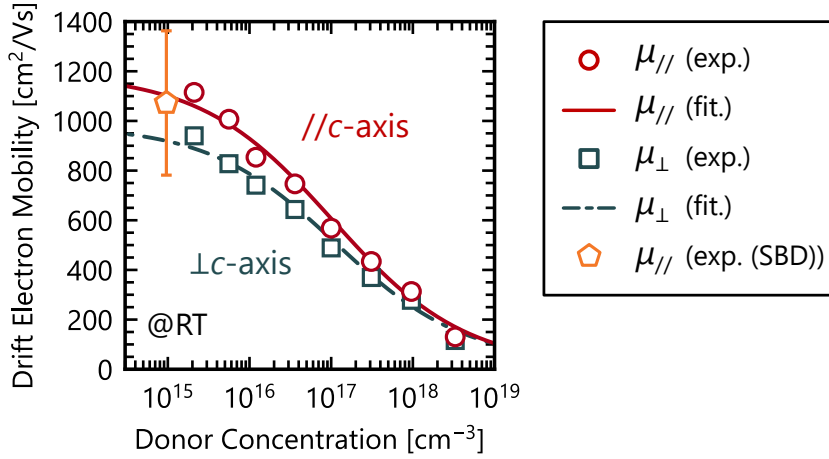


Figure 2.22: Drift mobility of electrons at room temperature obtained from the present analyses versus the donor concentration. The solid and dashed lines depict the fitting results expressed by Eqs. (2.16) and (2.17). The drift mobility along the c -axis estimated in Section 2.2 using SiC vertical SBDs is also depicted, and the averaged value shows good agreement with that obtained from the analyses based on Hall effect measurements.

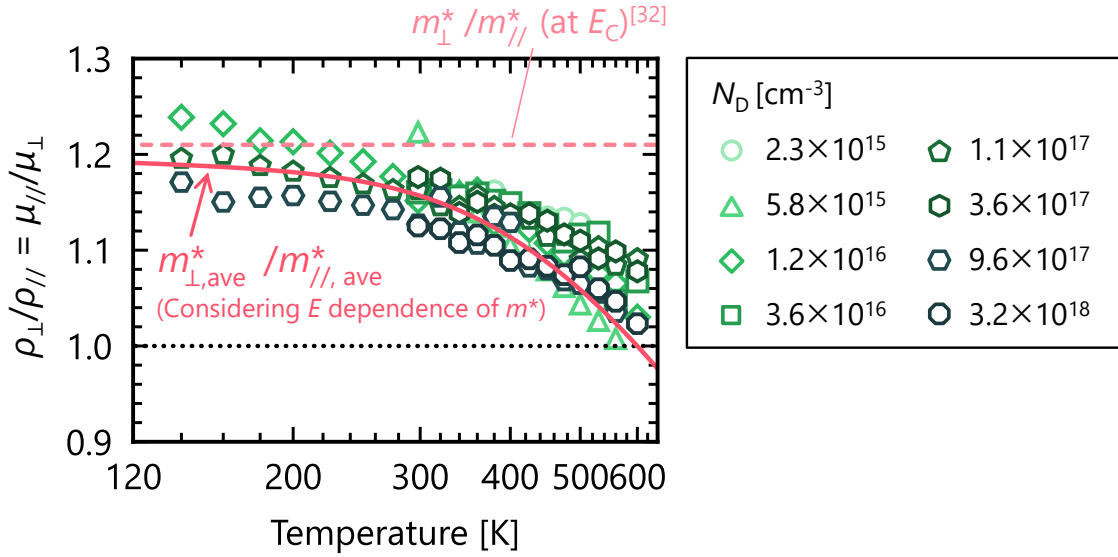


Figure 2.23: The electron mobility ratio obtained from the experimentally measured resistivity ratio ($\mu_{//}/\mu_{\perp} = \rho_{\perp}/\rho_{//}$) as a function of the temperature. The electron effective mass ratio ($m_{\perp}^*/m_{//}^* = 1.21$) at the conduction band minimum E_C [32] and that calculated considering the energy dependence of m^* ($m_{ave,\perp}^*/m_{ave,//}^*$) are also depicted by dashed and solid lines, respectively. While the $m_{\perp}^*/m_{//}^*$ at E_C deviates from the observed μ ratio at high temperatures, the calculated $m_{ave,\perp}^*/m_{ave,//}^*$ decreases with increasing temperature similarly with the experimental results, indicating that the anisotropic effective mass is the main origin of the anisotropy in the electron mobility. (Reproduced from R. Ishikawa *et. al.*, *Phys. Status Solidi B* **260**, 2300275 (2023), with the permission of Wiley.)

the anisotropy in the electron effective mass. The electron effective masses parallel and perpendicular to the c -axis in SiC ($m_{//}^*$ and $m_{\perp}^*$) are expressed as follows:

$$m_{//}^* = m_{\text{ML}}^*, \quad (2.20)$$

$$m_{\perp}^* = \frac{2m_{\text{M}\Gamma}^* m_{\text{MK}}^*}{m_{\text{M}\Gamma}^* + m_{\text{MK}}^*}, \quad (2.21)$$

where m_{ML}^* , $m_{\text{M}\Gamma}^*$, and m_{MK}^* are the effective masses along directions from the conduction minimum (M point) to various points in the Brillouin zone shown in Fig. 2.24(a). In a previous study, m^* at the bottom of the conduction band (E_C) has been reported to be $m_{\text{ML}}^* = 0.33m_0$, $m_{\text{M}\Gamma}^* = 0.58m_0$, and $m_{\text{MK}}^* = 0.31m_0$, where m_0 is the electron rest mass [32]. From these values, $m_{\perp}^*/m_{//}^*$ at E_C is calculated to be 1.21, which is depicted by the dashed line in Fig. 2.23. While the μ ratio at 140 K is close to the m^* ratio at E_C , the deviation from 1.21 becomes more significant at higher temperatures. This suggests that the electron effective mass anisotropy is stronger near E_C and weakens as the energy increases. Here, the electron energy distribution shifts to the higher energy region with increasing temperature, leading to a higher proportion of electrons with greater energy, as depicted in Fig. 2.24(b). Therefore, for a more appropriate comparison between the mobility anisotropy and the effective mass anisotropy, the effective mass with higher energies than E_C should be taken into account, although this is difficult to be determined experimentally.

2.4.2 Calculation Procedure of Anisotropy in Electron Effective Mass

To understand how the values of effective masses in SiC change at higher energy regions, and how this change influences the effective mass anisotropy, the conduction band structure (E - k dispersion) of SiC was calculated using first-principles methods, as shown in Fig. 2.24(c). A first-principles calculation package ABINIT [33] was employed to compute the band structure along each crystallographic axis. The calculations were based on density functional theory (DFT) with local density approximation [34], adopting Troullier-Martins pseudopotentials [35] without considering spin-orbit coupling. In addition to the first sub-band, the author considered the second sub-band [36], whose band minimum is located at 0.12 eV higher than that of the first sub-band. From the computed band structure, the relationship between the energy and the effective mass was derived by the following equation:

$$\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{\partial^2 E}{\partial k^2}. \quad (2.22)$$

The results of calculation for different axes are depicted in Fig. 2.24(d), which indicates that $m_{//}^*$ increases more rapidly with increasing the electron energy compared to $m_{\perp}^*$, and it becomes larger than $m_{\perp}^*$ at energies higher than about 0.08 eV in the first sub-band. In addition, $m_{//}^*$ is more than 2.7 times heavier than $m_{\perp}^*$ in the second sub-band.

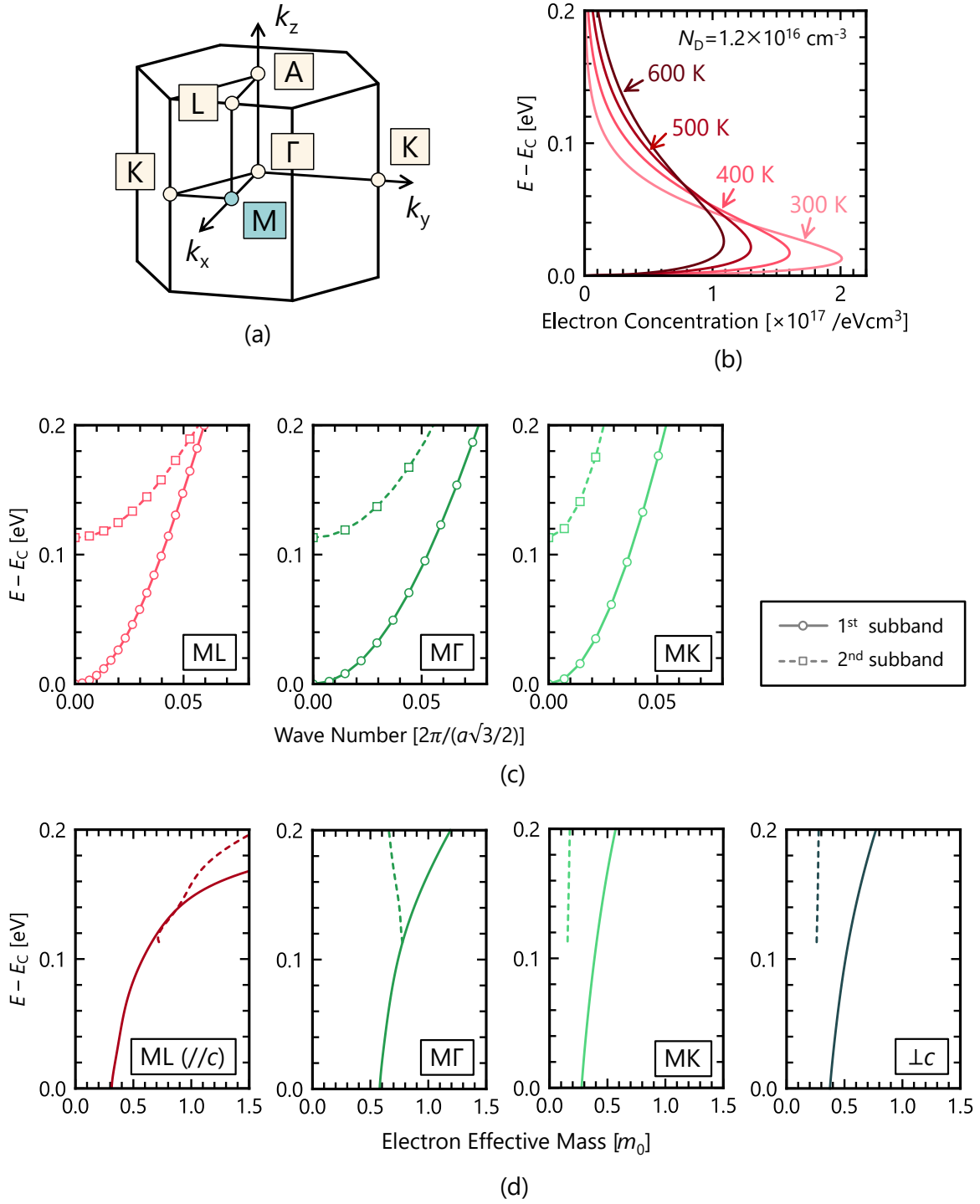


Figure 2.24: (a) Primitive cell and wavenumber axes of SiC, where the M point is the conduction band minimum. (b) Energy distribution of electrons in the first subband with $N_D = 1.2 \times 10^{16}$ cm⁻³ at several temperatures. (c) Conduction band structures of SiC (E - k dispersion). (d) Energy dependences of the electron effective masses along the ML, MK, and M Γ directions in SiC, and that perpendicular to the c -axis calculated by Eq. (2.21). (Partially reproduced from R. Ishikawa *et. al.*, *Phys. Status Solidi B* **260**, 2300275 (2023), with the permission of Wiley.)

Based on the energy dependence of the effective masses obtained in this way (shown in Fig. 2.24(d)) and the energy distribution of electrons (shown in Fig. 2.24(b)), a one-dimensional average effective mass (m_{ave}^*) along each crystallographic direction was calculated using the equation below:

$$\frac{1}{m_{\text{ave}}^*} = \frac{\sum_l \int (1/m^*(k)) \cdot f(E_l(k)) dk}{\sum_l \int f(E_l(k)) dk}. \quad (2.23)$$

Here, $f(E)$ represents the energy distribution function and l corresponds to the l th sub-band. The integration was performed over the line between the M point to the L point in the Brillouin zone to determine $m_{\text{ML,ave}}^*$, and in the same manner, $m_{\text{MF,ave}}^*$ and $m_{\text{MK,ave}}^*$ were calculated by the integration over the MF and MK lines. m_{ave}^* along each direction was calculated for each temperature by this equation as shown in Fig. 2.25 as a function of temperature, and then $m_{\text{ave,}\parallel}^*$ and $m_{\text{ave,}\perp}^*$ were determined using Eqs. (2.20) and (2.21), respectively. As shown in Fig. 2.25, $m_{\text{ave,}\parallel}^*$ becomes larger with increasing temperature while $m_{\text{ave,}\perp}^*$ remains nearly constant over the temperature. Note that Fig. 2.24(b) shows the energy distribution of electrons in the first sub-band and that of the second sub-band appears at 0.12 eV higher than E_C . At 300 K, the total electron concentration in the second sub-band is about 1% of that in the first sub-band, increasing to 12% at 600 K. Finally the ratio of average effective mass ($m_{\text{ave,}\perp}^*/m_{\text{ave,}\parallel}^*$) was determined and is depicted by the solid line in Fig. 2.23. $m_{\text{ave,}\perp}^*/m_{\text{ave,}\parallel}^*$ decreases with elevating temperature and closely matches the observed mobility ratio, confirming that the anisotropy in the electron mobility can be explained quantitatively by that in average electron effective mass. Besides, the larger increase of $m_{\text{ave,}\parallel}^*$ than $m_{\text{ave,}\perp}^*$ with increasing the temperature is probably the main reason why $\beta_{\parallel}$ is slightly larger than $\beta_{\perp}$ as discussed in Section 2.3.

Figure 2.26(a) shows the donor concentration dependence of the drift mobility ratio at room temperature. As observed, the ratio slightly decreases with increasing N_D , suggesting that the change is primarily due to alterations in the scattering mechanism rather than shifts in the energy distribution of electrons. The reason behind this consideration is that while the electron energy distribution changes with increasing N_D , the normalized distribution (distribution normalized by the total electron concentration in the conduction band) is almost unchanged as illustrated in Fig. 2.26(b), indicating the calculated average effective masses are largely unaffected by changes in the donor concentration. Therefore, the slight decrease in $\mu_{\parallel}/\mu_{\perp}$ with increasing N_D cannot be explained by the simple average effective mass ratio. Figure 2.26(c) depicts the momentum relaxation of the key scattering mechanism as a function of electron energy. While the phonon scattering is little affected by N_D , the impurity scattering becomes more pronounced as N_D increases, leading to a decrease in relaxation time, particularly for electrons with lower energy. This implies that at higher donor concentrations, lower-energy electrons are more easily scattered, making it more difficult for them to contribute to electrical conduction. On the other hand, high-energy electrons, which are scattered less, play a more significant role in conduction. As a result, the actual average effective mass ratio decreases with increasing N_D , because $m_{\perp}^*/m_{\parallel}^*$ is

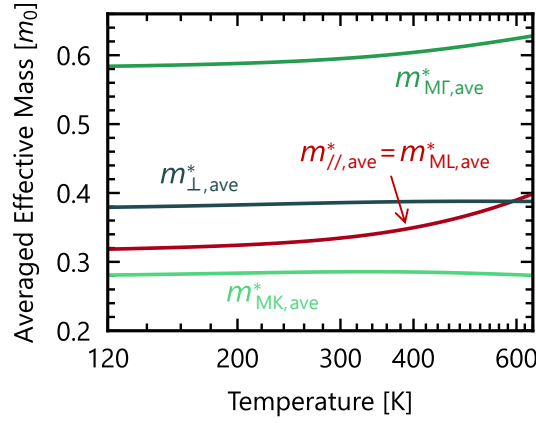


Figure 2.25: Averaged electron effective masses along various directions versus temperature calculated by considering the energy distribution of electrons and the energy dependences of electron effective masses.

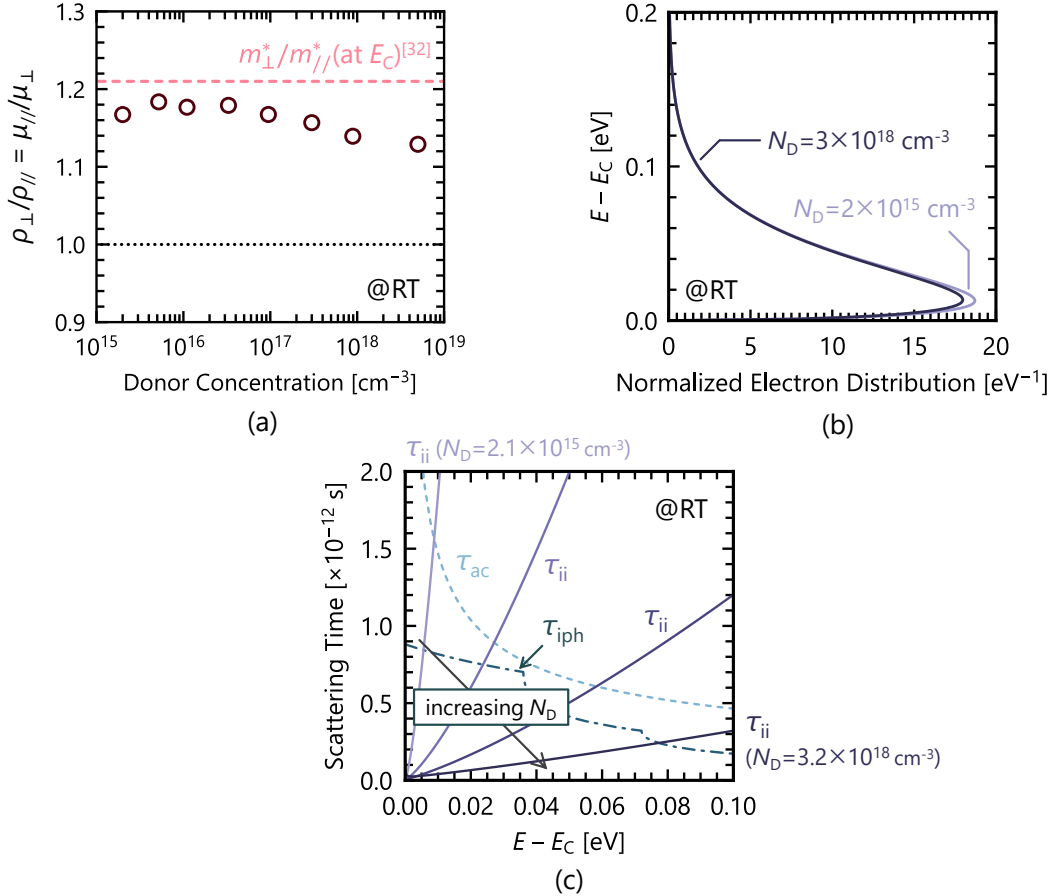


Figure 2.26: (a) The drift mobility ratio as a function of donor concentration (N_D), where the ratio slightly decreases with increasing N_D . (© IOP Publishing. Reproduced with permission from R. Ishikawa *et. al.*, *Appl. Phys. Express* **14**, 061005 (2021). All rights reserved.) (b) Normalized distribution of electrons for high and low N_D . (c) Scattering time versus the energy relationship for acoustic phonon (ac), intervalley phonon (iph), ionized impurity (ii) scattering for various N_D [1].

smaller at the higher-energy region as shown in Fig. 2.24(d), which explains qualitatively the N_D -dependent ratio of drift mobility.

2.4.3 Comparison of Experimental and Calculated Electron Mobilities

Based on the observation that the mobility ratio aligns well with the effective mass ratio shown in Fig. 2.23, it is inferred that the momentum relaxation time is nearly isotropic, i.e., the c -axis ($\tau_{//}$) is almost identical to that perpendicular to the c -axis ($\tau_{\perp}$). Then, the author attempted to reproduce both the electron mobilities parallel and perpendicular to the c -axis by assuming the isotropic relaxation time. For the calculation, previously reported $\tau_{\perp}$ [1] was used, along with the average electron effective masses $m_{\text{ave},//}^*$ and $m_{\text{ave},\perp}^*$ from Fig. 2.25. The momentum relaxation time ($\tau(E)$) for electrons in SiC is determined by five kinds of scattering process; ionized impurities (ii), neutral impurities (ni), acoustic phonon (ac), intervalley phonon (iph), and polar optical phonon (pop) scattering, and expressed by the equation below:

$$\frac{1}{\tau(E)} = \frac{1}{\tau_{\text{ii}}(E)} + \frac{1}{\tau_{\text{ni}}(E)} + \frac{1}{\tau_{\text{ac}}(E)} + \frac{1}{\tau_{\text{iph}}(E)} + \frac{1}{\tau_{\text{pop}}(E)}. \quad (2.24)$$

The average momentum relaxation time $\langle\tau\rangle$ can be calculated using the following integral:

$$\langle\tau\rangle = \frac{\int_0^{\infty} \tau(E) E^{3/2} \exp(-E/k_B T) dE}{\int_0^{\infty} E^{3/2} \exp(-E/k_B T) dE}. \quad (2.25)$$

The parameters describing the momentum relaxation time of each process have been reported for $\mu_{H,\perp}$ by a previous study [1]. Figure 2.27 shows the calculated mobility for (a) $N_D = 1.2 \times 10^{16} \text{ cm}^{-3}$ and (b) $N_D = 9.6 \times 10^{17} \text{ cm}^{-3}$, in which the calculated mobilities reproduce well the Hall mobilities experimentally obtained. The dashed lines in Fig. 2.27 represent the mobilities ascribed to each scattering mechanism, showing how various processes contribute to the total mobility. Although the mobility calculated using this approach is technically the “drift mobility,” the author compared it with the experimentally obtained “Hall mobility” because the parameters of each scattering are determined by assuming the Hall scattering factor as unity [1], and the calculated mobility can be considered to be the Hall mobility including the Hall scattering factor.

2.5 Summary

In this chapter, the low-field electron mobility along the c -axis was determined using two experimental approaches. A method using SiC(0001) vertical SBD was adopted as the first approach, and the mobility along the c -axis was estimated to be $1070 \text{ cm}^2/\text{Vs}$ with an accuracy of $\pm 290 \text{ cm}^2/\text{Vs}$ for the donor concentration (N_D) of $1 \times 10^{15} \text{ cm}^{-3}$ by taking

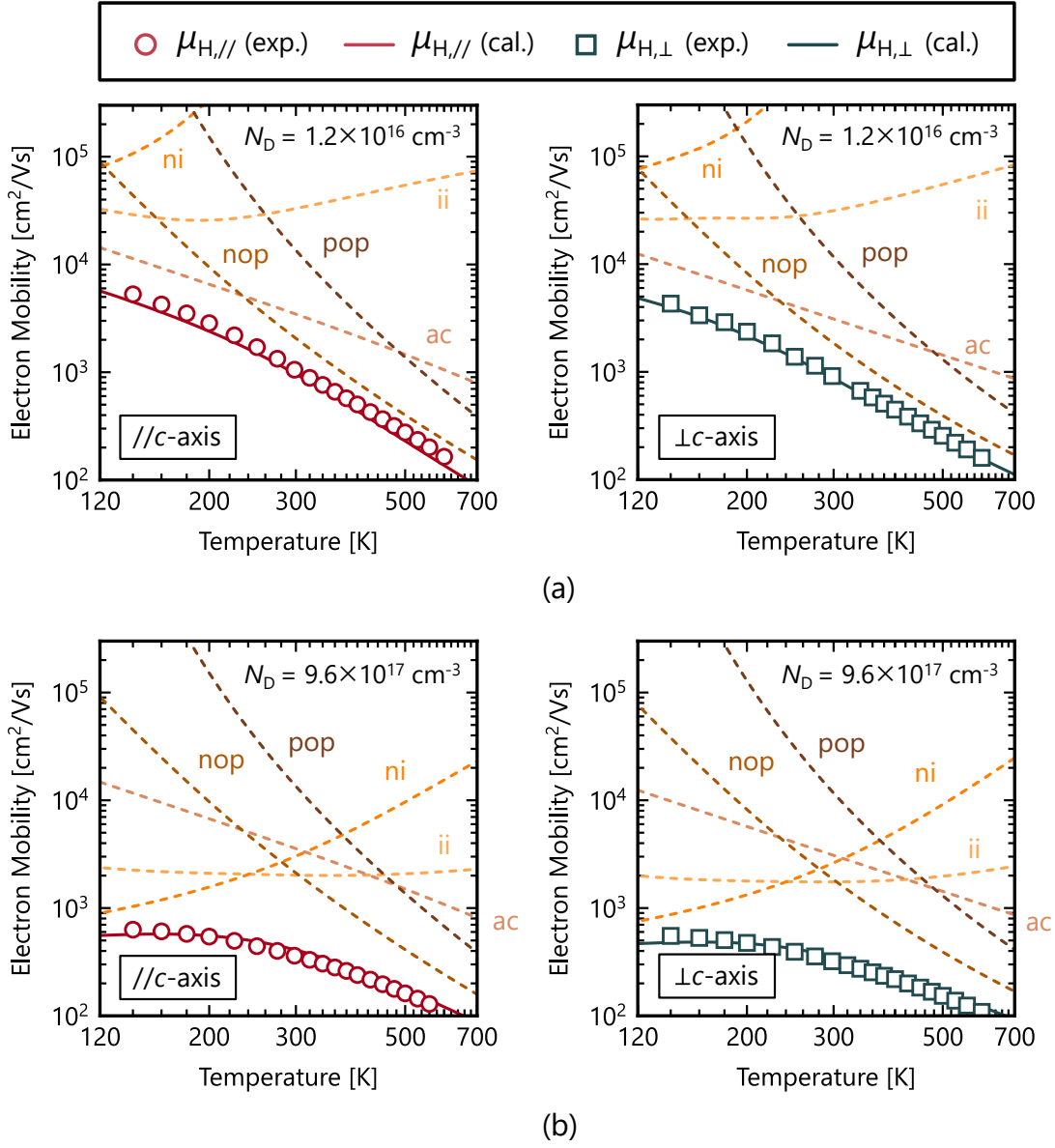


Figure 2.27: Electron mobilities obtained by experiments and calculation versus temperature for (a) $N_D = 1.2 \times 10^{16} \text{ cm}^{-3}$ and (b) $N_D = 9.6 \times 10^{17} \text{ cm}^{-3}$. The calculation of mobilities parallel and perpendicular to the c -axis were performed based on the momentum relaxation time reported for $\mu_{\perp}$ [1] (assuming $\tau_{//} = \tau_{\perp}$) and the averaged effective mass determined in the present study. The dashed lines show the mobility determined by each scattering mechanism, including ionized impurities (ii), neutral impurities (ni), acoustic phonon (ac), intervalley phonon (iph), and polar optical phonon (pop) scatterings. (Partially reproduced from R. Ishikawa *et. al.*, *Phys. Status Solidi B* **260**, 2300275 (2023), with the permission of Wiley.)

care of the current spreading and separation of resistance components. Even though the error was relatively large, the averaged value was close to the result determined by Hall effect measurement, which ensured the validity of the present analysis. In the second approach, the author performed Hall effect measurements on n-type SiC(11 $\bar{2}$ 0) epilayers and determined the electron mobility parallel and perpendicular to the c -axis over wide ranges of donor concentration ($N_D = 5 \times 10^{14}$ – 4×10^{18} cm $^{-3}$) and temperature (120–600 K). A high mobility of 1210 cm 2 /Vs was obtained for the direction parallel to the c -axis, which is the highest value ever measured for SiC at room temperature. From the systematic experimental results, empirical equations describing the donor concentration and temperature dependences of electron mobilities were determined. In addition, the electron mobility along the c -axis was found to be 10–20% higher than that perpendicular to the c -axis, and the origin of the anisotropy was discussed by focusing on the anisotropy in electron effective mass. A comparison between the observed mobility anisotropy and effective mass reported at the conduction band minimum suggested the necessity to take into account the energy dependence of effective mass. Then, the theoretical calculation was performed considering the energy distribution of electrons and the conduction band structure of SiC, and it was clarified that the anisotropy in electron mobility is quantitatively explained by that in effective mass. Finally, the temperature dependence of the electron mobility was calculated with assuming the relaxation time of scattering isotropic, which reproduced well the observed mobility for the both directions.

References

- [1] J. Pernot, W. Zawadzki, S. Contreras, J. L. Robert, E. Neyret, and L. Di Cioccio, *J. Appl. Phys.* **90**, 1869 (2001).
- [2] H. Iwata and K. M. Itoh, *J. Appl. Phys.* **89**, 6228 (2001).
- [3] S. Kagamihara, H. Matsuura, T. Hatakeyama, T. Watanabe, M. Kushibe, T. Shinohe, and K. Arai, *J. Appl. Phys.* **96**, 5601 (2004).
- [4] H. Harima, S. Nakashima, and T. Uemura, *J. Appl. Phys.* **78**, 1996 (1995).
- [5] W. J. Schaffer, G. H. Negley, K. G. Irvine, and J. W. Palmour, *Mater. Res. Soc. Symp. Proc.* **339**, 595 (1994).
- [6] T. Hatakeyama, T. Watanabe, M. Kushibe, K. Kojima, S. Imai, T. Suzuki, T. Shinohe, T. Tanaka, and K. Arai, *Mater. Sci. Forum* **433–436**, 443 (2003).
- [7] M. Schadt, G. Pensl, R. P. Devaty, W. J. Choyke, R. Stein, and D. Stephani, *Appl. Phys. Lett.* **65**, 3120 (1994).
- [8] H. Iwata, K. M. Itoh, and G. Pensl, *J. Appl. Phys.* **88**, 1956 (2000).

- [9] G. Bosch, *J. Phys. Chem. Solids* **27**, 795 (1966).
- [10] F. Roccaforte, F. La Via, V. Raineri, F. Mangano, and L. Calcagno, *Appl. Phys. Lett.* **83**, 4181 (2003).
- [11] F. La Via, G. Galvagno, F. Roccaforte, A. Ruggiero, and L. Calcagno, *Appl. Phys. Lett.* **87**, 142105 (2005).
- [12] A. Hürner, C. Bonse, G. Clemmer, B. Kallinger, T. Heckel, T. Erlbacher, H. Mitlehner, V. Häublein, A. J. Bauer, and L. Frey, *Mater. Sci. Forum* **778–780**, 487 (2014).
- [13] P. A. Ivanov, A. S. Potapov, T. P. Samsonova, and I. V. Grekhov, *Solid State Electron.* **123**, 15 (2016).
- [14] T. Kimoto and J. A. Cooper, *Fundamentals of Silicon Carbide Technology* (John Wiley & Sons, 2014).
- [15] D. K. Schroder, *Semiconductor Material and Device Characterization* (John Wiley & Sons, 3rd edition, 2006).
- [16] R. H. Cox and H. Strack, *Solid State Electron.* **10**, 1213 (1967).
- [17] R. Holm and E. Holm, *Electric Contacts Handbook* (Springer, 3rd edition, 1958).
- [18] Y. Negoro, T. Kimoto, H. Matsunami, F. Schmid, and G. Pensl, *J. Appl. Phys.* **96**, 4916 (2004).
- [19] A. Itoh, H. Akita, T. Kimoto, and H. Matsunami, *Appl. Phys. Lett.* **65**, 1400 (1994).
- [20] W. J. Choyke and G. Pensl, *MRS Bull.* **22**, 25 (1997).
- [21] A. A. Burk, M. J. O’Loughlin, R. R. Siergiej, A. K. Agarwal, S. Sriram, R. C. Clarke, M. F. MacMillan, V. Balakrishna, and C. D. Brandt, *Solid State Electron.* **43**, 1459 (1999).
- [22] T. Kimoto, S. Nakazawa, K. Hashimoto, and H. Matsunami, *Appl. Phys. Lett.* **79**, 2761 (2001).
- [23] G. Rutsch, R. P. Devaty, W. J. Choyke, D. W. Langer, L. B. Rowland, E. Niemann, and F. Wischmeyer, *Mater. Sci. Forum* **338–342**, 733 (2000).
- [24] H. Fujihara, J. Suda, and T. Kimoto, *Jpn. J. Appl. Phys.* **56**, 070306 (2017).
- [25] W. E. Nelson, F. A. Halden, and A. Rosengreen, *J. Appl. Phys.* **37**, 333 (1966).
- [26] M. Shinohara, M. Yamanaka, H. Daimon, E. Sakuma, H. Okumura, S. Misawa, K. Endo, and S. Yoshida, *Jpn. J. Appl. Phys.* **27**, L434 (1988).

- [27] M. Roschke and F. Schwierz, *IEEE Trans. Electron Devices* **48**, 1442 (2001).
- [28] D. M. Caughey and R. E. Thomas, *Proc. IEEE* **55**, 2192 (1967).
- [29] P. Y. Yu and M. Cardona, *Fundamentals of semiconductors: Physics and materials properties* (Springer, 4th edition, 2010).
- [30] C. Hamaguchi, *Basic Semiconductor Physics* (Springer, 2nd edition, 2010).
- [31] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (John Wiley & Sons, 2006).
- [32] N. T. Son, C. Persson, U. Lindefelt, W. M. Chen, B. K. Meyer, D. M. Hofmann, and E. Janzén, Cyclotron resonance studies of effective masses and band structure in SiC, *Silicon Carbide – Recent Major Advances* (eds. W. J. Choyke, H. Matsunami, and G. Pensl), (Springer, 2004), p. 437.
- [33] X. Gonze, B. Amadon, P. M. Anglade, J. M. Beuken, F. Bottin, P. Boulanger, F. Bruneval, D. Caliste, R. Caracas, M. Côté, T. Deutsch, L. Genovese, P. Ghosez, M. Giantomassi, S. Goedecker, D. R. Hamann, P. Hermet, F. Jollet, G. Jomard, S. Leroux, M. Mancini, S. Mazevet, M. J. T. Oliveira, G. Onida, Y. Pouillon, T. Rangel, G. M. Rignanese, D. Sangalli, R. Shaltaf, M. Torrent, M. J. Verstraete, G. Zerah, and J. W. Zwanziger, *Comput. Phys. Commun.* **180**, 2582 (2009).
- [34] S. Goedecker, M. Teter, and J. Hutter, *Phys. Rev. B* **54**, 1703 (1996).
- [35] N. Troullier and J. L. Martins, *Phys. Rev. B* **43**, 1993 (1991).
- [36] C. Persson and U. Lindefelt, *J. Appl. Phys.* **82**, 5496 (1997).

Chapter 3

High-Field Electron Velocity

3.1 Introduction

For a comprehensive understanding of the device performance and underlying physical phenomena, the high-field drift velocity is a key parameter because high electric fields often emerge under situations like short-circuit events and avalanche breakdown. While the high-field drift velocity of electrons in SiC perpendicular to the c -axis has been studied previously [1, 2], there are few reports on that parallel to the c -axis, leading to poor understanding of drift velocity anisotropy. The objective of this chapter is to experimentally determine the high-field drift velocity of electrons along both directions parallel and perpendicular to the c -axis. Conductance measurements on n-type SiC(11 $\bar{2}$ 0) layers were chosen as the preferred method, taking into account the restriction on crystal growth of SiC, and the study began with the setup of the measurement system and the preparation of test structures. The drift velocity of electrons was then investigated over a wide electric field strength range, and its anisotropy was analyzed focusing on the energy distribution of electrons.

3.2 Determination Method of High-Field Carrier Velocity

3.2.1 Conductance Measurement versus Time-of-Flight Method

To determine the high-field velocity in semiconductor materials, two primary methods are commonly used: the time-of-flight method [3, 4] and conductance measurement [5, 6], schematically illustrated in Fig. 3.1 and Fig. 3.2, respectively. In the time-of-flight method, a semiconductor layer is fully depleted by applying a reverse voltage on a pn or Schottky junction. Excess carriers are then generated in the depleted layer using a pulse laser, and these carriers are transported to the right-side electrode in Fig. 3.1(a) under the influence of the electric field. These transported carriers induce charges with opposite signs at the electrode, resulting in a current flow through an external resistance. Since this current

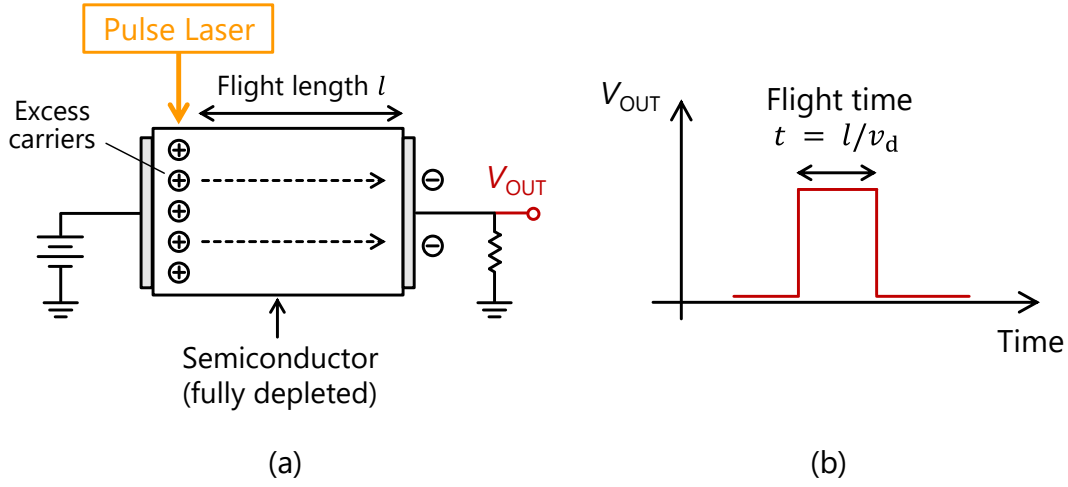


Figure 3.1: (a) Schematic illustration of the time-of-flight method, where excess carriers generated in a fully depleted semiconductor are transported to the opposite-side electrode, leading to the output of a pulse voltage. (b) Typical waveform of measured voltage, where the drift velocity v_d can be obtained from the flight time t and the flight length l .

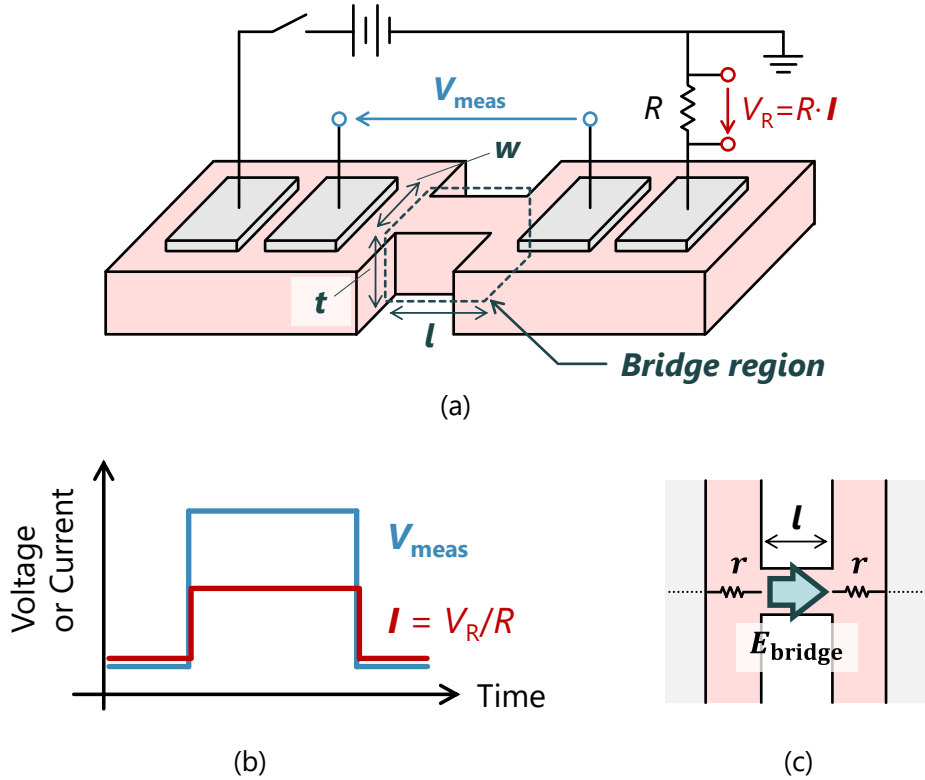


Figure 3.2: (a) Schematic illustration of conductance measurement, i.e., high-voltage 4-point probe measurement, with a test structure having a short and narrow bridge region. (b) Typical measured waveforms of voltage and current when applying a pulse voltage on the structure. (c) Top view schematic of the test structure near the bridge region with the definition of the resistance component r and the electric field in the bridge E_{bridge} .

flows until the excess carriers reach the electrode, their drift velocity can be determined from the flight time and flight length. This method is particularly attractive because it directly measures the drift velocity, avoiding inaccuracies such as the Hall scattering factor encountered in Hall effect measurement. It has been successfully applied to semiconductor materials such as Si, Ge, and GaAs [6–11], where extremely low doping concentration (typically below $1 \times 10^{11} \text{ cm}^{-3}$) allow for thick depleted layers, long flight times, and precise measurements (e.g., with a flight length of $500 \text{ } \mu\text{m}$, an applied voltage of $\sim 1000 \text{ V}$, a drift velocity of $\sim 1 \times 10^7 \text{ cm/s}$, and a flight time of $\sim 5 \text{ ns}$). However, for commercially available SiC wafers, the doping concentration is significantly higher compared with the above-mentioned materials ($\geq 1 \times 10^{14} \text{ cm}^{-3}$), leading to a short depletion layer and a short flight time in the picosecond range, making this method challenging to apply to SiC at the present stage. In contrast, the conductance measurement is essentially a high-voltage 4-point probe technique as shown in Fig. 3.2, which involves a short, narrow bridge structure and a high voltage source to enable high-field measurements. There is no restriction on the doping concentration for the conductance measurements in principle (except for the self-heating issues), and there are several reports that applied this method on materials with relatively high doping concentration, including SiC with $N_D \sim 10^{17} \text{ cm}^{-3}$ [1, 12–14]. However, the study on high-field velocity in SiC is limited to that perpendicular to the c -axis, leading to ambiguous database of material properties and poor understanding of transport mechanism. Based on these considerations, the conductance measurement was adopted in the present study to determine the high-field drift velocity in SiC.

3.2.2 Procedure and Requirement of Conductance Measurement

For the conductance measurement of electrons shown in Fig. 3.2(a), a high voltage is applied on the two outer terminals of the 4-terminal test structure, which includes a bridge region in the center fabricated on an n-type layer. Due to the higher resistance of the bridge region compared to those of other parts of the structure, a large portion of the voltage is applied to the bridge region, allowing high-field measurements. The voltage drop (V_{meas}) and the current (I) flowing through the external resistance (R) are then measured, as illustrated in Fig. 3.2(b). Note that a pulsed voltage is used instead of a DC voltage to maintain a stable temperature in the bridge region by reducing the self-heating effects in the structure. Using these measured values and the dimensions of the bridge, the drift velocity of carriers (v_d) and the electric field strength in the bridge (E_{bridge}) can be determined as follows:

$$v_d = \frac{I}{enwt}, \quad (3.1)$$

$$E_{\text{bridge}} = \frac{V_{\text{meas}} - 2r \cdot I}{l}, \quad (3.2)$$

where l , w , and t are the length, width, and thickness of the bridge, respectively. e is the elementary charge, n is the electron concentration, and r represents the resistance between

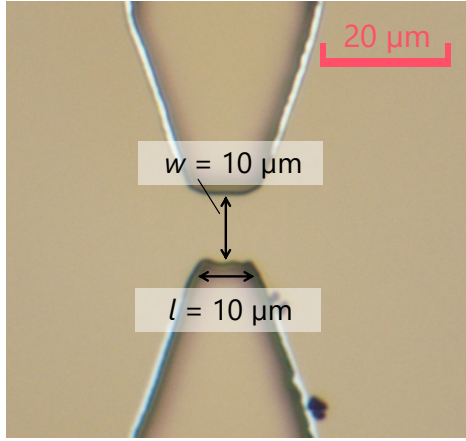
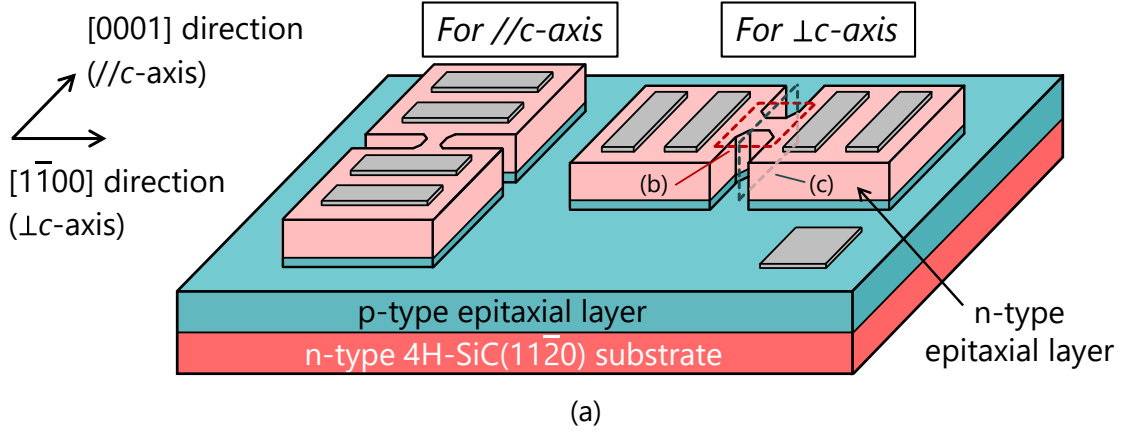
electrodes and bridge region shown in Fig. 3.2(c). In the present analysis, n was determined by Hall effect measurement as described in Chapter 2, and $2r$ was estimated based on the resistance between the inner two electrodes for multiple structures with different bridge lengths. By repeating this analysis at various applied voltages, the drift velocity versus electric field relationship can be obtained.

The essential requirements for those measurements and analyses are (i) a short and narrow bridge structure to achieve high-field measurement, and (ii) a short-pulse high-voltage source to suppress self-heating in the structure. The specific components were prepared as described in the next section.

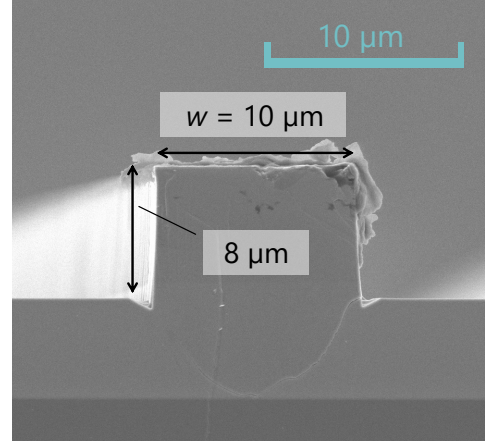
3.3 Measurement Setup and Sample Preparation

3.3.1 Design and Fabrication of Bridge Structures

Four-terminal test structures with bridge regions were fabricated on SiC(11 $\bar{2}$ 0) n-type epitaxial layers, which were electrically isolated from the n-type substrates by intermediate p-type epitaxial layers, as shown in Fig. 3.3(a). The donor concentration of the n-type epilayer was varied within a range from $2 \times 10^{15} \text{ cm}^{-3}$ to $3 \times 10^{16} \text{ cm}^{-3}$, and two types of structures for the drift velocity along the directions parallel and perpendicular to the c -axis were arranged side by side on the same sample. Since the samples were obtained from the same wafers as that described in Section 2.3, detailed information such as the donor concentration, compensating acceptor concentration, and thickness can be found in Table 2.2 and Table 2.3. The fabrication process is nearly identical to that of the n-type Hall bar structure described in Section 2.3; epitaxial growth was followed by ion implantation, mesa isolation, and ohmic metal formation with appropriate masks for each process. The main difference is the Schottky contact was not formed because the net donor concentration has already been measured, and ohmic metals were also deposited on the p-type epitaxial layer at the same time as the ohmic metal formation on n-type epilayers to obtain ohmic contacts on p-type layers. Furthermore, the condition of inductively-coupled plasma reactive ion etching (ICP-RIE) was slightly adjusted from that used for Hall bar fabrication to ensure vertical sidewalls: [SF₆/O₂/Ar: 10/20/100 sccm, ICP/Bias power: 500/90 W, pressure: 2 Pa, etching rate: 0.7 μm]. The bridge region was designed with a length $l = 2.5 - 20 \mu\text{m}$ and width $w = 10 \mu\text{m}$, and thickness t was calculated by subtracting the depletion layer width from the n-type epilayer thickness for each doping concentration and applied voltage. Figure 3.3(b) and (c) show a top-view optical microscope image near the bridge region and a cross-sectional SEM image of the bridge region, respectively, showing the successful formation of a narrow, short bridge structure with vertical sidewalls.



(b)



(c)

Figure 3.3: (a) Test structures with bridge regions along the [0001] and [1 $\bar{1}$ 00] directions fabricated on n-type SiC(11 $\bar{2}$ 0) epitaxial layer for measuring the electron drift velocity parallel and perpendicular to the c -axis. These structures were arranged side by side along with an electrode deposited on p-type epitaxial layer. (b) Optical microscope image of the fabricated test structure (top-view) and (c) SEM image of the bridge region (cross-section).

3.3.2 Positive High-Voltage Short-Pulse Circuit

Figure 3.4(a) shows a schematic illustration of a fabricated positive high-voltage short-pulse circuit. The output from a positive DC high-voltage source (HK-2P, Matsusada Precision) was converted into a pulse using a custom-made switching circuit, which includes two 1.2 kV SiC MOSFETs (IMW120R350M1H, Infineon) and a gate driver (2EDB9259T, Infineon). The gate driver receives small signal inputs from a function generator (81160A, Agilent Technologies) and controls the gate voltage of MOSFETs to produce a high-voltage pulse. A DC link capacitor was placed in parallel with the high-voltage source to ensure stable output voltage, and 15 V inputs were provided to both the low- and high-side of the gate driver from a DC voltage source through DC/DC converters. Figure 3.4(b) shows typical waveforms of the output voltages of the function generator (V_{fg} and $\overline{V_{fg}}$) and the switching circuit (V_{app}), where 10 V signals from the function generator are amplified to a 100 V pulse voltage with the pulse width of 2 μ s. The switching circuit achieves a short pulse width (minimum pulse width: 200 ns) and a flat waveform with minimal overshoot, which both are essential for accurate conductance measurements.

3.3.3 Measurement System Assembly

A schematic illustration of the conductance measurement system used in this study is shown in Fig. 3.5. The output from the switching circuit was connected to the test structure via a coaxial probe, and multiple voltages are monitored by an oscilloscope (DSO9254A, Agilent Technologies). For the measurement of V_{meas} and $V_R = RI$, a differential probe (N2790A) and a standard 10:1 passive probe were utilized, respectively. The applied voltage was varied from 2 V to 120 V, and R was selected in the range of 500 Ω to 2000 Ω to minimize the effects of noise and transient current for each condition including the applied voltage, bridge length, and donor concentration. To prevent air sparking and promote heat dissipation, the test structures were immersed in Fluorinert during measurements. In addition, the p-layer was connected to the ground to reduce transient currents from the depletion capacitor of the pn junction, and a detailed discussion on the effect of this grounding setup will be done in the following section with the experimental results of waveform measurements.

3.4 Results and Analyses

3.4.1 Voltage and Current Waveforms

Figure 3.6 shows the waveforms of V_{meas} and $V_R = RI$ with $N_D = 5 \times 10^{15} \text{ cm}^{-3}$, a direction parallel to the c -axis, $l = 10 \text{ }\mu\text{m}$, and $w = 10 \text{ }\mu\text{m}$. The plots in different colors represent the results for different applied voltages. As shown in Fig. 3.6, I approaches a constant value around 8 mA as the electric field E_{bridge} increases while V_{meas} increases at almost equal intervals, which indicates the saturation of the electron drift velocity at higher electric fields.

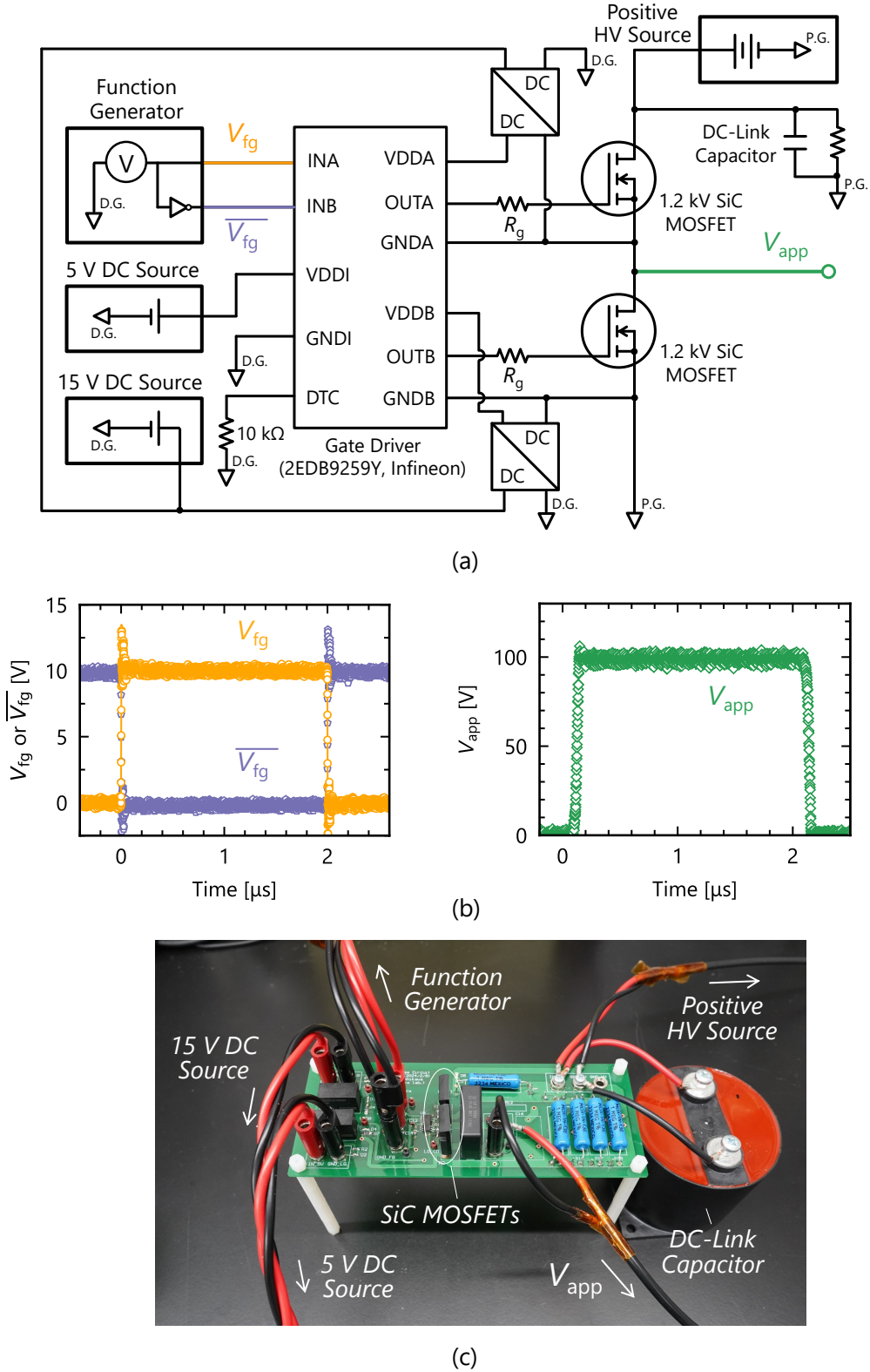


Figure 3.4: (a) Schematic diagram of the custom-made switching circuit for generation of short-pulse positive high voltage and (b) typical waveforms of outputs of the function generator and the switching circuit, where a small signal input from the function generator is amplified to a pulsed high voltage. (c) Photograph of fabricated switching circuit with notations of the connections with other equipment.

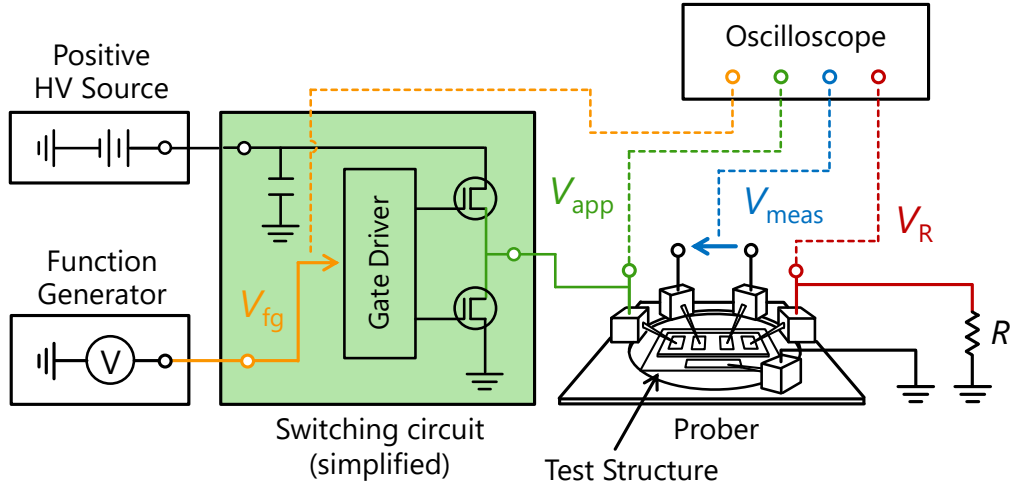


Figure 3.5: System assembly of conductance measurement for electron drift velocity including a positive high-voltage source, a function generator, a switching circuit, a prober, and an oscilloscope.

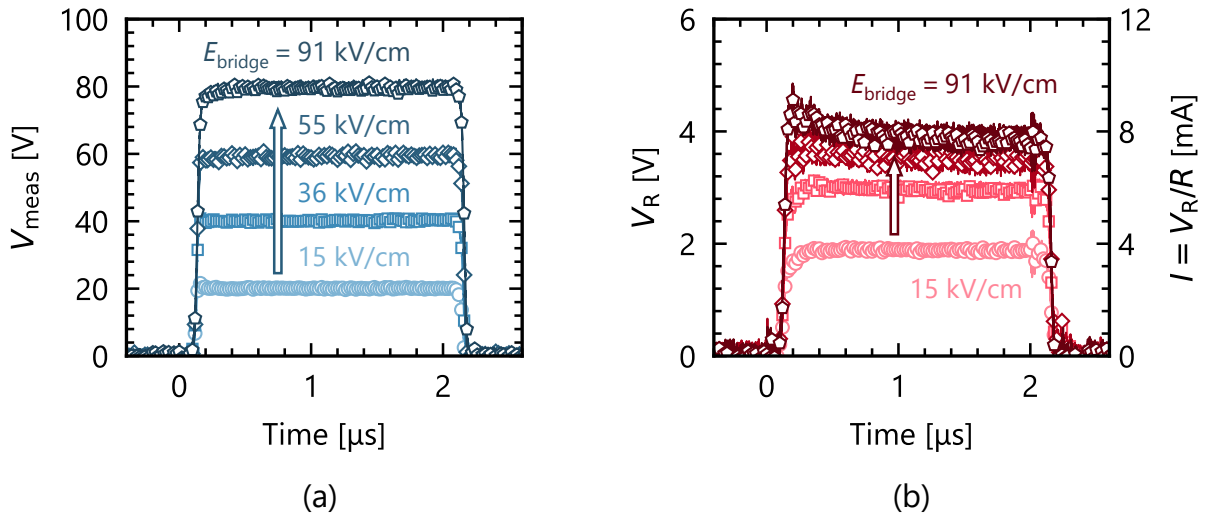


Figure 3.6: Waveforms of (a) voltage drop V_{meas} and (b) current I for different applied voltages obtained for a test structure parallel to the c -axis with $N_D = 5 \times 10^{15} \text{ cm}^{-3}$, $l = 10 \text{ } \mu\text{m}$, and $w = 10 \text{ } \mu\text{m}$.

Here, E_{bridge} was calculated using Eq. (3.2), and the resistance component for correction $2r$ was estimated by the following procedure. First, the resistance between the inner two electrodes was determined by applying low voltages (-10 – 10 V) to the structures with different l , as summarized in Fig. 3.7. Since this resistance is the sum of $2r$ and the bridge resistance R_{bridge} , and R_{bridge} is proportional to l , $2r$ was estimated from the y-axis intercept after performing linear extrapolation, as shown in Fig. 3.7, for each donor concentration and direction. It should be noted that this analysis assumes that $2r$ is independent of the applied voltage (i.e., the electron velocity does not saturate in the $2r$ region).

Before moving on to the analysis of the electron velocity, it is necessary to discuss the treatment of the transient current in this measurement. From the perspective of accuracy, the p-type epilayer was grounded to suppress the transient current flowing from a depletion capacitor of the pn junction to external resistance R . When a high voltage is applied on the electrode, a reverse voltage is applied on the pn junction between the n-type and p-type epilayers, and the extended depletion layer acts as a capacitor connected in parallel with the bridge. If the p-layer is left floating, the transient current (i.e., holes swept from the extended depletion layer) flows from the depletion capacitor of pn-junction to R as shown in Fig. 3.8(a). This transient current can lead to inaccurate measurements, as the observed current flowing in R would not be equal to the target current flowing in the bridge region. To avoid such situations, the p-layer was connected to the ground so that the transient current would flow directly into the ground without passing through R . Figure 3.8(b) shows the current waveforms for both setups: with the p-layer floating and with the p-layer grounded. Grounding the p-layer clearly reduces the transient current immediately after the turn-on, thereby ensuring greater accuracy. This grounding configuration was therefore used in all the measurements for the present study.

3.4.2 Electron Drift Velocity versus Electric Field Strength

The electric field and drift velocity of electrons were extracted using Eqs. (3.1) and (3.2) for various applied voltages, with the same measurements and analyses repeated on the structures with different l . The obtained results are summarized in Fig. 3.9, showing data for directions parallel and perpendicular to the c -axis with $N_D = 5 \times 10^{15}$, 1×10^{16} , and $3 \times 10^{16} \text{ cm}^{-3}$. The electron drift velocity was successfully determined over a wide range of electric fields (1 – 200 kV/cm), and the result that the obtained velocities from the structures with different l align closely indicates the reasonability of the analysis. The results show that, for both directions, the velocity increases linearly with the electric field in the low-field region while reaching saturation at the higher electric field.

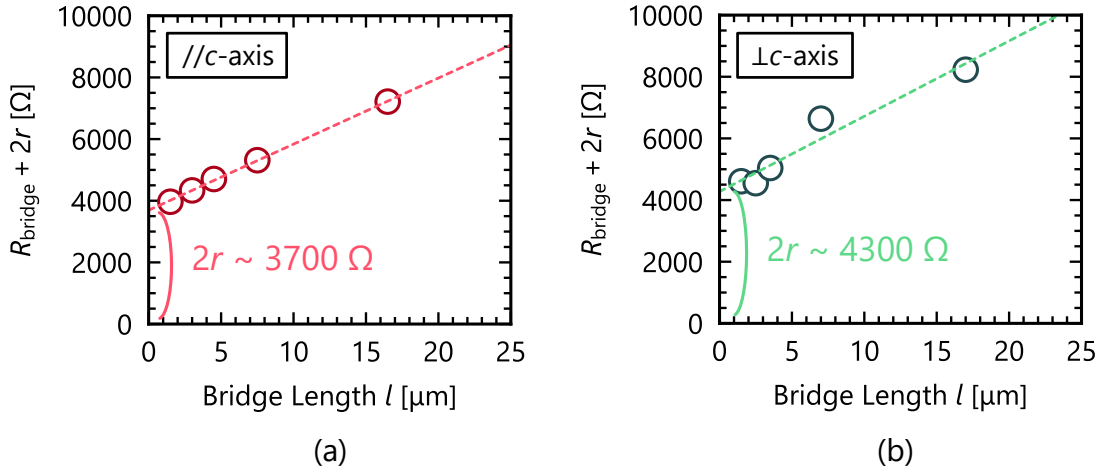


Figure 3.7: Bridge length (l) dependence of the resistance between the two internal electrodes of the test structure, i.e., the sum of the bridge resistance (R_{bridge}) and the resistance components $2r$ for the directions (a) parallel and (b) perpendicular to the c -axis ($N_D = 5 \times 10^{15} \text{ cm}^{-3}$ and $w = 10 \mu\text{m}$).

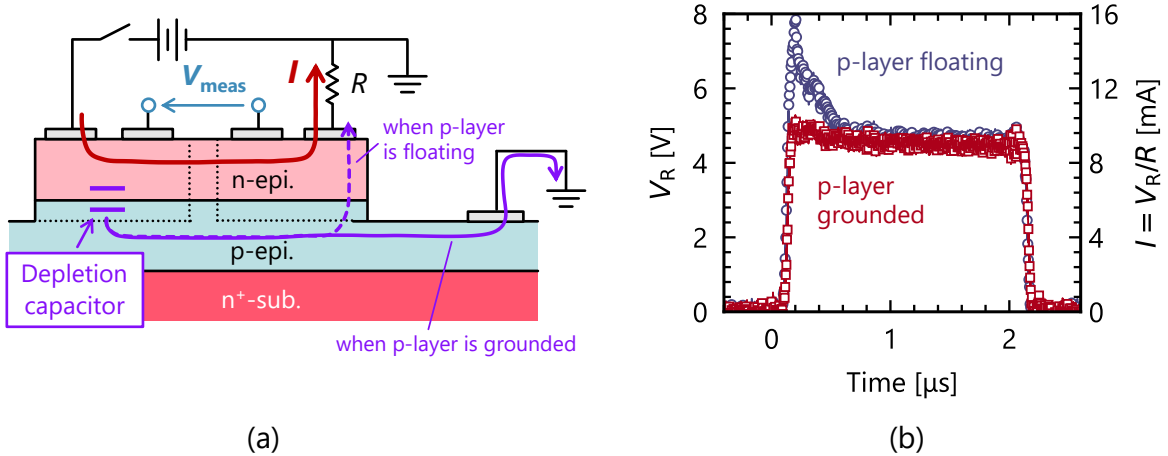


Figure 3.8: (a) Schematic of the current path when the p -layer is floating and grounded, where the transient current from the depletion capacitor of the pn junction is directly led to the ground without going through the external resistance (R) by grounding the p -layer. (b) Current waveforms under both conditions, where the transient current is clearly reduced by grounding the p -layer.

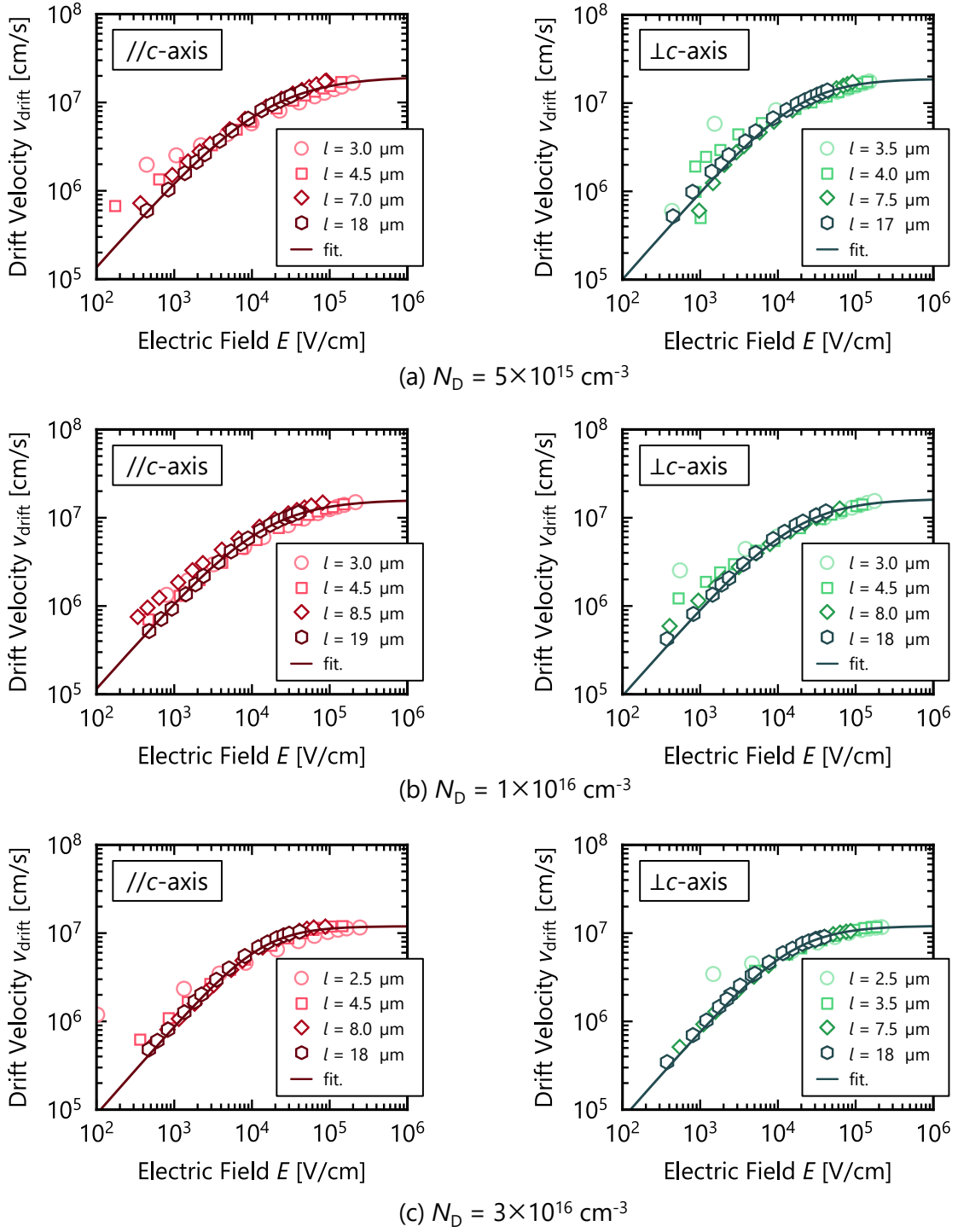


Figure 3.9: Drift velocity of electrons versus electric field strength obtained from the test structures with different bridge lengths (l) along both directions for (a) $N_D = 5 \times 10^{15} \text{ cm}^{-3}$, (b) $N_D = 1 \times 10^{16} \text{ cm}^{-3}$, and (c) $N_D = 3 \times 10^{16} \text{ cm}^{-3}$. Solid lines depict the fitting results based on Eq. (3.3) and the extracted parameters are summarized in Table 3.1.

3.4.3 Saturated Drift Velocity of Electrons

The low-field mobility and the high-field saturated velocity were extracted from the v_d – E_{bridge} relationship. After determining the low-field mobility (μ) by performing linear extrapolation in the low-field region ($E_{\text{bridge}} \leq 3 \times 10^3 \text{ V/cm}$), the saturated velocity (v_{sat}) was obtained by fitting the data using the following empirical equation [15]:

$$v_d = \frac{\mu E}{[1 + (\mu E/v_{\text{sat}})^\alpha]^{1/\alpha}}, \quad (3.3)$$

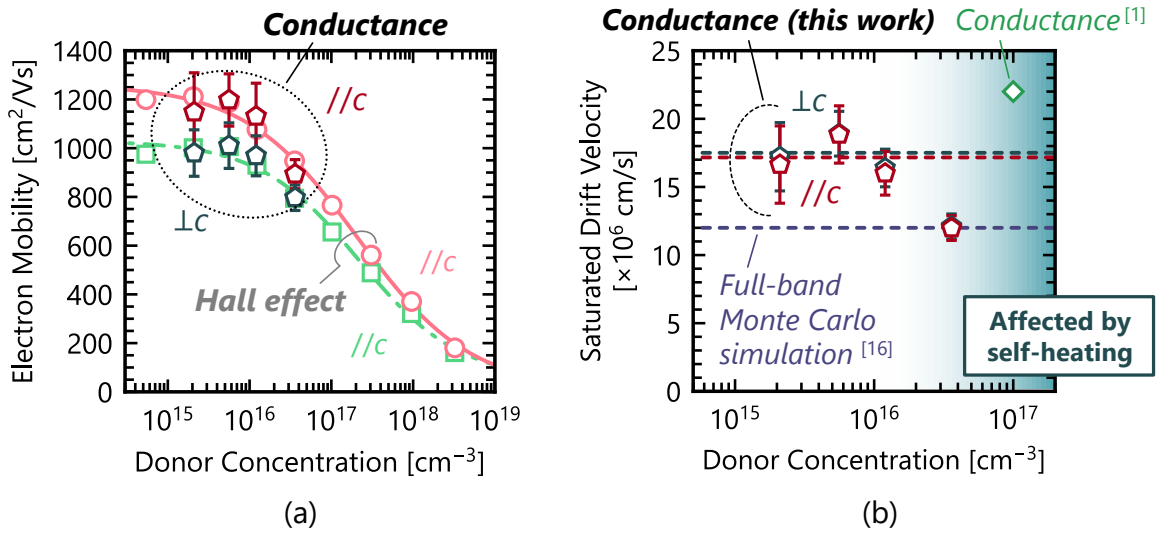
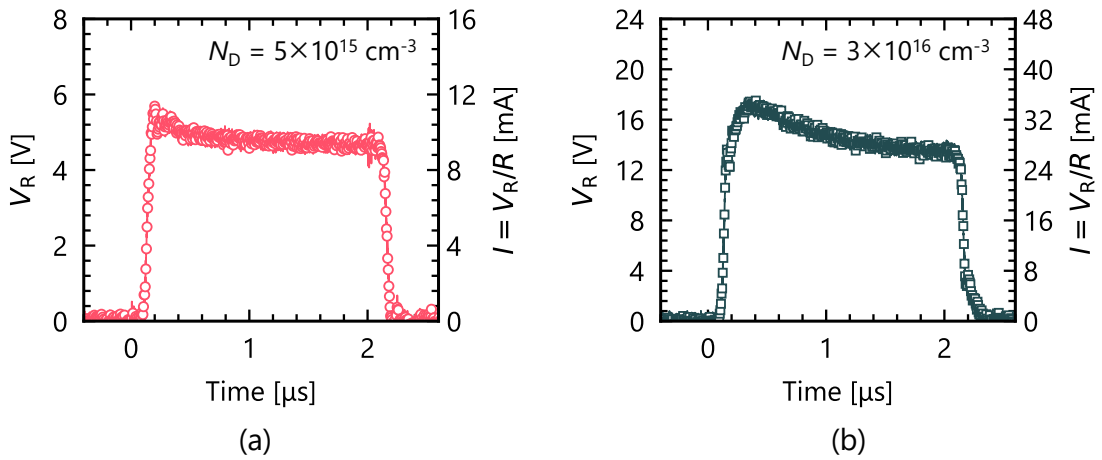
where α is a fitting parameter describing how bending the fitted curve is. The fitted curves are plotted as solid lines in Fig. 3.9, and the obtained parameters are summarized in Table 3.1 and Fig. 3.10 as functions of donor concentration. Note that the error bars in Fig. 3.10 include both the fitting error and the measurement error of the bridge dimensions. As shown in Fig. 3.10(a), the obtained mobilities by conductance measurements are consistent with those by Hall effect measurements, which indicates the present measurements and analyses are reasonable. Regarding the saturated drift velocity, lower values were observed for the heavily-doped sample. However, because the saturated velocity is a material property fundamentally determined by interactions of electrons with optical phonons, it should theoretically be independent of the donor concentration. Therefore, approximately a 30% decrease in the saturated velocity is therefore attributed to other factors, primarily self-heating of the structure.

Figure 3.11 shows current waveforms under high electric fields ($\sim 100 \text{ kV/cm}$) for lightly-doped ($N_D = 5 \times 10^{15} \text{ cm}^{-3}$) and heavily-doped ($N_D = 3 \times 10^{16} \text{ cm}^{-3}$) samples. The current remains nearly constant over time for the case of lightly-doped sample, it decreases as time progresses for the heavily-doped case. This reduction in current is likely due to the self-heating because higher doping concentration results in a higher current and greater amount of Joule heating, and the stable waveform observed for donor concentration below $1 \times 10^{16} \text{ cm}^{-3}$ suggests that these results are little influenced by self-heating. Then, the saturated drift velocities were determined by averaging the results for the donor concentration below $1 \times 10^{16} \text{ cm}^{-3}$ to be $1.7 \times 10^7 \text{ cm/s}$ for the both directions parallel and perpendicular to the c -axis.

The saturated drift velocity perpendicular to the c -axis obtained in the present study ($v_{\text{sat},\perp} = 1.7 \times 10^7 \text{ cm/s}$) is lower than the previously reported value by performing conductance measurements on SiC(0001) samples ($v_{\text{sat},\perp} = 2.2 \times 10^7 \text{ cm/s}$ with $N_D = 1 \times 10^{17} \text{ cm}^{-3}$) [1], which is also depicted in Fig. 3.10(b). This discrepancy likely arises from challenges in accurate conductance measurements on heavily-doped samples where both the effects of transient current and self-heating become more pronounced. Therefore, the results obtained for lightly-doped samples in this study are considered more reliable. On the other hand, the theoretically calculated value of saturated velocity ($1.3 \times 10^7 \text{ cm/s}$) [16] is smaller than the experimental values obtained here, which may be attributed to the Hall scattering factor or a simplified scattering model used in the calculation. Since the Hall

Table 3.1: Extracted low-field mobility (μ), high-field saturated velocity (v_{sat}), and α obtained for each direction and donor concentration (N_D).

	//c-axis			$\perp$ c-axis		
N_D [cm^{-3}]	μ [cm^2/Vs]	v_{sat} [cm/s]	α	μ [cm^2/Vs]	v_{sat} [cm/s]	α
2×10^{15}	1190	1.7×10^7	0.62	980	1.7×10^7	0.58
5×10^{15}	1200	1.9×10^7	0.78	1010	1.9×10^7	1.02
1×10^{16}	1170	1.6×10^7	0.87	970	1.6×10^7	0.93
3×10^{16}	900	1.2×10^7	1.24	800	1.2×10^7	1.06

**Figure 3.10:** (a) Low-field mobility and (b) high-field saturated velocity of electrons as functions of donor concentration, where the saturated velocities obtained in the previous experiment [1] and calculation [16] are also depicted.**Figure 3.11:** Current waveforms under high electric field for different donor concentrations. The decreasing current as time progresses for $N_D = 3 \times 10^{16} \text{ cm}^{-3}$ indicates that the result is affected by self-heating of the structure.

electron concentration was employed for the analysis of conductance measurements, the obtained velocities reflect the influence of the Hall scattering factor. As discussed in Section 2.3.4, the Hall scattering factor of electrons is greater than unity, which implies a potential overestimation of the experimentally determined saturated drift velocity.

3.5 Discussion

From the analyses in the previous section, the saturated drift velocity of electrons was found to be nearly isotropic, whereas the low-field mobility exhibits 10-20% anisotropy at room temperature. This electric field-dependent anisotropy of electron transport properties was further discussed by focusing on the effective mass (m^*), as both μ and v_{sat} are expressed using m^* as follows [17]:

$$\mu = \frac{e\langle\tau\rangle}{m^*}, \quad (3.4)$$

$$v_{\text{sat}} = \sqrt{\frac{8\hbar\omega}{3\pi m^*}}, \quad (3.5)$$

where $\langle\tau\rangle$ is the averaged momentum relaxation time of electrons and $\hbar\omega$ is the energy of optical phonons. Considering the reported values of m^* at the conduction band minimum ($m_{\perp}^* = 0.40m_0$ and $m_{\parallel}^* = 0.33m_0$ at E_C), the observed μ ratio (~ 1.2) is consistent with the m^* ratio (~ 1.2) while the observed v_{sat} ratio (~ 1.0) is slightly different from the square root of the m^* ratio (~ 1.1). This difference can be qualitatively explained by considering the energy dependence of the effective mass. Under high electric fields, electrons are distributed with higher energies than at thermal equilibrium state [16], as shown in Fig. 3.12(a). Here, as calculated in Section 2.4, the effective mass along the c -axis is lighter than that perpendicular to the c -axis near E_C , while it becomes heavier rather than that perpendicular at higher energy region as shown again in Fig. 3.12(b). These results imply that for the low-field mobility, electrons near E_C are dominant in the electrical conduction, meaning that 20% anisotropy in effective mass near E_C directly leads to 20% anisotropy in mobility. In contrast, for the high-field drift velocity, a greater number of electrons with higher energy participate in conduction, where effective mass shows the opposite anisotropy, resulting in almost isotropic drift velocity. In summary, the contracting anisotropy in low- and high-field transport can be qualitatively explained by the energy-dependent anisotropy of the effective mass.

3.6 Summary

In this chapter, the author determined the anisotropic drift velocity of electrons using n -type SiC(11 $\bar{2}$ 0) epilayers. Conductance methods were adopted for the measurements of drift velocities in SiC since it has no restriction for the doping concentration in principle and it is considered to be suitable for SiC, whose minimum doping concentration ($\sim 1 \times 10^{14}$) is

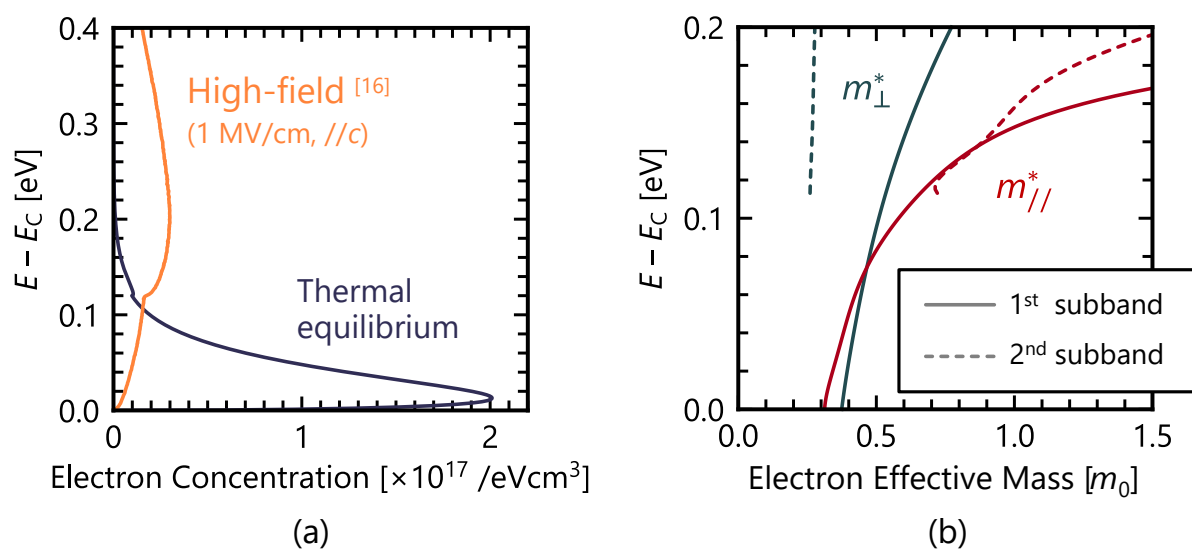


Figure 3.12: (a) Electron distributions in the conduction band under thermal equilibrium state and high electric field (1 MV/cm, //c-axis) [16]. (b) Energy dependence of electron effective masses parallel and perpendicular to the c -axis calculated in Section 2.4.

relatively higher than the other semiconductor such as Si and Ge. The electron velocity was measured over a wide range of electric fields from 1 to 200 kV/cm by combining the n-type bridge structures and a high-voltage short-pulse source. Saturation of electron drift velocity was observed around 100 kV/cm, with saturated drift velocities of 1.7×10^7 cm/s for both directions parallel and perpendicular to the c -axis. Careful consideration of the effects of transient current and self heating ensured the accuracy of these results. In addition, the relaxation of velocity anisotropy at high electric field was qualitatively explained by the change in the energy distribution of electrons.

References

- [1] I. A. Khan and J. A. Cooper, *IEEE Trans. Electron Devices* **47**, 269 (2000).
- [2] W. v. Muench and E. Pettenpaul, *J. Appl. Phys.* **48**, 4823 (1977).
- [3] W. E. Spear, *Proc. Phys. Soc. B* **70**, 669 (1957).
- [4] D. K. Schroder, *Semiconductor Material and Device Characterization* (John Wiley & Sons, 3rd edition, 2006).
- [5] E. J. Ryder and W. Shockley, *Phys. Rev.* **81**, 139 (1951).
- [6] C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *Solid State Electron.* **20**, 77 (1977).
- [7] C. B. Norris and J. F. Gibbons, *IEEE Trans. Electron Devices* **14**, 38 (1967).
- [8] C. Jacoboni, F. Nava, , C. Canali, , and G. Ottaviani **24**, 1014 (1981).
- [9] D. M. Chang and J. G. Ruch, *Appl. Phys. Lett.* **12**, 111 (1968).
- [10] J. G. Ruch and G. S. Kino, *Appl. Phys. Lett.* **10**, 40 (1967).
- [11] J. A. Cooper and D. F. Nelson, *J. Appl. Phys.* **54**, 1445 (1983).
- [12] R. D. Larrabee, *J. Appl. Phys.* **30**, 857 (1959).
- [13] J. M. Barker, D. K. Ferry, D. D. Koleske, and R. J. Shul, *J. Appl. Phys.* **97**, 063705 (2005).
- [14] K. Hirakawa and H. Sakaki, *J. Appl. Phys.* **63**, 803 (1988).
- [15] D. M. Caughey and R. E. Thomas, *Proc. IEEE* **55**, 2192 (1967).
- [16] H. Tanaka, T. Kimoto, and N. Mori, *Mater. Sci. Semicond. Process.* **173**, 108126 (2024).
- [17] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (John Wiley & Sons, 2006).

Chapter 4

Low-Field Hole Mobility

4.1 Introduction

The low-field hole mobility is a crucial material property that directly determines several characteristics of SiC devices, especially those of bipolar devices such as the carrier profile in the blocking layer, on-resistance, switching characteristics, etc [1]. While the hole mobility perpendicular to the c -axis has been studied extensively so far [2–5], a systematic database of that parallel to the c -axis is not yet available to researchers and engineers in the field. Although there exists only a single report that focused on the anisotropy in hole mobility to the best of the author’s knowledge [6], the origin on its anisotropy is not clarified yet mainly due to the lack of comprehensive data on the temperature and doping concentration dependences. In this chapter, the author determined the hole mobility along the c -axis as well as that perpendicular to the c -axis through Hall effect measurements conducted on SiC(11 $\bar{2}$ 0) samples. Furthermore, a theoretical analysis was performed by considering the energy distribution of holes and the valence band structure of SiC to discuss the contribution of the anisotropy of hole effective mass to the observed anisotropy in hole mobility.

4.2 Hole Mobility Determined by Hall Effect Measurement

In this section, the design and process flow of Hall bar structures specifically intended for measuring the anisotropic hole mobility will be explained. While the fundamental principle of measurement and basic design guidelines largely mirror those outlined for electron mobility in Section 2.3, the signs of equations to determine the carrier concentration and mobility (Eqs. (2.6) and (2.8)) should be adjusted according to the conversion of conduction type from n-type to p-type, and the basic equations for analysis on p-type semiconductor are given as follow [7]:

$$V_H = -\frac{\gamma_H BI}{ept} \quad \therefore p = -\frac{\gamma_H BI}{eV_H t}, \quad (4.1)$$

$$V_\rho = \rho I \frac{L}{Wt} \quad \therefore \rho = \frac{V_\rho Wt}{IL} \quad (4.2)$$

$$\mu = \frac{1}{ep\rho} = -\frac{LV_H}{\gamma_H BWV_\rho}. \quad (4.3)$$

Here, p is the hole concentration, μ is the hole mobility, and the remaining parameters are consistent with those defined in Section 2.3: V_H and V_ρ are the Hall voltage the voltage drop illustrated in Fig. 2.9, L , W , and t is the length, width, and thickness of the measurement region, B is the magnetic field, e is the elementary charge, γ_H is the Hall scattering factor, and ρ is the resistivity. In a similar manner to the case of electrons, the hole mobility and hole concentration obtained based on the assumption $\gamma_H = 1$ is referred as “Hall hole mobility” (μ_H) and “Hall hole concentration” (p_H), to distinguish them from the “drift hole mobility” (μ) and “hole concentration” (p), respectively. The relationships between μ_H and μ , and p_H and p are given by:

$$\mu_H = \gamma_H \mu, \quad p_H = p / \gamma_H. \quad (4.4)$$

This methodology forms the basis for measuring hole mobility, and the Hall bar structure discussed in the next section was adopted for the present measurement, which facilitates accurate determination of the anisotropic hole mobility in p-type semiconductors.

4.2.1 Design and Fabrication of Hall Bar Structures

Hall bar structures for determining hole mobility were designed with careful consideration of factors crucial for accurate measurement, as discussed in Section 2.3. The overall design guidelines were largely similar to those employed for electron mobility measurements, with the primary differences being the wider bridge and the larger connection region at terminals 1–4, where they intersect with the bar region. The resistivity of the p-type SiC layer is expected to be much higher than that of the n-type SiC layer because the hole mobility is approximately 1/10 of the electron mobility and the ionization ratio of acceptors in p-type SiC is also smaller compared to that of donors in n-type SiC. As a result, achieving a sufficiently high current for accurate measurements requires applying a higher voltage applied between terminals 5 and 6, which could exceed the maximum voltage limits of the equipment, especially at low temperatures. In addition, the resistance between the electrodes 1–4 and the bar region also becomes higher, which may cause inaccuracies in measurements. To mitigate this issue, certain structural adjustments should be made so that the resistance is low enough. Then, the structure parameters were selected as illustrated in Fig. 4.1(a): $L_1 = 200 \mu\text{m}$, $L_2 = 260 \mu\text{m}$, $L_3 = 40 \mu\text{m}$, and $W = 160 \mu\text{m}$, and as shown in Fig. 4.1(b), the connection regions with the terminals 1–4 to the bridge were designed to $200 \mu\text{m}$ -wide and heavily doped regions were formed by aluminum (Al) ion implantation to enhance measurement accuracy.

Figure 4.2 shows the schematics of fabricated Hall bar structures on SiC(11 $\bar{2}$ 0) p-type epitaxial layers grown on n-type substrates with intermediate n-type epitaxial layers, (a)

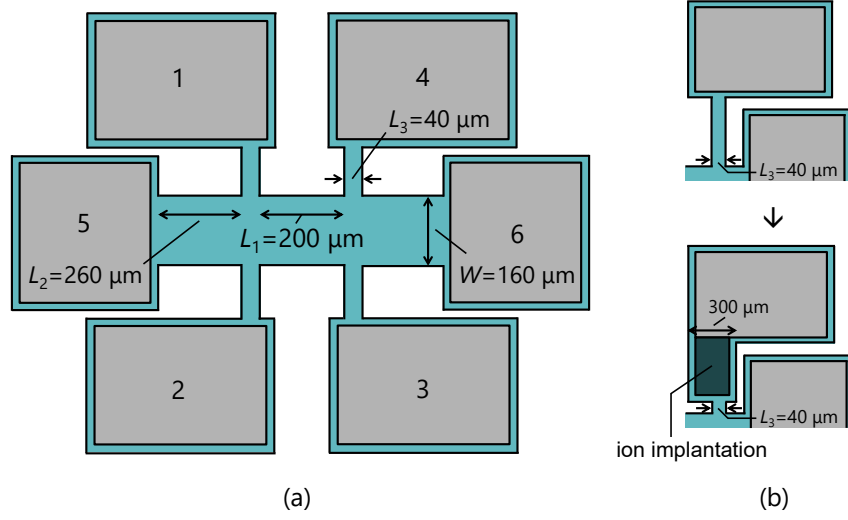


Figure 4.1: (a) Schematic illustration and main dimensions of the designed Hall bar structure for measuring hole mobilities, and (b) detailed structure of the connection part of electrodes 1–4 and bar region. The design of the connection part is modified compared with the structure for electron mobility because p-type layers exhibit higher resistivities than n-type layers for the same doping concentration.

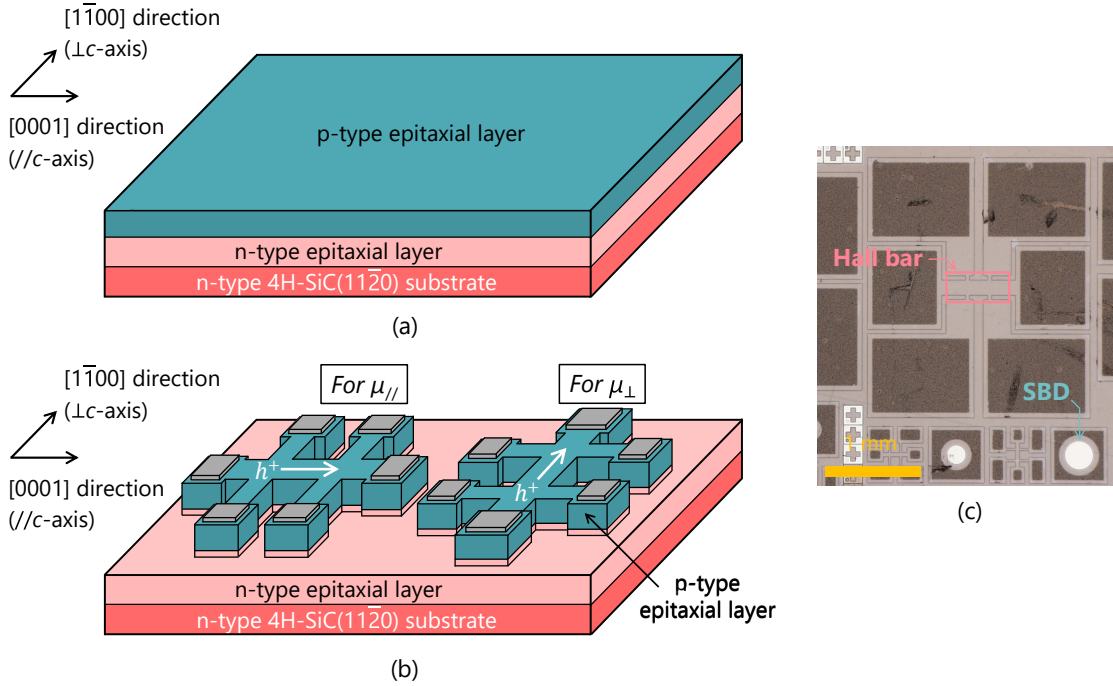


Figure 4.2: (a) p-type epitaxial layer grown on an n-type SiC(11 $\bar{2}$ 0) substrate with an intermediate n-type epitaxial layer. (b) Hall bar structures along the [0001] and [1100] directions for measuring the Hall hole mobility along the c -axis ($\mu_{H,||}$) and that perpendicular to the c -axis ($\mu_{H,\perp}$) fabricated on the sample shown in Figure (a). (Reproduced from R. Ishikawa *et al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.) (c) Optical microscope image of fabricated structures including a Hall bar structure for measuring hole mobility and lateral Schottky barrier diodes (top view).

before and (b) after the fabrication process. The p-type and n-type epitaxial layers were prepared by introducing Al and nitrogen (N) atoms during the chemical vapor deposition (CVD) process. Hall bar structures with different orientations were arranged side by side on the same sample, which were aligned along the $[0001]$ and $[1\bar{1}00]$ directions to determine the Hall hole mobility parallel and perpendicular to the c -axis ($\mu_{H,||}$ and $\mu_{H,\perp}$), respectively. The acceptor concentrations of the p-type epilayers were varied to have seven kinds of value in a wide range from $8 \times 10^{15} \text{ cm}^{-3}$ to $7 \times 10^{18} \text{ cm}^{-3}$. Lateral Schottky barrier diodes were also fabricated on the same samples to measure the net acceptor concentration. The detailed fabrication process is explained using Fig. 4.3 and Fig. 4.4 as follows:

1. Epitaxial Growth

- (a) Continuous growth of p-/n-type layers on SiC(11 $\bar{2}$ 0) substrate by the CVD process.

2. Ion Implantation

- (a) Deposition of SiO₂ ($\sim 2.1 \mu\text{m}$) by plasma-enhanced chemical vapor deposition (PECVD) with TEOS/O₂ flow.
- (b) Formation of a resist pattern by photolithography.
- (c) Dry etching of SiO₂ using a resist mask by capacitive-coupled plasma reactive ion etching (CCP-RIE) with CF₄/H₂ flow, and resist removal using a piranha solution.
- (d) Formation of the p⁺ region by Al ion implantation (concentration: $1 \times 10^{20} \text{ cm}^{-3}$, thickness: 200 nm), followed by the removal of residual SiO₂ with a HF solution.
- (e) Activation annealing with a carbon cap (1750°C, 20 min, under Ar flow) [8].

3. Mesa Isolation

- (a) Deposition of SiO₂ ($\sim 3.0 \mu\text{m}$) by PECVD with TEOS/O₂ flow.
- (b) Formation of a resist pattern by photolithography.
- (c) Dry etching of SiO₂ using a resist mask by CCP-RIE, followed by resist removal using a piranha solution.
- (d) Dry etching of SiC with SiO₂ as a mask by inductively-coupled plasma reactive ion etching (ICP-RIE) with SF₆/O₂/Ar flow under the following condition: [SF₆/O₂/Ar: 10/20/100 sccm, ICP/Bias power: 500/100 W, pressure: 2 Pa, etching rate: $0.7 \mu\text{m}$], and the removal of remaining SiO₂ with HF solution.
- (e) Thermal oxidation (1150°C, 30 min) and removal of generated SiO₂ film ($\sim 50 \text{ nm}$) with a HF solution to eliminate etching damage, followed by another thermal oxidation (1150°C, 10 min) to form a SiO₂ passivation film ($\sim 20 \text{ nm}$).

4. Ohmic Metal Formation

- (a) Formation of a resist pattern by photolithography, followed by localized removal of the SiO₂ passivation film using buffered HF (BHF) with a resist mask.
- (b) Al/Ti electrode deposition (150 nm/40 nm) and lift-off process.

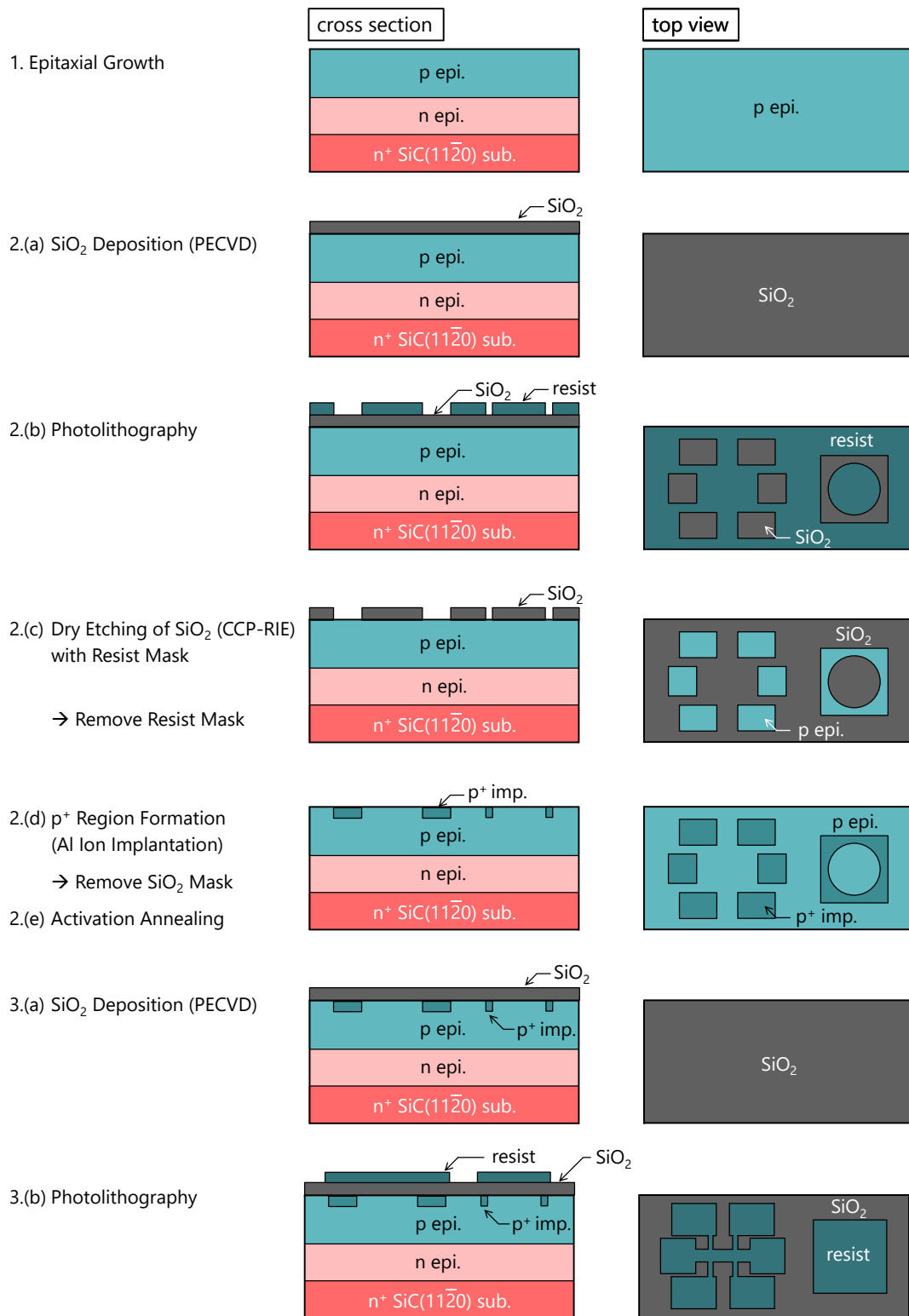


Figure 4.3: Fabrication process flow of Hall bar structure for measuring hole mobility and lateral Schottky barrier diode for C - V measurement (1/2).

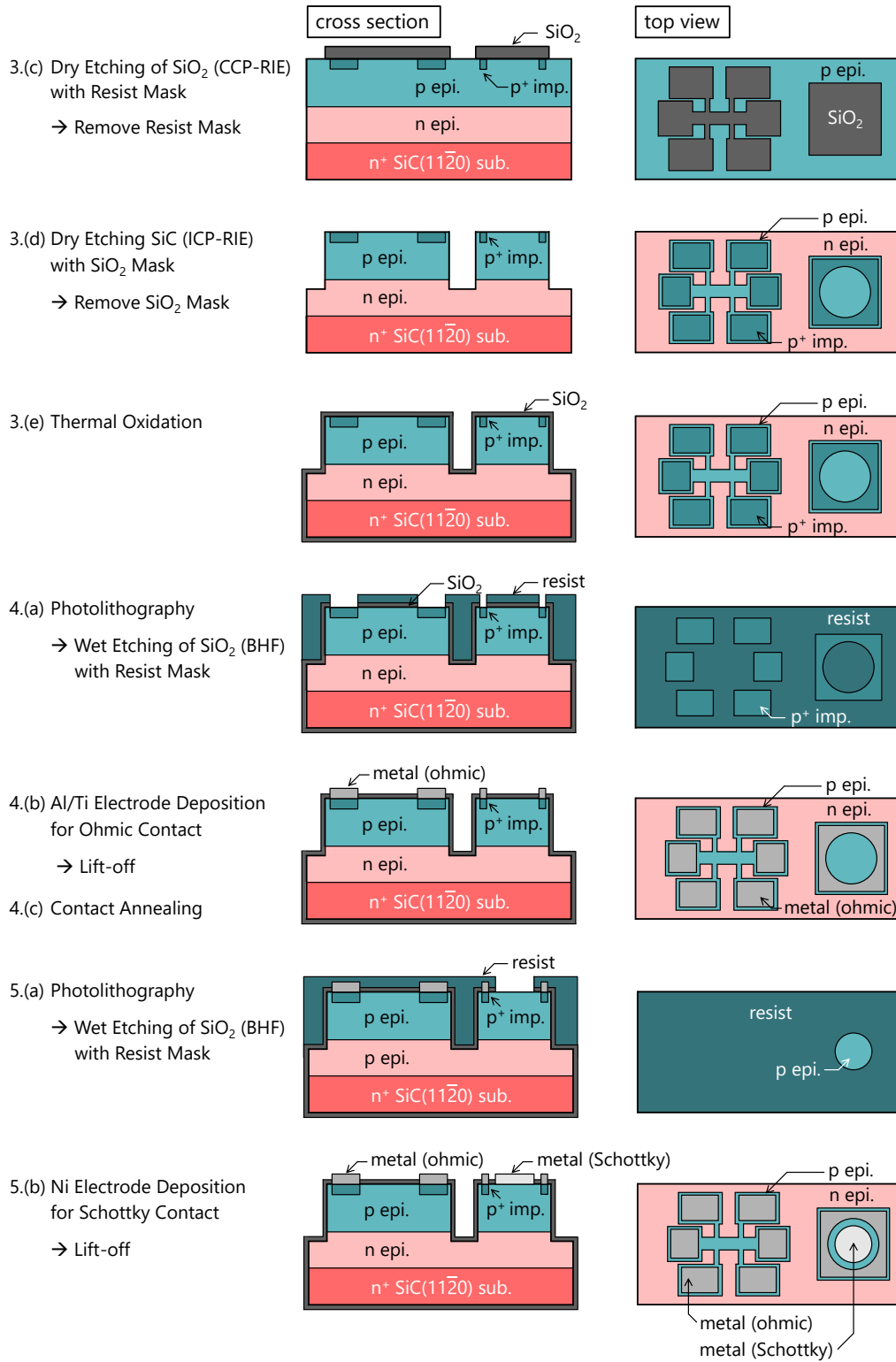


Figure 4.4: Fabrication process flow of Hall bar structure for measuring hole mobility and lateral Schottky barrier diode for C - V measurement (2/2).

- (c) Contact annealing (1000°C, 2 min, vacuum).

5. Schottky Metal Formation

- (a) Formation of a resist pattern by photolithography, followed by localized removal of the SiO₂ passivation film using BHF with a resist mask.
- (b) Ni electrode deposition (~ 150 nm) and lift-off process.

Figure 4.2(c) shows an optical microscope image of a Hall bar structure and a lateral SBD.

The Hall hole concentration, resistivity, and Hall hole mobility were determined for both directions via Hall effect measurements on these fabricated structures with a magnetic field strength of 0.5 T in the temperature range from 140 K to 600 K. So that the measurement voltages are not affected by noise of measurement system and self-heating, the current values for the measurements were selected properly for each acceptor concentration and temperature, where typical values are 10 μ A for $N_A = 8 \times 10^{15} \text{ cm}^{-3}$ and 1 mA for $N_A = 7 \times 10^{18} \text{ cm}^{-3}$ at room temperature. capacitance–voltage (C – V) measurements of the lateral SBDs were also performed to obtain the net acceptor concentrations of the p-layers.

4.2.2 Hole Mobility versus Acceptor Concentration and Temperature

4.2.2.1 Acceptor Concentration Dependence of Hole Mobility

The acceptor concentration dependences of Hall hole mobilities parallel and perpendicular to the c -axis ($\mu_{H, //}$ and $\mu_{H, \perp}$) obtained at room temperature are shown in Figure 4.5(a). The present study determined $\mu_{H, //}$ over a wide acceptor concentration range, from $8 \times 10^{15} \text{ cm}^{-3}$ to $7 \times 10^{18} \text{ cm}^{-3}$, while there have been no reports on the absolute value of $\mu_{H, //}$. $\mu_{H, //}$ was found to be approximately 9–13% lower than $\mu_{H, \perp}$ ($\mu_{H, //} < \mu_{H, \perp}$) at room temperature, which contrasts with the behavior of electrons (the Hall electron mobility parallel to the c -axis is higher than that perpendicular to the c -axis as mentioned in Section 2.3). Note that $\mu_{H, \perp}$ obtained by using SiC(11 $\bar{2}$ 0) samples shows a slightly different trend – lower for $N_A \leq 4 \times 10^{17} \text{ cm}^{-3}$ and higher for $N_A \geq 4 \times 10^{17} \text{ cm}^{-3}$ – compared with $\mu_{H, \perp}$ obtained with SiC(0001) previously [3], and this discrepancy may be attributed to differences in the Hall scattering factor due to the different directions of the magnetic field. The tendencies where $\mu_{H, //}$ and $\mu_{H, \perp}$ decrease with increasing N_A can be the underlying carrier scattering mechanism in the same manner as the case of electron mobility; impurity scattering becomes more pronounced while the effect of phonon scattering remains constant.

The acceptor concentrations of p-layers were determined by C – V measurements on lateral SBDs and secondary ion mass spectrometry (SIMS) analyses. Figure 4.6(a) and (b) show the net acceptor concentration obtained from C – V measurements and the acceptor- and donor-type impurities (Al and N) concentrations obtained from SIMS analyses, respectively. As summarized in Table 4.1, the net acceptor concentration shows good agreement with the Al atom concentration, and N concentration was confirmed to be on the order

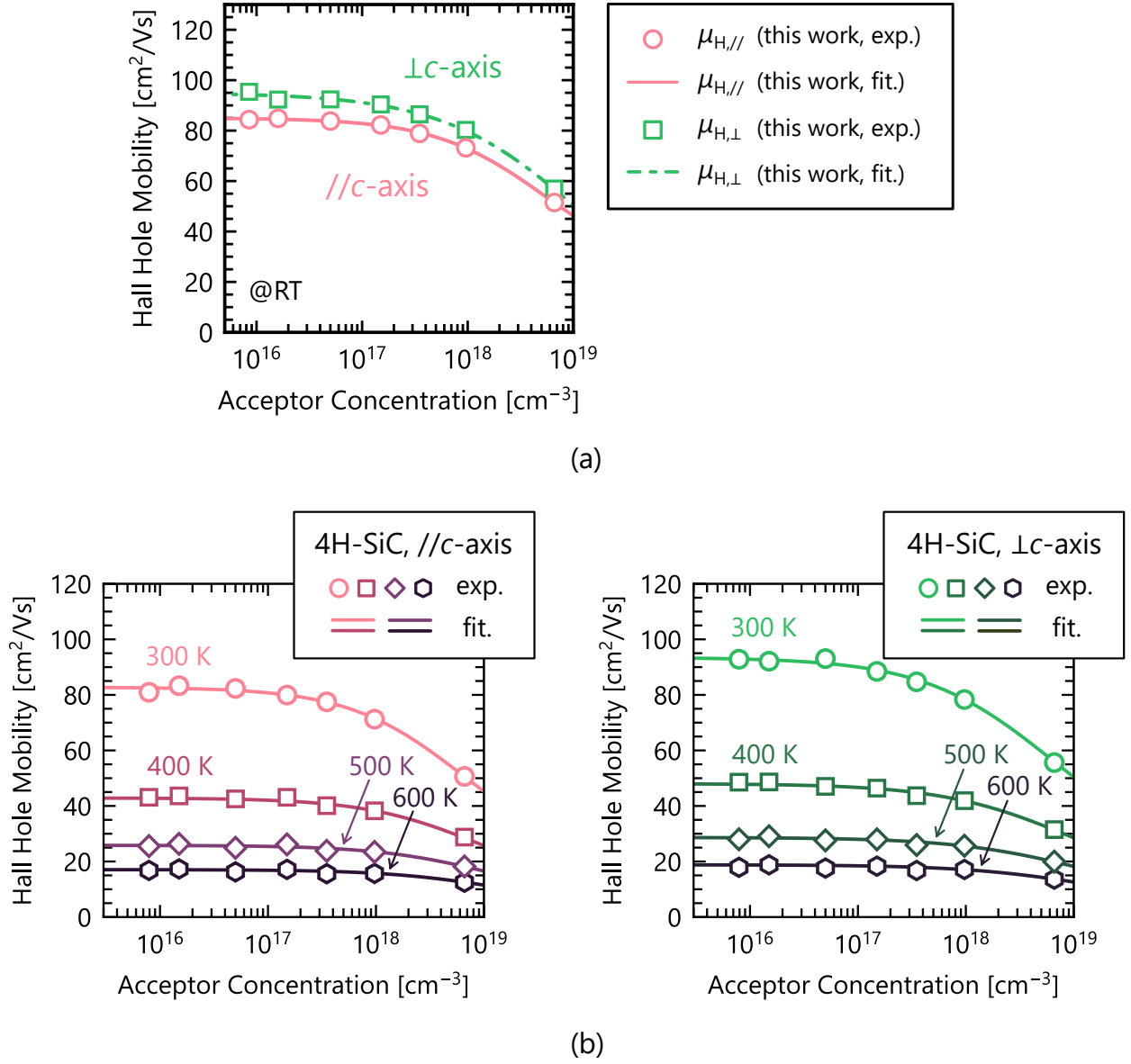


Figure 4.5: Acceptor concentration dependences of the Hall hole mobilities parallel and perpendicular to the c -axis ($\mu_{H,\perp}$ and $\mu_{H,\parallel}$) at (a) room temperature and (b) several temperatures from 300 K to 600 K. The red and green lines depict the fitting results expressed by Eqs. (4.6) and (4.7). (Reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

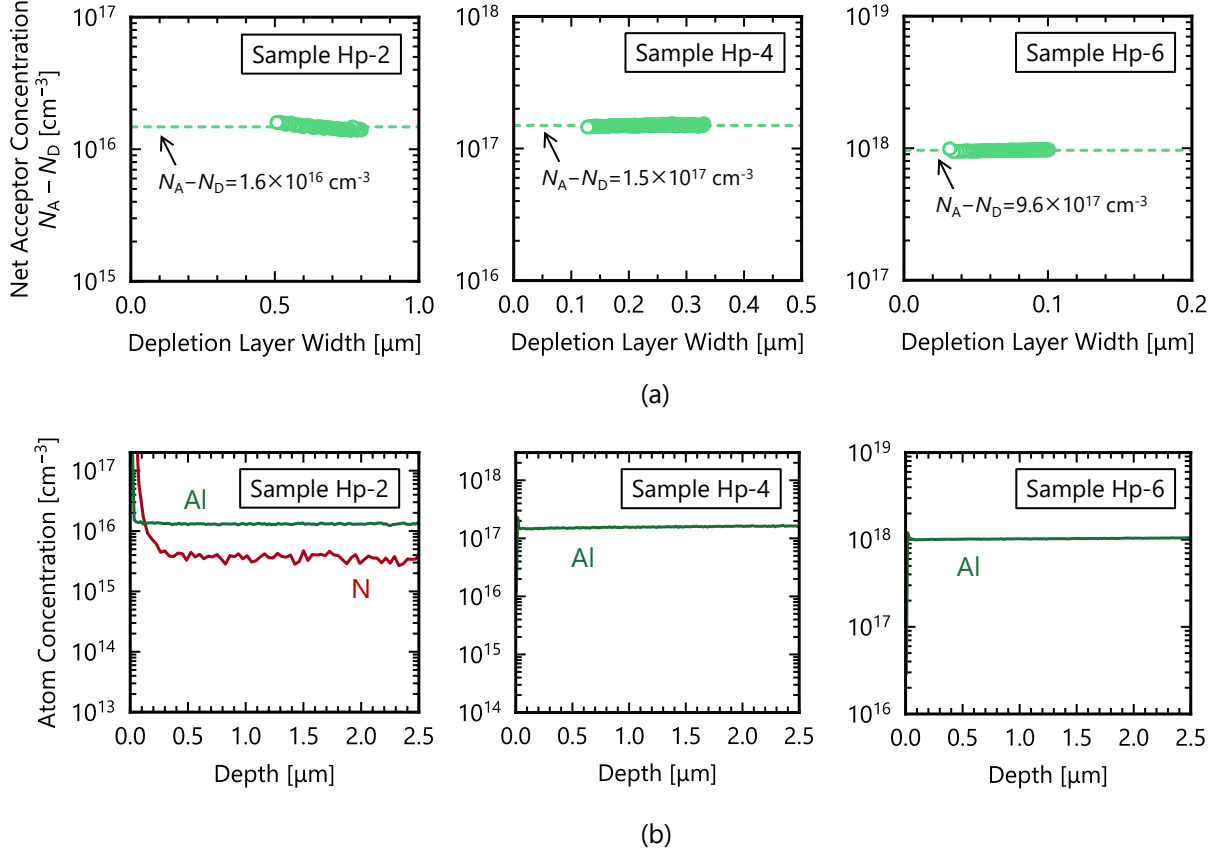


Figure 4.6: Depth profiles of (a) the net acceptor concentrations determined by C - V measurements of lateral Schottky barrier diodes and (b) the Al and N atom concentrations obtained by SIMS analyses. The averaged values of them are summarized in Table 4.1.

Table 4.1: Summary of the net acceptor concentrations ($N_A - N_D$) obtained from C - V measurements, and the acceptor- and donor-type impurity concentrations ($[\text{Al}]$ and $[\text{N}]$) determined by SIMS analyses.

Sample No.	Designed N_A	$N_A - N_D$ (C - V)	$[\text{Al}]$ (SIMS)	$[\text{N}]$ (SIMS)
Hp-1	$5 \times 10^{15} \text{ cm}^{-3}$	$8.5 \times 10^{15} \text{ cm}^{-3}$	$7.9 \times 10^{15} \text{ cm}^{-3}$	$\sim 1 \times 10^{15} \text{ cm}^{-3}$
Hp-2	$1 \times 10^{16} \text{ cm}^{-3}$	$1.6 \times 10^{16} \text{ cm}^{-3}$	$1.3 \times 10^{16} \text{ cm}^{-3}$	$< 1 \times 10^{15} \text{ cm}^{-3}$
Hp-3	$3 \times 10^{16} \text{ cm}^{-3}$	$5.0 \times 10^{16} \text{ cm}^{-3}$	$4.8 \times 10^{16} \text{ cm}^{-3}$	—
Hp-4	$1 \times 10^{17} \text{ cm}^{-3}$	$1.5 \times 10^{17} \text{ cm}^{-3}$	$1.6 \times 10^{17} \text{ cm}^{-3}$	—
Hp-5	$3 \times 10^{17} \text{ cm}^{-3}$	$3.5 \times 10^{17} \text{ cm}^{-3}$	$3.9 \times 10^{17} \text{ cm}^{-3}$	—
Hp-6	$1 \times 10^{18} \text{ cm}^{-3}$	$9.6 \times 10^{17} \text{ cm}^{-3}$	$1.0 \times 10^{18} \text{ cm}^{-3}$	—
Hp-7	$5 \times 10^{18} \text{ cm}^{-3}$	$6.6 \times 10^{18} \text{ cm}^{-3}$	$6.8 \times 10^{18} \text{ cm}^{-3}$	—

of 10^{15} cm^{-3} . The donor-type impurities concentrations were assumed to be $1 \times 10^{15} \text{ cm}^{-3}$ for the samples Hp-1 and $5 \times 10^{14} \text{ cm}^{-3}$ for the others, and the acceptor concentration was calculated by adding the donor-type impurities concentrations ($[N]$) to the net acceptor concentration, i.e., $N_A \simeq (N_A - N_D) + [N]$.

Figure 4.5(b) and (c) show the acceptor concentration dependences of $\mu_{H,||}$ and $\mu_{H,\perp}$ at several temperatures ranging from 300 K to 600 K. The solid lines represent the fitted curves using the following Cauchy-Thomas-based empirical equation [9], expressing both acceptor concentration and temperature dependences:

$$\mu = \frac{(\mu_{\max} - \mu_{\min}) \cdot (T/300 \text{ K})^{\delta_1}}{1 + (N_A/N_{\text{ref}})^{\alpha} \cdot (T/300 \text{ K})^{\delta_2}} + \mu_{\min} \cdot (T/300 \text{ K})^{\delta_3}, \quad (4.5)$$

which contains six fitting parameters; $\mu_{\max}$, $\mu_{\min}$, N_{ref} , α , δ_1 , δ_2 , and δ_3 . The fitting procedure is carried out in two stages; first, $\mu_{\max}$, $\mu_{\min}$, N_{ref} , and α were determined from the acceptor concentration dependence of the hole mobilities at 300 K; then δ_1 , δ_2 , and δ_3 were adjusted to reproduce the temperature dependences of them. From systematic experimental data over the temperature range from 300 K to 600 K, the fitting equations for $\mu_{H,||}$ and $\mu_{H,\perp}$ were derived as follows:

$$\mu_{H,||} = \frac{(83 - 20) \cdot (T/300 \text{ K})^{-2.3}}{1 + (N_A/6.4 \times 10^{18} \text{ cm}^{-3})^{0.83} \cdot (T/300 \text{ K})^{-0.9}} + 20 \cdot (T/300 \text{ K})^{-2.2} \text{ cm}^2/\text{Vs}, \quad (4.6)$$

$$\mu_{H,\perp} = \frac{(94 - 40) \cdot (T/300 \text{ K})^{-2.3}}{1 + (N_A/6.2 \times 10^{18} \text{ cm}^{-3})^{0.72} \cdot (T/300 \text{ K})^{-0.9}} + 40 \cdot (T/300 \text{ K})^{-2.2} \text{ cm}^2/\text{Vs}. \quad (4.7)$$

The fitting results closely match the experimental data as illustrated by solid lines in Fig. 4.5, and these equations covering wide ranges of acceptor and temperature are valuable for accurate simulations and optimum designing of any SiC devices.

4.2.2.2 Temperature Dependence of Hole Mobility

Figure 4.7 depicts the Hall hole mobilities along the directions parallel and perpendicular to the c -axis as a function of temperature for various N_A values, which indicates that the Hall mobilities and temperature exhibit an almost linear relationship in the log-log plots from 300 K to 600 K. Then, in a similar manner to the case of electrons, β defined by $\mu \propto T^{-\beta}$ were determined via linear extrapolation for the discussion on the scattering mechanism of holes, and the results are shown in Fig. 4.7, which indicates almost independent β of N_A dissimilarly to the β for electrons. This difference is attributed to the differing effects of ionized impurity scattering. The change in β values with increasing doping concentration is attributed to the change in the dominant scattering mechanism; from phonon scattering to ionized impurity scattering, which have negative and positive correlations with the temperature, respectively, as discussed in Section 2.3 with Fig. 2.18(a). Therefore, while β is greater than 2 for both electron and hole mobilities in SiC [2, 3, 10, 11] in lightly-doped samples, it becomes smaller for higher doping concentrations. Here, the mobility determined

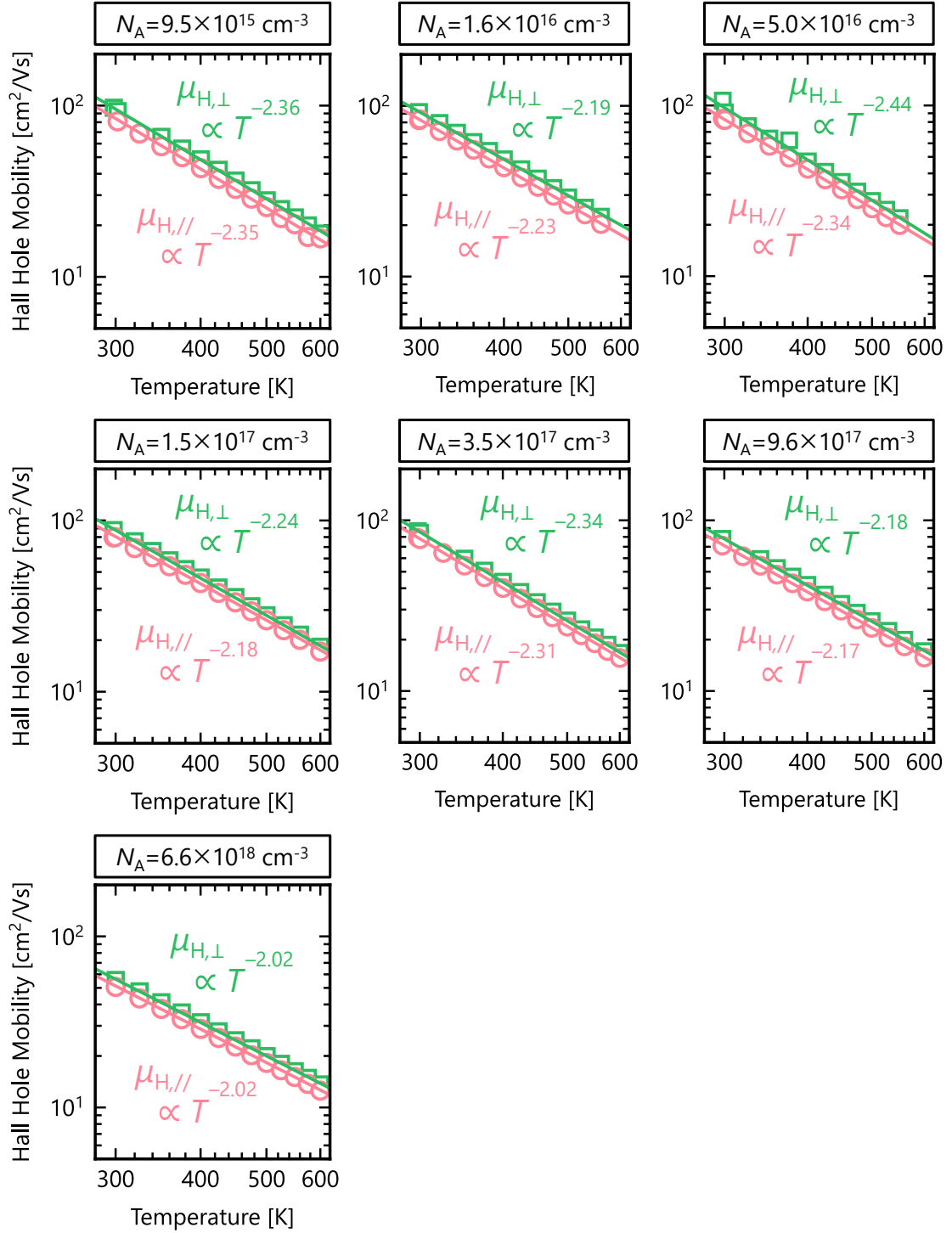


Figure 4.7: Temperature dependence of the Hall hole mobilities for different acceptor concentrations (N_A). β determined by $\mu \propto T^{-\beta}$ slightly decreases with increasing N_A . (Partially reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

by the ionized impurity scattering (μ_{ii}) is inversely proportional to the ionized impurity concentration, which is strongly dependent on the concentration of dopant (i.e., acceptor in p-type and donor in n-type SiC epilayer) and their ionization energy. The ionization energy of Al acceptors (~ 200 meV) in p-type SiC is known to be larger than that of N donors (~ 61 meV for cubic site and ~ 126 meV for hexagonal site) in n-type SiC [12]. The larger ionization energy leads to the lower ionized impurity concentration as shown in Fig. 4.8(a), which depicts the calculated ionized impurity concentration for n-type and p-type SiC with various doping concentration by solving the charge neutrality equation. Therefore, the almost independent β of the acceptor concentration for holes, as summarized in Fig. 4.8(b), can be explained by the larger ionization energy of Al acceptors in p-type SiC which weakens the effect of ionized impurity scattering. The calculated β by taking into account the ionization ratio shown in Fig. 4.8(a) and relaxation time of scattering reported for the direction perpendicular to the c -axis [2] is also depicted in Fig. 4.8(b), which actually reproduced the observed β well.

4.2.2.3 Discussion

In this section, the effects of anisotropic hole mobility on the device performance will be discussed. SiC unipolar devices are typically fabricated with n-type drift layers, which allow for lower on-resistances compared to p-type drift layers as the mobility of electrons in SiC is approximately 10 times higher than that of holes, and the ionization ratio of dopants in n-type layers is also higher than that of p-type layers. Consequently, the electron mobility is more essential for the basic characteristics of SiC unipolar devices. However, p-type regions do exist in unipolar power devices, making the hole mobility significant for overall device performance. During switching transients of SiC power MOSFETs, holes drift along the horizontal direction within the p-type body region, as shown in Fig. 4.9(a), according to the changes between the accumulation and depletion states of the channel. If the resistivity along this direction is high, the voltage distribution induced by this transient current can activate the parasitic bipolar transistor formed by the source, body, and drift region, resulting in unintended leakage current from the drain to the source through the p-body. The observed anisotropy of hole mobility ($\mu_{H,\perp} > \mu_{H,\parallel}$) indicates the resistivity along the horizontal direction (perpendicular to the c -axis) is smaller, which helps suppress this leakage current. Therefore, it can be concluded that the observed anisotropy positively impacts the performance of SiC unipolar devices.

For the application of SiC bipolar devices, the hole mobility along the c -axis becomes as crucial as the electron mobility along the same axis. In SiC pin diodes, as depicted in Fig. 4.9(b), the hole mobility along the c -axis directly affects the device performance such as on-resistance and switching speed since holes are transported in blocking layers along this direction. Although the measurement results presented in this study, the anisotropic hole mobilities in p-type SiC, can provide valuable insight into the optimization and simulation of SiC bipolar devices, the hole mobility in n-type layer i.e., minority carrier mobility of

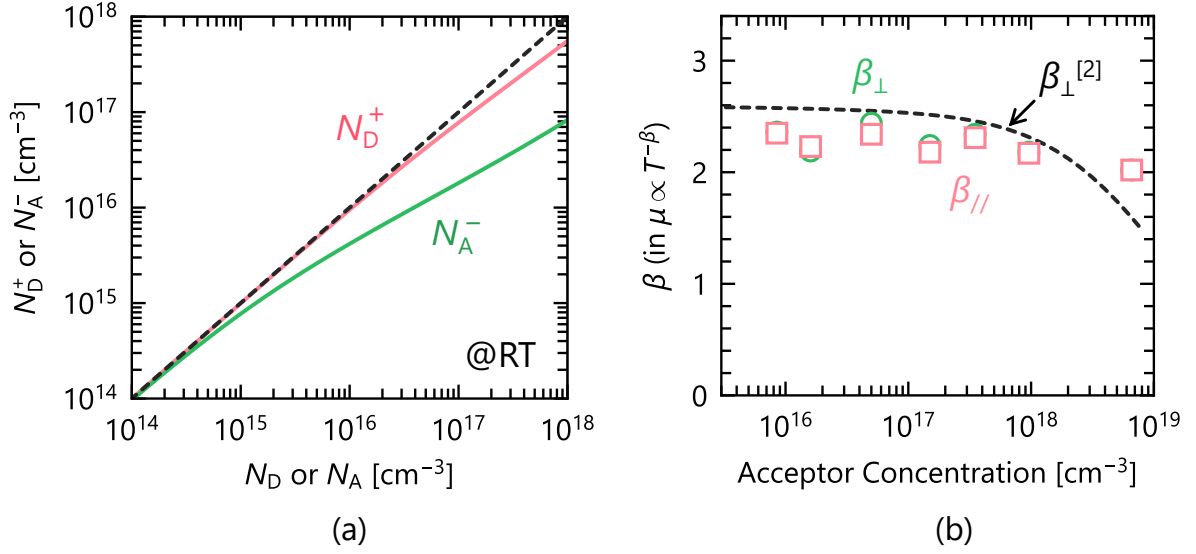


Figure 4.8: (a) Ionized acceptor concentration (N_A^-) in p-type and ionized donor concentration (N_D^+) in n-type SiC versus doping concentration. Lower N_A^- than N_D^+ results in a smaller dependence of β on doping concentration for holes. (b) Acceptor concentration (N_A) dependence of β for $\mu_{H,\parallel}$ and $\mu_{H,\perp}$ ($\beta_{\parallel}$ and $\beta_{\perp}$). $\beta_{\perp}$ calculated based on the scattering mechanism in SiC reported by a previous study [2] is also depicted by a dashed line. (Reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

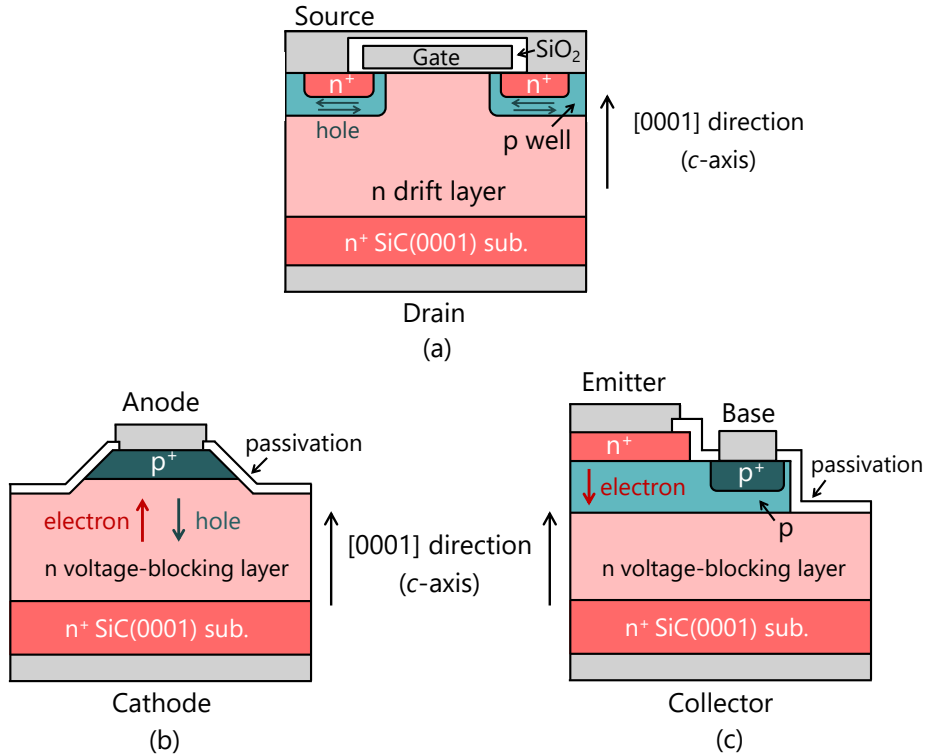


Figure 4.9: Sectional schematic illustrations of SiC MOSFET, pin diode, and BJT.

holes, is of greater relevance. This is because holes are transported in the lightly-doped n-type region, where the transport mechanism may differ from those of majority carriers due to distinct scattering processes [7]. Similarly, in bipolar junction transistors (BJTs) illustrated in Fig. 4.9(c), the minority carrier mobility of electrons injected into the p-base region becomes significant, which may similarly differ from the majority carrier mobility of electrons. Since standard Hall effect measurements are inherently limited to determining majority carrier mobilities, alternative techniques such as the time-of-flight method [13, 14] or carrier-resolved photo Hall effect measurement [15] are necessary to accurately determine the minority carrier mobilities.

4.2.3 Hall Scattering Factor

The Hall scattering factor γ_H was attempted to estimate as functions of temperature and acceptor concentration in a similar manner to Section 2.3.4. Since both the Hall hole concentration p_H and the hole concentration p are necessary for the determination of γ_H as seen in Eq. (4.4), they were carefully determined carefully by experiments and calculation, respectively.

Hall hole concentration can be derived through Eq. (4.1), where the thickness t is a critical parameter for precise p_H determination. Then, the author performed the scanning electron microscope (SEM) observation for the determination of t . The obtained results are shown in Fig. 4.10, where a visual contrast between layers with different conduction types enables identifying the boundary between the p-type and n-type layers, and the measured thicknesses of the top p-type epilayers are summarized in Table 4.2. In addition, since there exist no holes in the depletion layer of the pn junction, the actual t was determined by subtracting a calculated depletion layer thickness from the p-type epitaxial layer thickness measured by SEM. For the calculation, the donor concentration of the n-type epilayer was assumed to be $3 \times 10^{16} \text{ cm}^{-3}$ (designed value), and the depletion layer widths were estimated to be about $0.4 \text{ } \mu\text{m}$ for $N_A = 1 \times 10^{16} \text{ cm}^{-3}$ and 10 nm for $N_A = 1 \times 10^{18} \text{ cm}^{-3}$. Arrhenius plots of the obtained Hall hole concentrations determined using t calculated by the above procedure are shown by symbols in Fig. 4.11(a). The Hall hole concentration increases with increasing temperature and approaches a constant value, indicating the saturation temperature range of acceptors.

The hole concentration p was calculated using the following charge neutrality equation taking into account the excited state i of acceptors [3];

$$p + N_D = \frac{N_A}{1 + \sum_i^{E_{Ai} > \Delta E} g_i \exp\left(\frac{E_{A,i} - \Delta E - E_V}{k_B T}\right)},$$

$$E_{A1} = 0.22 \text{ eV}, \quad E_{Ai} = 13.6 \text{ eV} \times \frac{1}{\varepsilon_s^2 i^2} \quad (i = 2, 3, 4, \dots), \quad g_i = 4i^2, \quad (4.8)$$

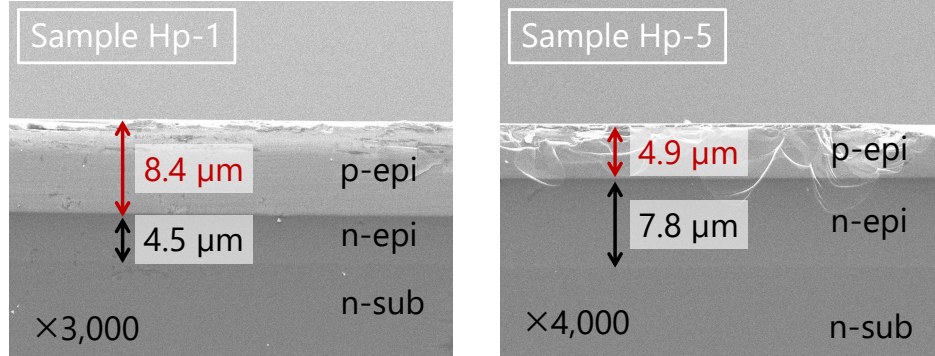


Figure 4.10: SEM images of the samples (cross-section) before the fabrication of Hall bar structures. The thicknesses of p-type epilayers were determined from the contrast in the image.

Table 4.2: Summary of the thicknesses of top p-type epilayers determined by SEM observation.

Sample No.	N_A	Designed Thickness	Actual Thickness (SEM)
Hp-1	$5 \times 10^{15} \text{ cm}^{-3}$	$10 \text{ } \mu\text{m}$	$8.4 \text{ } \mu\text{m}$
Hp-2	$1 \times 10^{16} \text{ cm}^{-3}$	$8 \text{ } \mu\text{m}$	$7.6 \text{ } \mu\text{m}$
Hp-3	$3 \times 10^{16} \text{ cm}^{-3}$	$8 \text{ } \mu\text{m}$	$7.6 \text{ } \mu\text{m}$
Hp-4	$1 \times 10^{17} \text{ cm}^{-3}$	$5 \text{ } \mu\text{m}$	$4.9 \text{ } \mu\text{m}$
Hp-5	$3 \times 10^{17} \text{ cm}^{-3}$	$5 \text{ } \mu\text{m}$	$4.9 \text{ } \mu\text{m}$
Hp-6	$1 \times 10^{18} \text{ cm}^{-3}$	$5 \text{ } \mu\text{m}$	$5.0 \text{ } \mu\text{m}$
Hp-7	$5 \times 10^{18} \text{ cm}^{-3}$	$5 \text{ } \mu\text{m}$	$4.9 \text{ } \mu\text{m}$

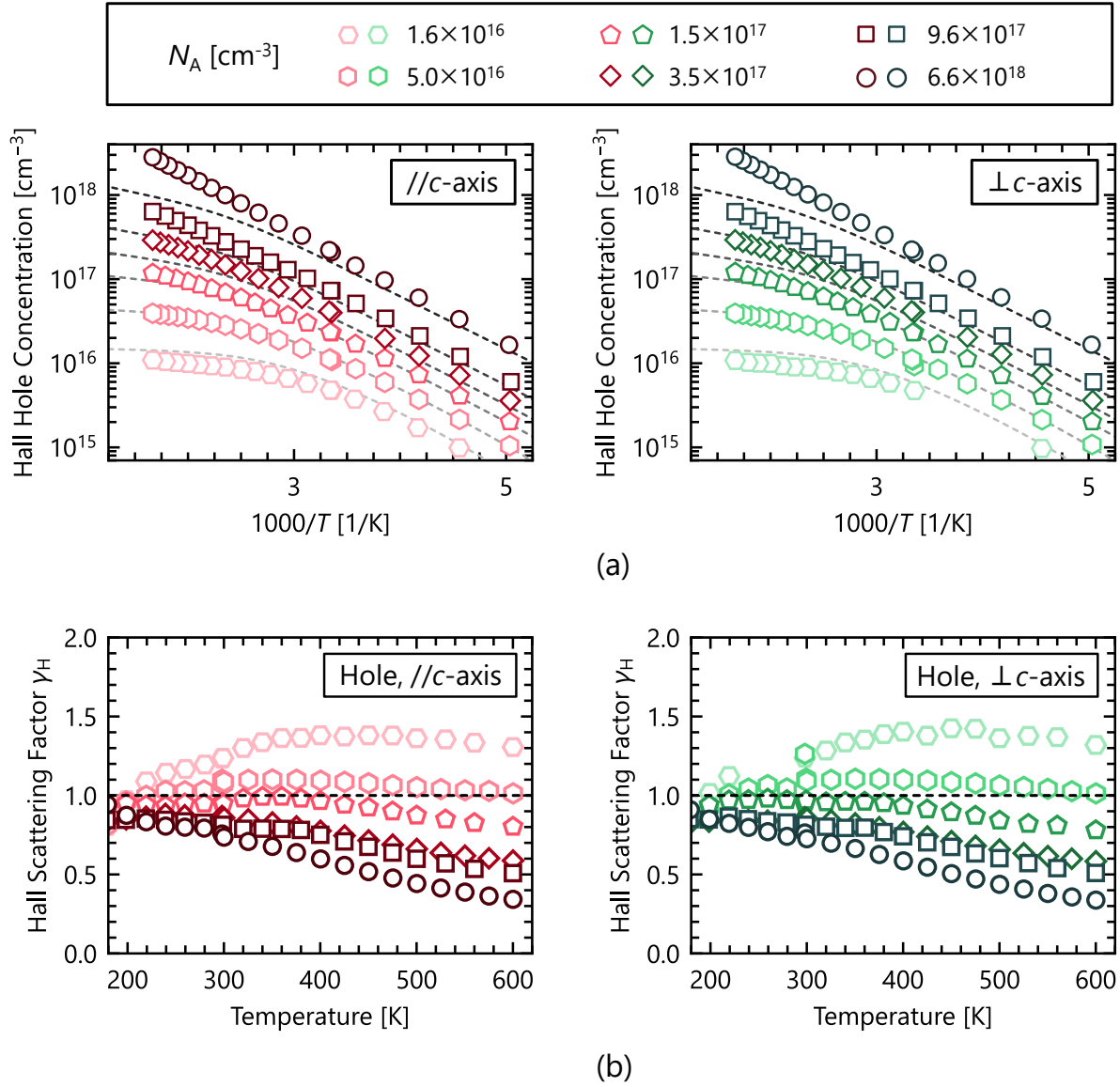


Figure 4.11: (a) Arrhenius plot of the Hall hole concentrations parallel and perpendicular to the c -axis for different acceptor concentrations. The dashed lines depict the calculated hole concentration from the charge neutrality equation. (b) Hall scattering factors for holes obtained from the present analyses as functions of temperature.

$$\Delta E = \frac{e^2}{\pi \varepsilon_s \varepsilon_0 L_A}, \quad \frac{4}{3} \pi (L_A/2)^3 = 1/N_A.$$

Here, $E_{Ai} - \Delta E$ corresponds to the ionization energy of acceptors, E_V is the valence band maximum, g_i is the degeneracy factor, k_B is the Boltzmann constant, ε_s is the relative dielectric constant of SiC (assumed to be 9.95), ε_0 is the dielectric constant of vacuum, and L_A is the average distance between two adjacent ionized impurities. The compensating donor concentrations were assumed to be $5 \times 10^{14} \text{ cm}^{-3}$ based on the SIMS analyses. The calculated results are depicted by dashed lines in Fig. 4.11(a), which show relatively good agreement with experimentally measured p_H .

Figure 4.11(b) presents the extracted Hall scattering factors of holes derived from the difference between p_H and p with various N_A and temperatures. The Hall scattering factors of holes were observed to decrease with increasing N_A and also slightly decline at elevating temperatures, eventually falling below unity. While these dependences are opposite to those observed for electrons discussed in Section 2.4.3, a similar tendency has been reported for the Hall scattering factor of holes along the in-plane direction of SiC(0001) [16]. The underlying mechanism for these phenomena has been discussed in another paper as below [3]. At higher temperatures, an increase in the number of high-energy holes enhances the anisotropy of the valence band structure, leading to the reduction in γ_H below unity. The dependence on N_A can be explained by the diminished difference in mobilities between light and heavy hole bands due to the stronger effect of impurity scattering, resulting in the gradual decrease of γ_H with increasing N_A . However, it is important to note that the magnetic field directions differ between the previous study (the $\langle 0001 \rangle$ direction) and the present one (the $\langle 1\bar{1}00 \rangle$ direction), which implies that the Hall scattering factors should also differ fundamentally. Therefore, a more complicated analysis of Hall scattering factors of holes considering the valence band structure of SiC is required for further discussion, which currently has not been performed.

4.3 Theoretical Analysis on Origin of Mobility Anisotropy

In this section, the hole mobility anisotropy is experimentally determined, and then the origin of mobility anisotropy is discussed based on the theoretical calculation of effective mass anisotropy.

4.3.1 Determination of Hole Mobility Anisotropy

The ratio of drift mobility ($\mu_{//}/\mu_{\perp}$) was determined from the ratio of resistivity ($\rho_{\perp}/\rho_{//}$) because the resistivity ratio is directly related to the drift mobility ratio while the Hall mobility ratio is not always identical to the drift mobility ratio due to the influence of

the Hall scattering factor, as discussed in Section 2.4. The drift mobility ratio of holes experimentally obtained for several acceptor concentrations and temperatures is shown in Fig. 4.12 by symbols, where the ratio remains nearly constant at around 0.9 across the observed range of acceptor concentration and temperature. Similar to the case of electron, the author focused on the anisotropy in the effective mass holes (m^*) to understand the origin of hole mobility anisotropy because the drift hole mobility (μ) is given by the following equation:

$$\mu = \frac{e\langle\tau\rangle}{m^*}, \quad (4.9)$$

where $\langle\tau\rangle$ is the averaged momentum relaxation time of holes. The hole effective masses at the valence band maximum (E_V) have been investigated experimentally by optically-detected cyclotron resonance (ODCR) for the both directions parallel and perpendicular to the c -axis ($m_{//}^*$ and $m_{\perp}^*$) [17]; $m_{//}^* = 1.75m_0$ and $m_{\perp}^* = 0.66m_0$, where m_0 is the electron rest mass. These reported values at E_V result in the effective mass ratio $m_{\perp}^*/m_{//}^* = 0.38$, which is much lower than the observed μ ratio (~ 0.9) in the present study as shown by the dashed line in Fig. 4.12. Since holes have an energy distribution and the valence band structure of SiC is non-parabolic, with holes present in not only the light hole and heavy hole bands but also the split-off band [3], it is suggested that the actual m^* anisotropy is also significantly influenced by holes with higher energies than E_V . This leads to a large deviation in the m^* ratio at E_V from the experimentally obtained μ ratio. Therefore, the determination of the m^* anisotropy considering the energy dependence of m^* is necessary for a more rigorous comparison with the anisotropy of μ .

4.3.2 Calculation Procedure of Anisotropy in Hole Effective Mass

For the consideration above, the energy dependence of hole effective mass was calculated based on the valence band structure of SiC by the procedure below. Since the determination of the effective mass both parallel and perpendicular to the c -axis requires m^* along three directions in the Brillouin zone (ΓA , ΓM , and ΓK) because $m_{//}^*$ and $m_{\perp}^*$ are given by the equations below;

$$m_{//}^* = m_{\Gamma A}^*, \quad (4.10)$$

$$\frac{2}{m_{\perp}^*} = \frac{1}{m_{\Gamma M}^*} + \frac{1}{m_{\Gamma K}^*}. \quad (4.11)$$

Here, $m_{\Gamma A}^*$, $m_{\Gamma M}^*$, and $m_{\Gamma K}^*$ are the effective masses along ΓA , ΓM , and ΓK directions, respectively. Each point in the Brillouin zone is illustrated in Fig. 4.13(a), and the calculated valence band structures along ΓA , ΓM , and ΓK directions are shown in Fig. 4.13(c). These E - k dispersions are obtained based on the dispersions in Ref. 3 computed by a first-principles calculation package ABINIT [18] applying density functional theory (DFT) with the effect of spin-orbit coupling. Local density approximation (LDA) [19] was employed including the

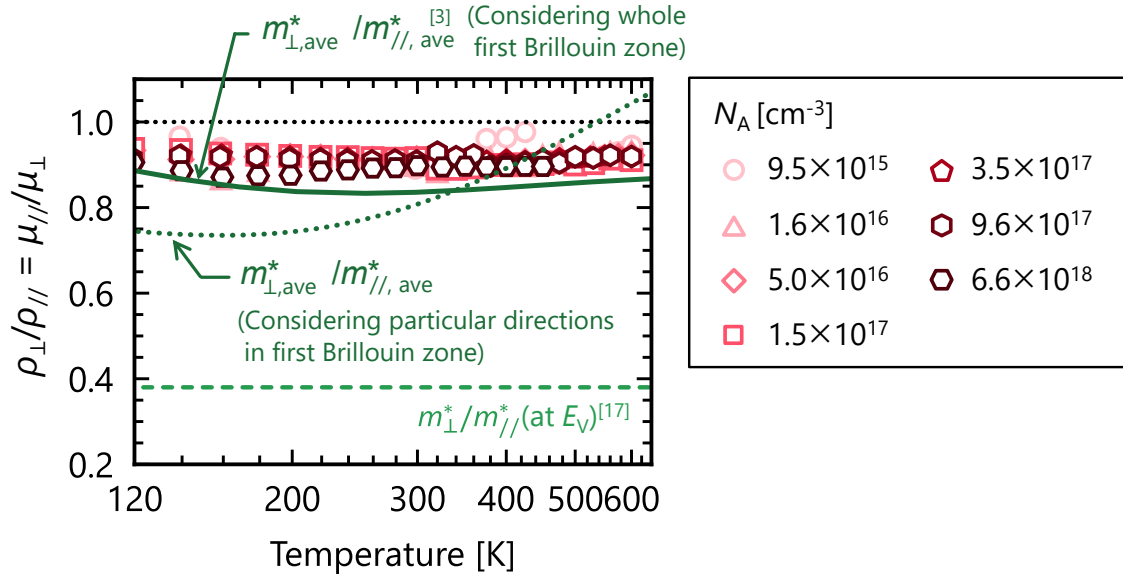


Figure 4.12: The hole mobility ratio obtained from the experimentally measured resistivity ratio ($\mu_{\parallel}/\mu_{\perp} = \rho_{\perp}/\rho_{\parallel}$) as a function of the temperature. The ratios are about 0.9 and almost independent of the acceptor concentration and temperature. A green dashed line depicts the hole effective mass ratio at the valence band maximum ($m_{\perp}^*/m_{\parallel}^* = 0.38$ at E_V) [17], which is almost twice lower than the mobility ratio. The temperature dependences of the calculated effective mass ratios ($m_{\text{ave}, \perp}^*/m_{\text{ave}, \parallel}^*$) taking into account the valence band structure along the particular directions using Eq. (4.13) and the full-band dispersion using Eq. (4.14) [3] are also depicted by dotted and solid lines, respectively. (Reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

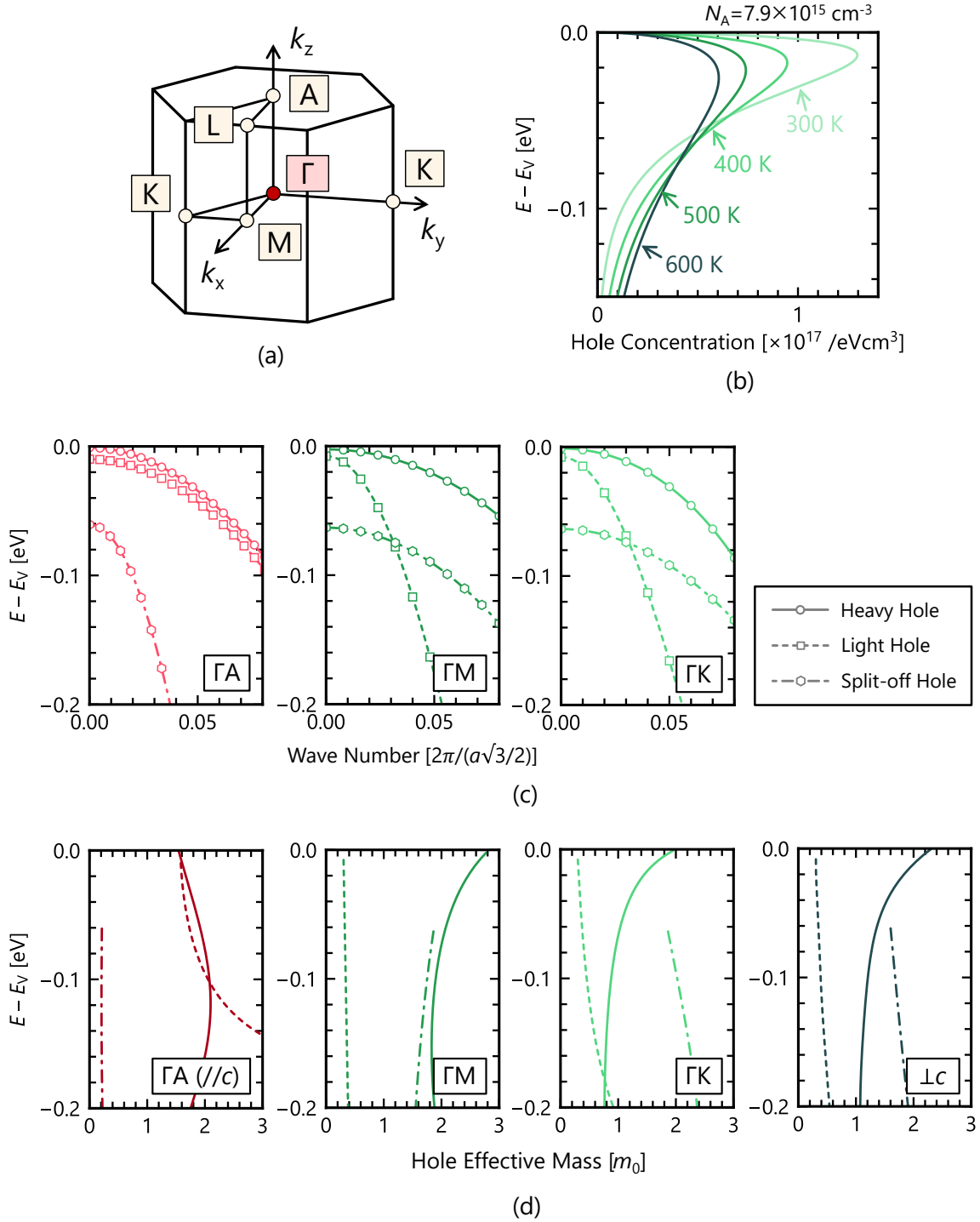


Figure 4.13: (a) Primitive cell and wavenumber axes of SiC, where the Γ point is the valence band maximum. (b) Energy distribution of holes in the heavy hole band with $N_A = 7.9 \times 10^{15}$ cm⁻³ at several temperatures. (c) Valence band structures of SiC ($E-k$ dispersion) and (d) energy dependences of the hole effective masses along the ΓA , ΓM , and ΓK directions in SiC. (Reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

effect of spin-orbit coupling with the HGH (Hartwigsen-Goedecker-Hutter) pseudopotentials. [20]. It should be noted that three kinds of bands (light hole, heavy hole, and split-off bands) were considered for the calculation, and Fig. 4.13(c) depicts one of the two almost spin degenerate lines for each band just to avoid complexity. In addition, although the light hole band and the split-off band are anticrossing actually [21, 22], they were regarded to be crossing for simplicity and switched at the intersections for the ΓM and ΓK directions, and fitted by polynomials so that the E - k dispersion becomes smoother. Based on the obtained valence band structure, the authors determined the hole effective mass at each wavenumber by

$$\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{\partial^2 E}{\partial k^2}, \quad (4.12)$$

where $\hbar$ and k are the Dirac constant and the wavenumber, respectively. $m^*(k)$ along each direction is depicted as a function of $E(k)$ in Fig. 4.13(d).

The authors calculated averaged effective masses (m_{ave}^*) based on the above-mentioned m^* - E relationship using an approximate equation,

$$\frac{1}{m_{\text{ave}}^*} = \frac{\sum_l \int (1/m^*(k)) \times f(E_l(k)) dk}{\sum_l \int f(E_l(k)) dk}. \quad (4.13)$$

Here, three bands (light hole, heavy hole, and split-off bands) were taken into account and l represents the l th band, and $f(E)$ is the energy distribution function of holes for each band, as illustrated in Fig. 4.13(b). One-dimensional integration, along the line from the Γ point to the A point in the Brillouin zone was performed to determine m_{ave}^* along the ΓA direction, and similarly, integrations along ΓM and ΓK lines were conducted for $m_{\Gamma M, \text{ave}}^*$ and $m_{\Gamma K, \text{ave}}^*$. The obtained m_{ave}^* are shown in Fig. 4.14(a) as a function of temperature, where $m_{\text{ave}, //}^*$ and $m_{\text{ave}, \perp}^*$ determined by Eqs. (4.10) and (4.11) are also depicted, and resulting averaged effective mass ratios are shown in Fig. 4.12 as the dotted line. The comparison reveals that the values of the μ ratio are closer to the m_{ave}^* ratio rather than the m^* ratio at E_V ($m_{\perp}^*/m_{//}^* = 0.38$). However, with increasing temperature, m_{ave}^* ratio increases more steeply compared to that of the experimentally obtained μ , and their temperature dependences still differ from each other. This discrepancy indicates that the temperature dependence of the hole mobility cannot be fully explained by the simplified averaging approach using Eq. (4.13). Therefore, a more refined calculation is necessary to discuss the contribution of effective mass anisotropy to the hole mobility anisotropy.

Equation (4.13) offers an approximated method for determining the averaged effective mass along a specific direction based on several assumptions on the band structure and carrier distribution. This approach reduces computational complexity by relying only on the E - k dispersion along a single direction originating from Γ point, which is relatively straightforward to extract using first-principles calculations. However, for more accurate calculation, it is essential to account for the entire band structure within the first Brillouin

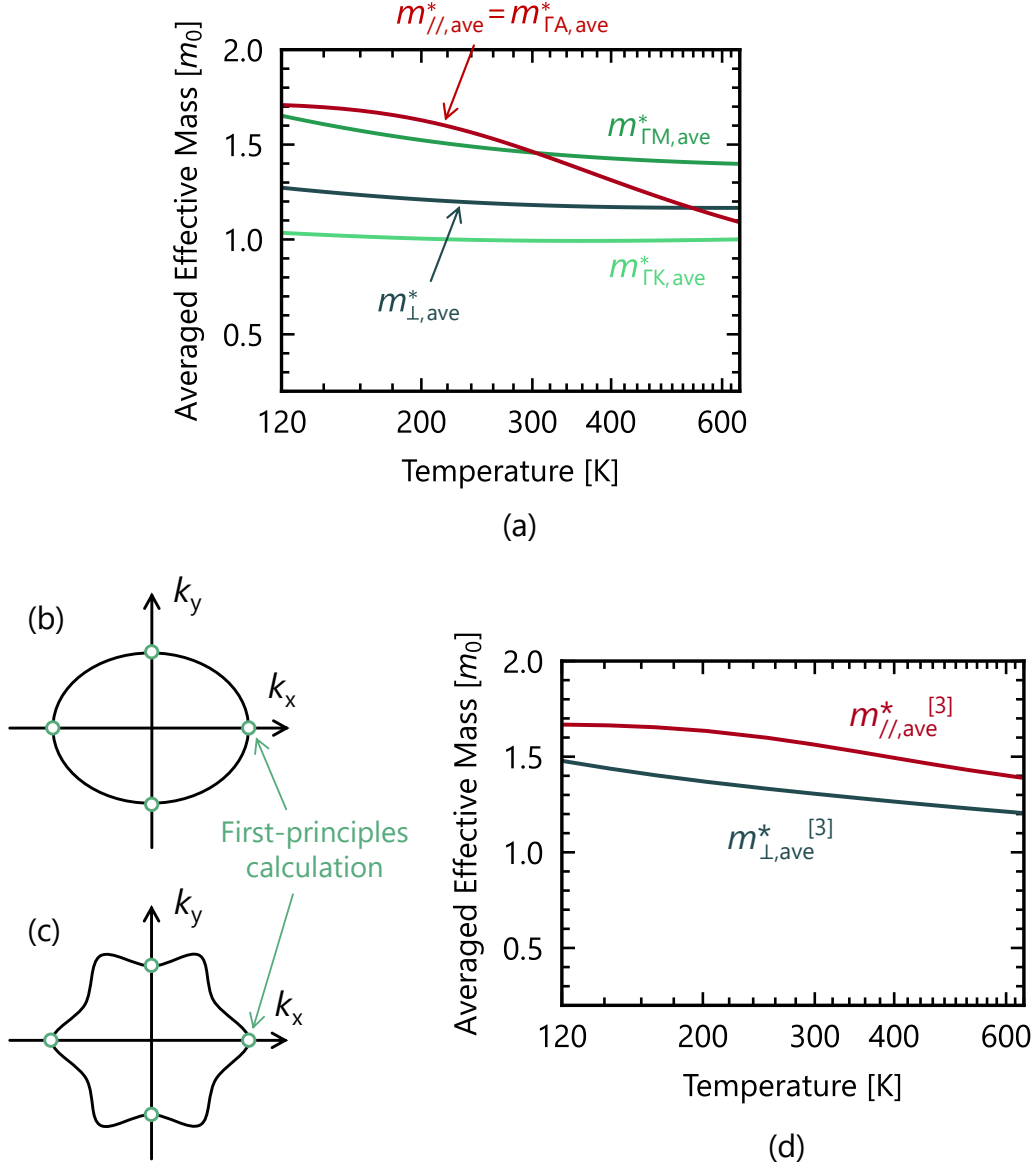


Figure 4.14: (a) Averaged hole effective mass along each direction ($m_{ave, //}^*$ and $m_{ave, \perp}^*$) calculated using Eq. (4.13) versus temperature, where the energy distribution of holes and the energy dependence of hole effective mass along the particular directions were taken into account. Schematic illustration of the equi-energy lines of (b) the assumed band structure by Eq. (4.15) and (c) the actual valence band structure of SiC. (d) Temperature dependence of the calculated hole effective mass considering the full-band dispersion using Eq. (4.14) [3]. (Reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

zone, which can be achieved through the following equation:

$$\frac{1}{m_{\text{ave}}^*} = \frac{\sum_l \iiint_{\text{BZ}} (1/m^*(k_x, k_y, k_z)) \times f(E_l(k_x, k_y, k_z)) dk_x dk_y dk_z}{\sum_l \iiint_{\text{BZ}} f(E_l(k_x, k_y, k_z)) dk_x dk_y dk_z}. \quad (4.14)$$

where l corresponds to the l th band and k_x , k_y , and k_z are the wavevectors shown in Fig. 4.13(a). The averaged m^* along each direction (Γ A, Γ M, and Γ K) can be calculated by performing a three-dimensional integration of m_{ave}^* along each direction over the whole first Brillouin zone with Eq. (4.14). In contrast, the simplified equation (Eq. (4.13)) can be derived from Eq. (4.14) under two key assumptions. The first assumption pertains to the band structure and is expressed as:

$$E(k_x, k_y, k_z) = E(k_x, 0, 0) + E(0, k_y, 0) + E(0, 0, k_z) - 2E(0, 0, 0). \quad (4.15)$$

The second one concerns the energy distribution function of carriers, which follows:

$$f(E) \propto \exp(-E/k_B T). \quad (4.16)$$

To evaluate the validity of the band structure assumption (Eq. (4.15)) in the valence band structure of SiC, the equi-energy lines of bands were spotlighted. Figure 4.14(b) illustrates the schematic of the equi-energy line of the band structure in the (k_x, k_y) plane assumed by Eq. (4.15), which exhibits an elliptic outline. The open circles in the figure represent the points obtained from the first-principles calculation along specific directions. However, the actual equi-energy surface of the valence band structure of SiC deviates significantly from this elliptic approximation, exhibiting a more complex structure with alternating convex and concave parts, as shown in Fig. 4.14(c) [3]. This result indicates that the assumption described by Eq. (4.15) is not suitable for the valence band structure in SiC. Therefore, it is not sufficient to take into account the E - k dispersions along specific directions, and the whole first Brillouin zone should be considered for precise calculation of the averaged hole effective mass. Previous work by the authors' group utilized $k \cdot p$ method based on the first-principles calculation, and the valence band structure along every direction from the Γ point in the first Brillouin zone has been determined, leading to the calculation of averaged effective mass considering the entire first Brillouin zone [3]. It is noted that the region of E - k dispersion far from the Γ point in the Brillouin zone has minimal impact on the calculation of the m_{ave}^* because the hole concentration with such k is low enough due to the high energy of these holes. The temperature dependences of $m_{\text{ave},//}^*$ and $m_{\text{ave},\perp}^*$ calculated using Eq. (4.14) are shown in Fig. 4.14(d), and the m_{ave}^* ratio ($m_{\text{ave},\perp}^*/m_{\text{ave},//}^*$) is plotted as the solid line in Fig. 4.12. The calculated m_{ave}^* ratio remains approximately 0.8–0.9 and exhibits little temperature dependence. The close agreement with the experimentally obtained μ ratio confirms that the observed anisotropy in hole mobility can be quantitatively explained by the m_{ave}^* anisotropy considering the E - k dispersion over the entire first Brillouin zone.

4.3.3 Comparison of Experimental and Calculated Hole Mobilities

Finally, the authors attempted to theoretically reproduce the experimentally obtained Hall hole mobilities. The calculation of the Hall mobility requires the effective mass and the momentum relaxation time (τ), which incorporates contributions from five scattering mechanisms – ionized impurities (ii), neutral impurities (ni), acoustic phonon (ac), nonpolar optical phonon (nop), and polar optical phonon (pop) scattering – and the total relaxation time is given as follows:

$$\frac{1}{\tau} = \frac{1}{\tau_{ii}} + \frac{1}{\tau_{ni}} + \frac{1}{\tau_{ac}} + \frac{1}{\tau_{nop}} + \frac{1}{\tau_{pop}}, \quad (4.17)$$

In a previous report by the author's group, the momentum relaxation times for each scattering mechanism (τ_{ii} , τ_{ni} , τ_{ac} , τ_{nop} , and τ_{pop}) were extracted as functions of the wavevector and energy of holes. Then, the Hall hole mobility has been calculated by the relaxation time approximation considering the E - k dispersion of the valence band of SiC, where the magnetic field along the [0001] direction was assumed [3]. Based on these results, in this study, the Hall hole mobilities both parallel and perpendicular to the c -axis when applying the magnetic field along the $[11\bar{2}0]$ direction were calculated from the deviation of the distribution function from equilibrium due to the electric and magnetic fields along these directions. Note that these calculation accounted for the anisotropy of τ and different directions of acceleration by the electric field were considered for the calculation of $\mu_{H,\parallel}$ and $\mu_{H,\perp}$ (the [0001] and $[1\bar{1}00]$ directions, respectively).

The calculated Hall hole mobilities for $N_A = 1.3 \times 10^{16} \text{ cm}^{-3}$ and $1.0 \times 10^{18} \text{ cm}^{-3}$ are shown in Fig. 4.15, indicating good agreement of the calculated results with the experimental ones. It is notable that the temperature dependence of the Hall mobility when applying the magnetic field along the $[11\bar{2}0]$ direction is a little different from that under the magnetic field along the [0001] direction. This discrepancy arises from the differing temperature dependence of the Hall scattering factor γ_H [3]. In addition, the ac scattering is dominant around 300 K and the effects of the nop and pop scatterings become stronger at $T \geq 400$ K, leading to the steeper decrease of μ_H with increasing temperature even for $N_A = 1.0 \times 10^{18} \text{ cm}^{-3}$. At a lower temperature, the ni scattering also affects μ_H for the higher N_A sample while the ii scattering is almost negligible over the measured temperature range for both the samples. These results are consistent with the almost independent β of N_A discussed in Fig. 4.8.

4.4 Summary

In this chapter, the anisotropic low-field hole mobility was studied by Hall effect measurements on p-type SiC($11\bar{2}0$) epilayer over wide ranges of acceptor concentration ($N_A = 8 \times 10^{15}$ – $7 \times 10^{18} \text{ cm}^{-3}$) and temperature (120–600 K). From the systematic experimental

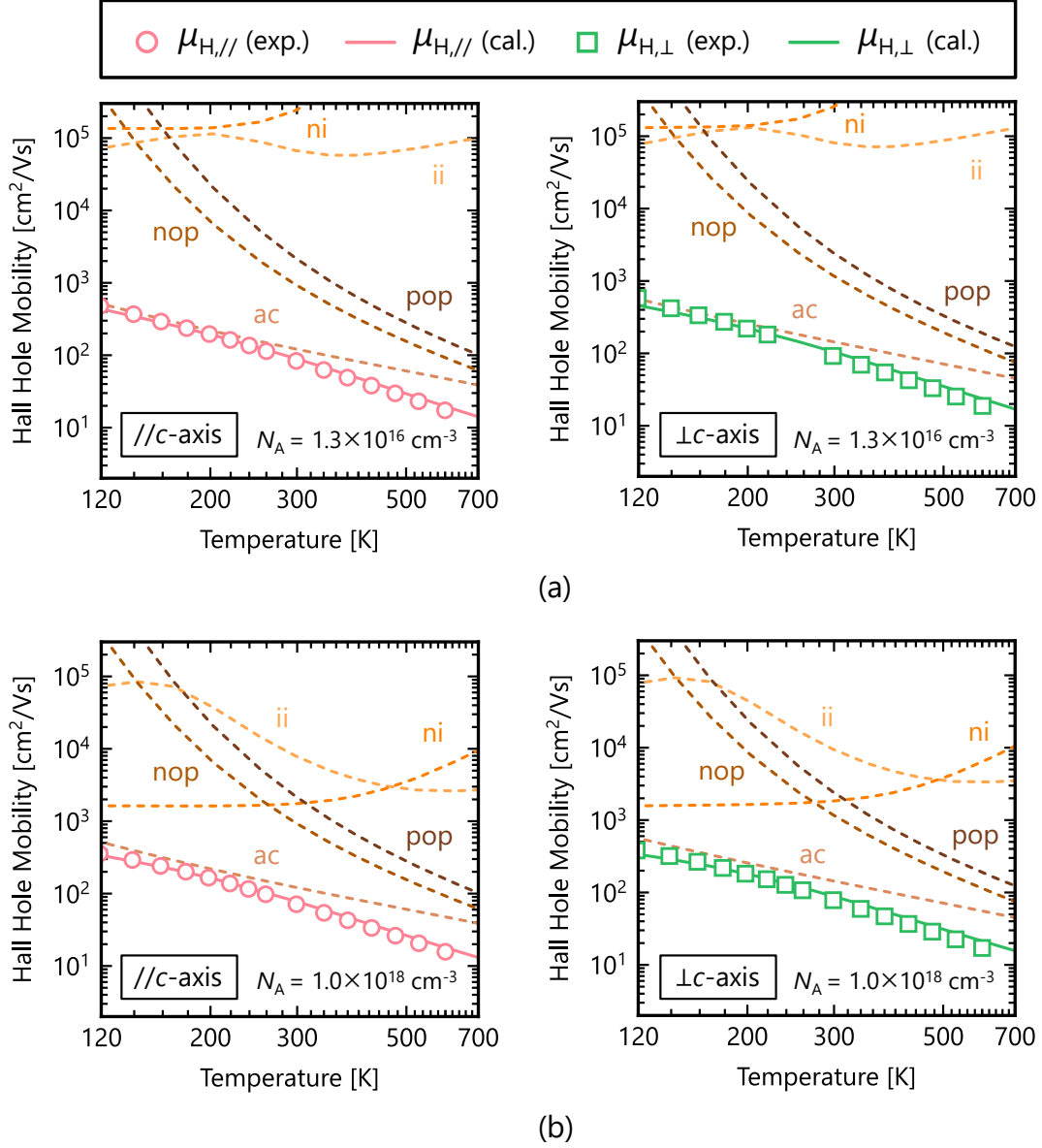


Figure 4.15: Hall Hole mobilities obtained by experiments and calculation versus temperature for (a) $N_A = 1.3 \times 10^{16} \text{ cm}^{-3}$ and (b) $N_A = 1.0 \times 10^{18} \text{ cm}^{-3}$. The calculation of mobilities parallel and perpendicular to the c -axis was performed based on the anisotropic momentum relaxation time and the anisotropic averaged effective mass [3]. The dashed lines show the mobility determined by each scattering mechanism, including ionized impurities (ii), neutral impurities (ni), acoustic phonon (ac), polar optical phonon (pop), and nonpolar optical phonon (nop) scatterings. (Reproduced from R. Ishikawa *et. al.*, *J. Appl. Phys.* **135**, 075704 (2024), with the permission of AIP Publishing.)

results, empirical equations describing the acceptor concentration and temperature dependences of mobilities were determined. Unlike electron mobility, the hole mobility along the c -axis was 10% lower than that perpendicular to the c -axis, and this anisotropy was discussed by focusing on the anisotropic hole effective mass. Theoretical calculation was performed by considering the energy distribution of holes and the valence band structure of SiC revealed that the anisotropy in hole effective mass quantitatively explains the observed anisotropy in the hole mobility. Note that the valence band structure over the whole Brillouin zone was taken into account accompanied by its the complex structure. In addition, the temperature dependence of the hole mobility was successfully reproduced well for both directions by the calculated hole mobility considering anisotropic effective mass and relaxation time.

References

- [1] B. J. Baliga, *Fundamentals of Power Semiconductor Devices* (Springer, 2nd edition, 2019).
- [2] A. Koizumi, J. Suda, and T. Kimoto, *J. Appl. Phys.* **106**, 013716 (2009).
- [3] H. Tanaka, S. Asada, T. Kimoto, and J. Suda, *J. Appl. Phys.* **123**, 245704 (2018).
- [4] J. Pernot, S. Contreras, and J. Camassel, *J. Appl. Phys.* **98**, 023706 (2005).
- [5] A. Parisini and R. Nipoti, *J. Appl. Phys.* **114**, 243703 (2013).
- [6] T. Hatakeyama, T. Watanabe, M. Kushibe, K. Kojima, S. Imai, T. Suzuki, T. Shinohe, T. Tanaka, and K. Arai, *Mater. Sci. Forum* **433–436**, 443 (2003).
- [7] D. K. Schroder, *Semiconductor Material and Device Characterization* (John Wiley & Sons, 3rd edition, 2006).
- [8] Y. Negoro, T. Kimoto, H. Matsunami, F. Schmid, and G. Pensl, *J. Appl. Phys.* **96**, 4916 (2004).
- [9] D. M. Caughey and R. E. Thomas, *Proc. IEEE* **55**, 2192 (1967).
- [10] J. Pernot, W. Zawadzki, S. Contreras, J. L. Robert, E. Neyret, and L. Di Cioccio, *J. Appl. Phys.* **90**, 1869 (2001).
- [11] H. Iwata and K. M. Itoh, *J. Appl. Phys.* **89**, 6228 (2001).
- [12] T. Kimoto and J. A. Cooper, *Fundamentals of Silicon Carbide Technology* (John Wiley & Sons, 2014).
- [13] W. E. Spear, *Proc. Phys. Soc. B* **70**, 669 (1957).

- [14] D. D. Tang, F. F. Fang, M. Scheuermann, and T. C. Chen, *Appl. Phys. Lett.* **49**, 1540 (1986).
- [15] O. Gunawan, S. R. Pae, D. M. Bishop, Y. Virgus, J. H. Noh, N. J. Jeon, Y. S. Lee, X. Shao, T. Todorov, D. B. Mitzi, and B. Shin, *Nature* **575**, 151 (2019).
- [16] S. Asada, T. Okuda, T. Kimoto, and J. Suda, *Appl. Phys. Express* **9**, 041301 (2016).
- [17] N. T. Son, C. Persson, U. Lindefelt, W. M. Chen, B. K. Meyer, D. M. Hofmann, and E. Janzén, Cyclotron resonance studies of effective masses and band structure in SiC, *Silicon Carbide – Recent Major Advances* (eds. W. J. Choyke, H. Matsunami, and G. Pensl), (Springer, 2004), p. 437.
- [18] X. Gonze, B. Amadon, P. M. Anglade, J. M. Beuken, F. Bottin, P. Boulanger, F. Bruneval, D. Caliste, R. Caracas, M. Côté, T. Deutsch, L. Genovese, P. Ghosez, M. Giantomassi, S. Goedecker, D. R. Hamann, P. Hermet, F. Jollet, G. Jomard, S. Leroux, M. Mancini, S. Mazevet, M. J. T. Oliveira, G. Onida, Y. Pouillon, T. Rangel, G. M. Rignanese, D. Sangalli, R. Shaltaf, M. Torrent, M. J. Verstraete, G. Zerah, and J. W. Zwanziger, *Comput. Phys. Commun.* **180**, 2582 (2009).
- [19] S. Goedecker, M. Teter, and J. Hutter, *Phys. Rev. B* **54**, 1703 (1996).
- [20] C. Hartwigsen, S. Goedecker, and J. Hutter, *Phys. Rev. B Condens. Matter* **58**, 3641 (1998).
- [21] G. Wellenhofer and U. Rössler, *Diam. Relat. Mater.* **6**, 1342 (1997).
- [22] C. Persson and U. Lindefelt, *J. Appl. Phys.* **82**, 5496 (1997).

Chapter 5

High-Field Hole Velocity

5.1 Introduction

As the final part of this study aimed at a thorough determination of carrier transport properties in SiC, the high-field drift velocity of holes was focused on in this chapter. The high-field drift velocity of holes is as essential as the parameters investigated in the previous chapters since holes are transported in high-field regions in many situations such as during short-circuit events and avalanche breakdown phenomena. Despite its importance, no prior studies have reported the high-field drift velocity of holes in SiC, even along the direction perpendicular to the c -axis. Then, experimental determination of the high-field drift velocity of holes along both directions parallel and perpendicular to the c -axis was established as the goal of this chapter, and conductance measurements on p-type SiC(11 $\bar{2}$ 0) layers were performed over a wide range of electric fields. The experimental setup and the test structures were designed and fabricated for these measurements separately from those for electrons, followed by the experimental results of hole drift velocity and discussion on its anisotropy.

5.2 Measurement Setup and Sample Preparation

To determine the anisotropic hole drift velocity in p-type SiC, the conductance measurement described in Section 3.2 was performed on bridge structures fabricated on p-type SiC(11 $\bar{2}$ 0) layers. Similar to the approach used for electrons, a short and narrow p-type bridge structure and a negative high-voltage short-pulse circuit were designed for the high-field measurements, with the key differences being the polarity of conductivity type and the applying voltage.

5.2.1 Design and Fabrication of Bridge Structures

Figure 5.1(a) shows a four-terminal structure with a bridge region fabricated on SiC(11 $\bar{2}$ 0) p-type epitaxial layers for conductance measurements to determine the drift velocity of

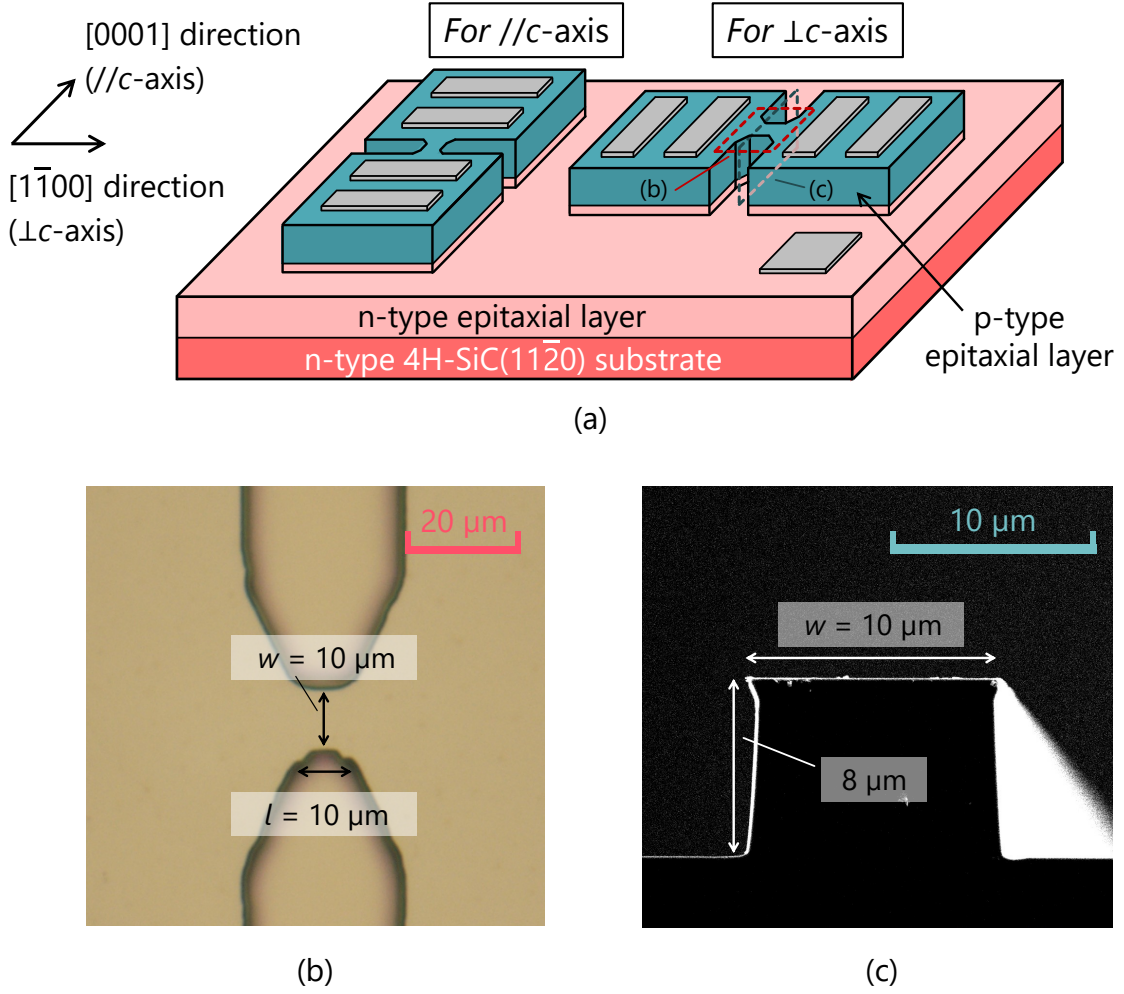


Figure 5.1: (a) Test structures with bridge regions along the [0001] and [1 $\bar{1}$ 00] directions fabricated on p-type SiC(11 $\bar{2}$ 0) epitaxial layer for measuring the hole drift velocity parallel and perpendicular to the c -axis. These structures were arranged side by side along with an electrode deposited on the n-type epitaxial layer. (b) Optical microscope image of the fabricated test structure (top-view) and (c) SEM images of the bridge region (cross-section).

holes. The orientation of the structures was varied to measure the hole velocities parallel and perpendicular to the c -axis, and they were arranged side by side on the same sample. The acceptor concentration of the p-type epilayer was varied from $1 \times 10^{16} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$, and the bridge region was designed with a length $l = 2.5 - 20 \text{ } \mu\text{m}$ and width $w = 10 \text{ } \mu\text{m}$. Since the samples used in this chapter are chips cut from the same wafers with epitaxial layers as those described in Section 4.2.1, detailed information such as the acceptor concentration, compensating donor concentration, and thickness can be found in Table 4.1 and Table 4.2. Note that the thickness t was obtained by subtracting the calculated depletion layer width from the p-type epilayer thickness measured by the scanning electron microscope (SEM) observation. The fabrication process is almost identical to that of the p-type Hall bar structure described in Section 4.2, where epitaxial growth, Al-ion implantation, mesa isolation, and ohmic metal formation (Al/Ti) were included while Schottky contact formation was not performed since the net acceptor concentrations of samples have already been known. It should be emphasized that ohmic metals (Al/Ti) were also deposited on the part of the exposed n-type epitaxial layer after the isolation process, simultaneously with the ohmic metal formation on the p-type epilayer to create ohmic contacts on the n-type layer. The condition of inductively-coupled plasma reactive ion etching (ICP-RIE) to form vertical sidewalls is [$\text{SF}_6/\text{O}_2/\text{Ar}$: 10/20/100 sccm, ICP/Bias power: 500/90 W, pressure: 2 Pa, etching rate: $0.7 \text{ } \mu\text{m}$]. The top-view optical microscope image including the bridge region of the test structure and the cross-sectional SEM image of the bridge region are shown in Fig. 5.1(b) and (c), which ensures that a narrow, short bridge structure with vertical sidewalls are successfully fabricated.

5.2.2 Negative High-Voltage Short-Pulse Circuit

A high-voltage short-pulse source with positive output has been established in Section 3.3, and it might not be impossible to use for the p-type conductance measurements. However, in the case when a positive voltage is applied to the structure p-layer/n-layer illustrated in Fig. 5.1(a), the pn junction between the p-layer and n-layer momentarily turns on, potentially leading to undesirable current flow that could interfere with measurements. In addition, the analysis might become complicated as the current and potential distributions may remain complex even after reaching a steady state. On the other hand, in the case of a negative voltage, such complications are not expected and the current flowing is largely limited in the p-type layer since the pn junction is reversely biased. Consequently, a negative high-voltage short-pulse circuit was implemented for the measurements, as schematically illustrated in Fig. 5.2(a). The major difference from the positive pulse-voltage source is that a negative DC high-voltage source (HK-2N, Matsusada Precision) was used, the SiC MOSFETs (IMW120R350M1H, Infineon) were flipped so that the drain and source are swapped, and the connection near the source terminal, DC/DC converter, and gate driver (2EDB9259T, Infineon) was modified. The typical waveforms of the output voltages of the

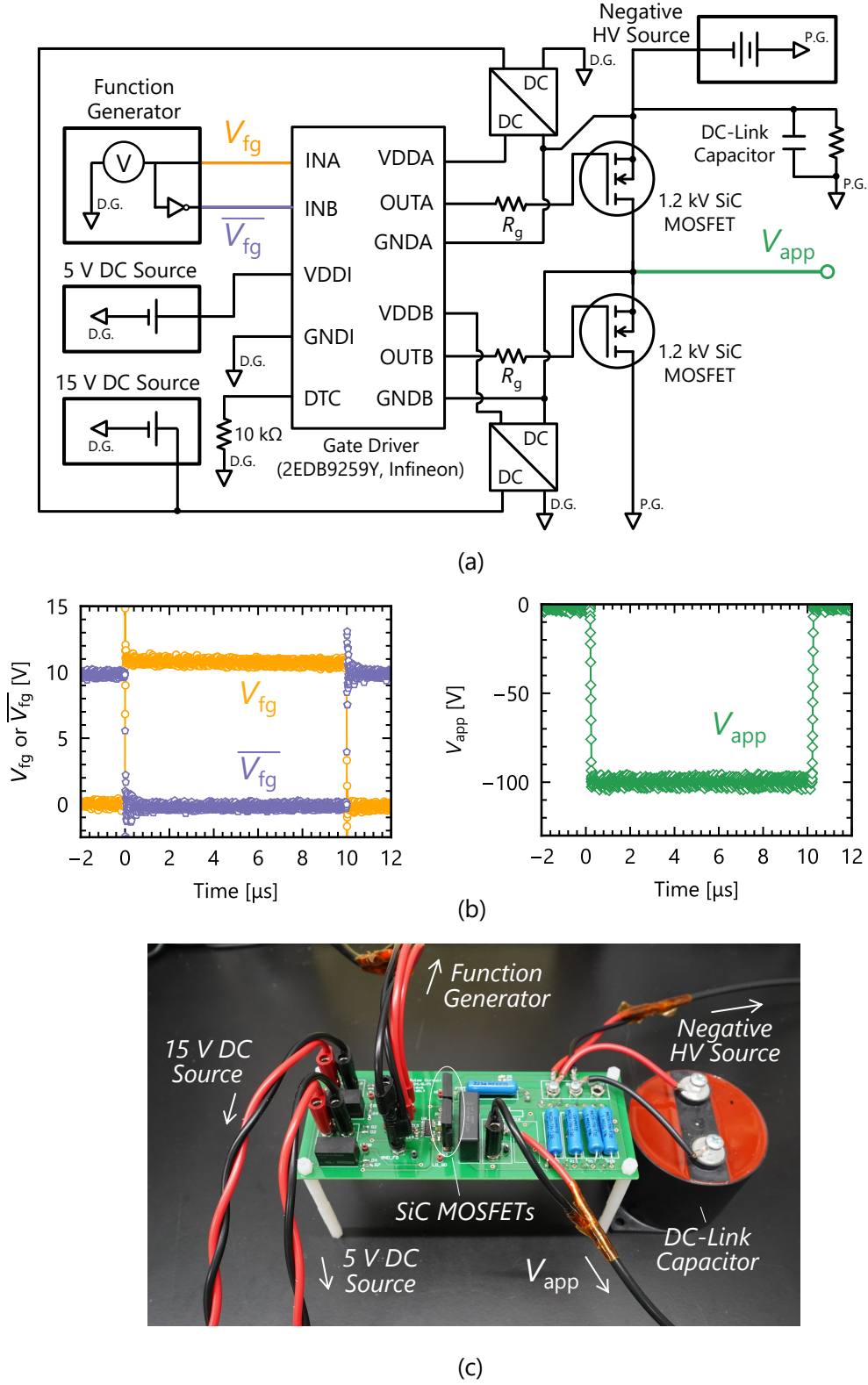


Figure 5.2: (a) Schematic diagram of custom-made switching circuit to generate short-pulse negative high-voltage and (b) typical waveforms of outputs of the function generator and the switching circuit, where a small signal input from the function generator is amplified to a negative pulsed high voltage. (c) Photograph of fabricated switching circuit.

function generator (81160A, Agilent Technologies) (V_{fg} and $\overline{V_{fg}}$) are shown in Figure 5.2(b) with that of the switching circuit (V_{app}). The 10 V signals from the function generator are amplified to a -100 V pulse voltage with a pulse width of $10 \mu s$, for example. A short pulse width (minimum pulse width: 200 ns), a flat waveform, and minimal overshoot were achieved by making the wire shorter and optimizing the gate resistance for precise conductance measurements.

5.2.3 Measurement System Assembly

The negative pulse voltage generated by the switching circuit was applied to the bridge structure via a coaxial prober, and the voltages were monitored by an oscilloscope (DSO9254A, Agilent Technologies) as illustrated in Fig. 5.3. A differential probe (N2790A) and a standard 10:1 passive probe were utilized for the measurement of voltages V_{meas} and $V_R = RI$, where R is the external resistance and I is the current, and the applied voltage was varied from 2 V to 200 V. R was selected in the range of 300–2000 Ω to minimize the effects of noise and transient current for each condition including the applied voltage, bridge length, and acceptor concentration. In addition, the test structures were immersed in Fluorinert during measurements to prevent air sparking and promote heat dissipation. Besides, the n-layer was connected to the ground to reduce transient currents from the depletion capacitor of the pn junction, and a detailed discussion on the effect of this grounding setup will be done in the next section after showing the experimental results of measured waveforms. Note that the equations to determine the drift velocity of holes (v_d) and the electric field in the bridge region (E_{bridge}) should be modified from the case of electron drift velocity (Eqs. (3.1) and Eqs. (3.2)) due to the opposite sign of V_{meas} and I :

$$v_d = -\frac{I}{enwt}, \quad (5.1)$$

$$E_{bridge} = -\frac{V_{meas} - 2r \cdot I}{l}, \quad (5.2)$$

where l , w , and t are the length, width, and thickness of the bridge, respectively, e is the elementary charge, p is the hole concentration, and r represents the resistance between electrodes and bridge region. In this analysis, p was determined by Hall effect measurement as described in Chapter 4, and $2r$ was estimated based on the resistance between the inner two electrodes for the structures with different bridge lengths.

5.3 Results and Analyses

5.3.1 Voltage and Current Waveforms

The measured waveforms of V_{meas} and $V_R = RI$ are shown in Fig. 5.4, with plots in different colors representing the results for different applied voltage, where the results for the direction

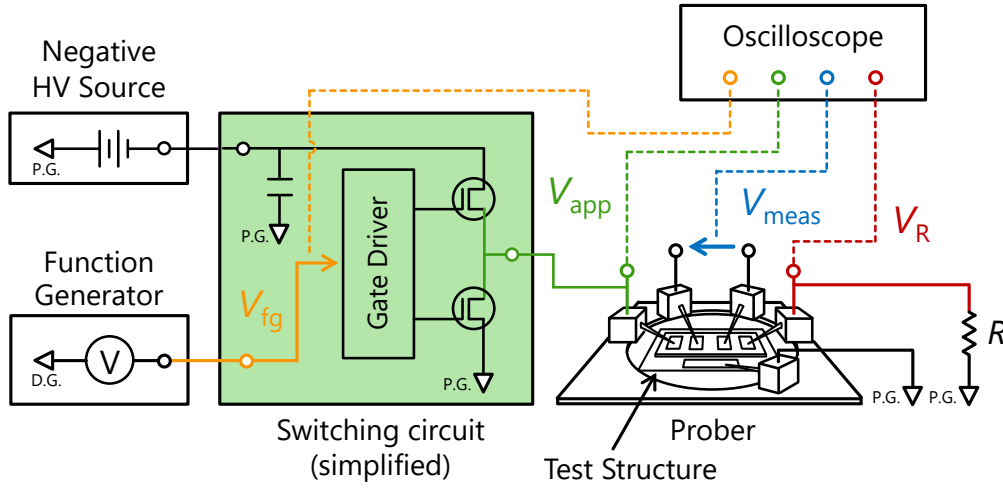


Figure 5.3: System assembly of conductance measurement for hole drift velocity including a negative high-voltage source, a function generator, a switching circuit, a prober, and an oscilloscope.

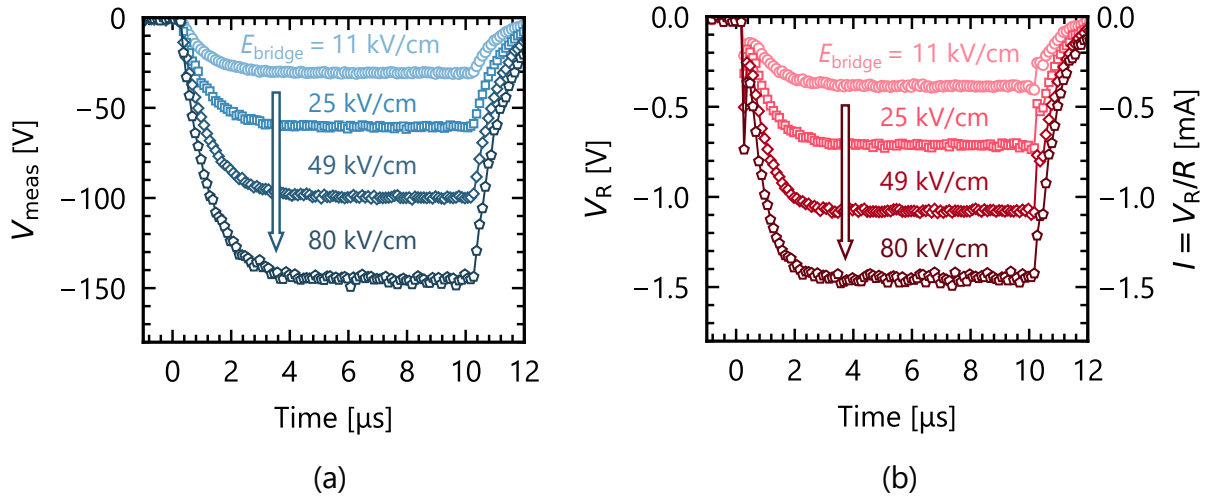


Figure 5.4: Waveforms of (a) voltage drop V_{meas} and (b) current I for different applied voltages obtained for a test structure parallel to the c -axis with $N_A = 1 \times 10^{16} \text{ cm}^{-3}$, $l = 10 \text{ } \mu\text{m}$, and $w = 10 \text{ } \mu\text{m}$.

parallel to the c -axis, $N_A = 1 \times 10^{16} \text{ cm}^{-3}$, $l = 10 \text{ } \mu\text{m}$, and $w = 10 \text{ } \mu\text{m}$ are taken as examples. Both V_{meas} and I were observed to increase as the electric field E_{bridge} increases, which is a different trend compared with the case of electrons where I approaches a constant value. This result implies that the hole drift velocity does not exhibit obvious saturation even at $E_{\text{bridge}} = 80 \text{ kV/cm}$. From these waveforms, V_{meas} and I were determined as the averaged values in $4\text{--}9 \text{ } \mu\text{s}$, and then E_{bridge} was calculated using Eq. (5.2) after estimating the resistance component for correction $2r$ in the same manner with the case of electrons described in Section 3.4. Figure 5.5 shows the resistance between the inner two electrodes by linear fitting in the voltage range of $-20\text{--}20 \text{ V}$ for various l , and then $2r$ was estimated from the y-axis intercept after performing linear extrapolation for each acceptor concentration and direction. Here, it should be noted that this analysis assumes that $2r$ is independent of the applied voltage (i.e., the hole velocity does not saturate in the $2r$ region).

In the present measurements, the p-type epilayer was grounded to ensure the accuracy by suppressing the transient current flowing from a depletion capacitor of pn junction to external resistance R , in a similar manner to the case of electrons described in Section 3.4. The pn junction between the p-type and n-type epilayers is reversely biased when a negative high voltage is applied on the electrode, and the depletion layer of the pn junction is expected to perform as a capacitor connected in parallel with the bridge. The transient current from this capacitor (i.e., electrons swept from the extended depletion layer) can flow to R as illustrated in Fig. 5.6(a) if the n-layer is left floating. This is because the transient current makes the observed current flowing in R different from the target current flowing in the bridge region. With the aim of avoiding this interference, the n-layer was grounded in order to lead the transient current directly into the ground without flowing in R . The current waveforms for both setups: with the n-layer floating and with it the n-layer grounded are compared in Fig. 5.6(b), where the transient current is slightly reduced and the current waveform becomes less noisy by grounding the n-layer, especially immediately after the turn-on, thereby ensuring a little bit greater accuracy. The configuration grounding the n-layer was therefore used in all the measurements for the present study.

5.3.2 Hole Drift Velocity versus Electric Field Strength

Figure 5.7 shows the electric field and drift velocity of holes along directions parallel and perpendicular to the c -axis extracted using Eqs. (5.1) and (5.2) for various applied voltages and bridge lengths. It can be observed that the drift velocity of holes shows a nearly linear relationship with the electric field, even in the relatively high-field region (on the order of 10 kV/cm). Although the tendency toward saturation appears at a high electric field around 100 kV/cm , no clear saturation occurs in the observed range of electric field ($1\text{--}200 \text{ kV/cm}$). Note that the maximum electric field plotted in Fig. 5.7 is lower for more heavily-doped samples as pronounced leakage currents affect the accurate measurements and these results were excluded from Fig. 5.7.

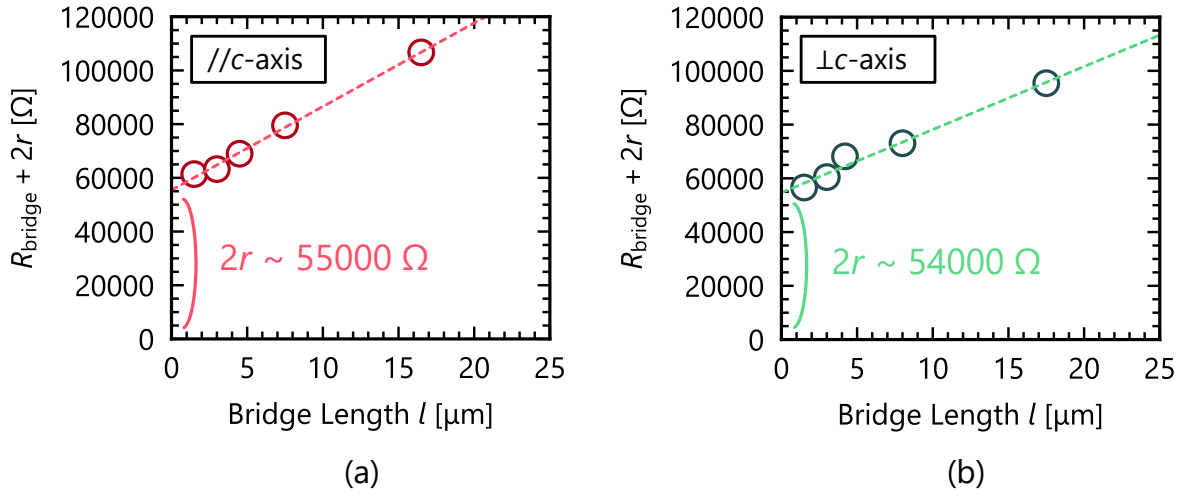


Figure 5.5: Bridge length (l) dependences of the resistance between the two internal electrodes of the test structure, i.e., the sum of the bridge resistance (R_{bridge}) and the resistance components $2r$ for the directions (a) parallel and (b) perpendicular to the c -axis ($N_A = 1 \times 10^{16} \text{ cm}^{-3}$ and $w = 10 \text{ μm}$).

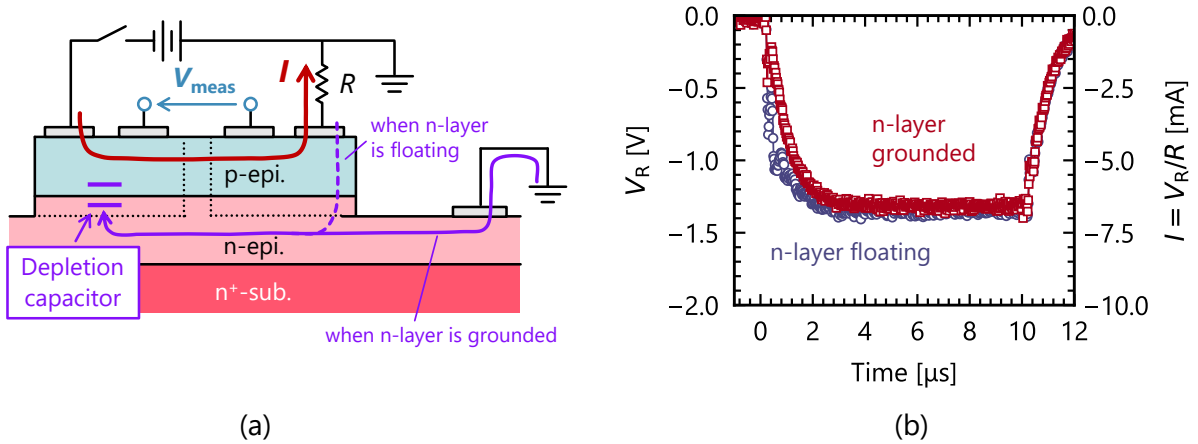


Figure 5.6: (a) Schematic of the current path when the n-layer is floating and grounded, where the transient current from the depletion capacitor of the pn junction is directly led to the ground without going through the external resistance R by grounding the n-layer. (b) Current waveforms under both conditions, where the transient current is clearly reduced by grounding the n-layer.

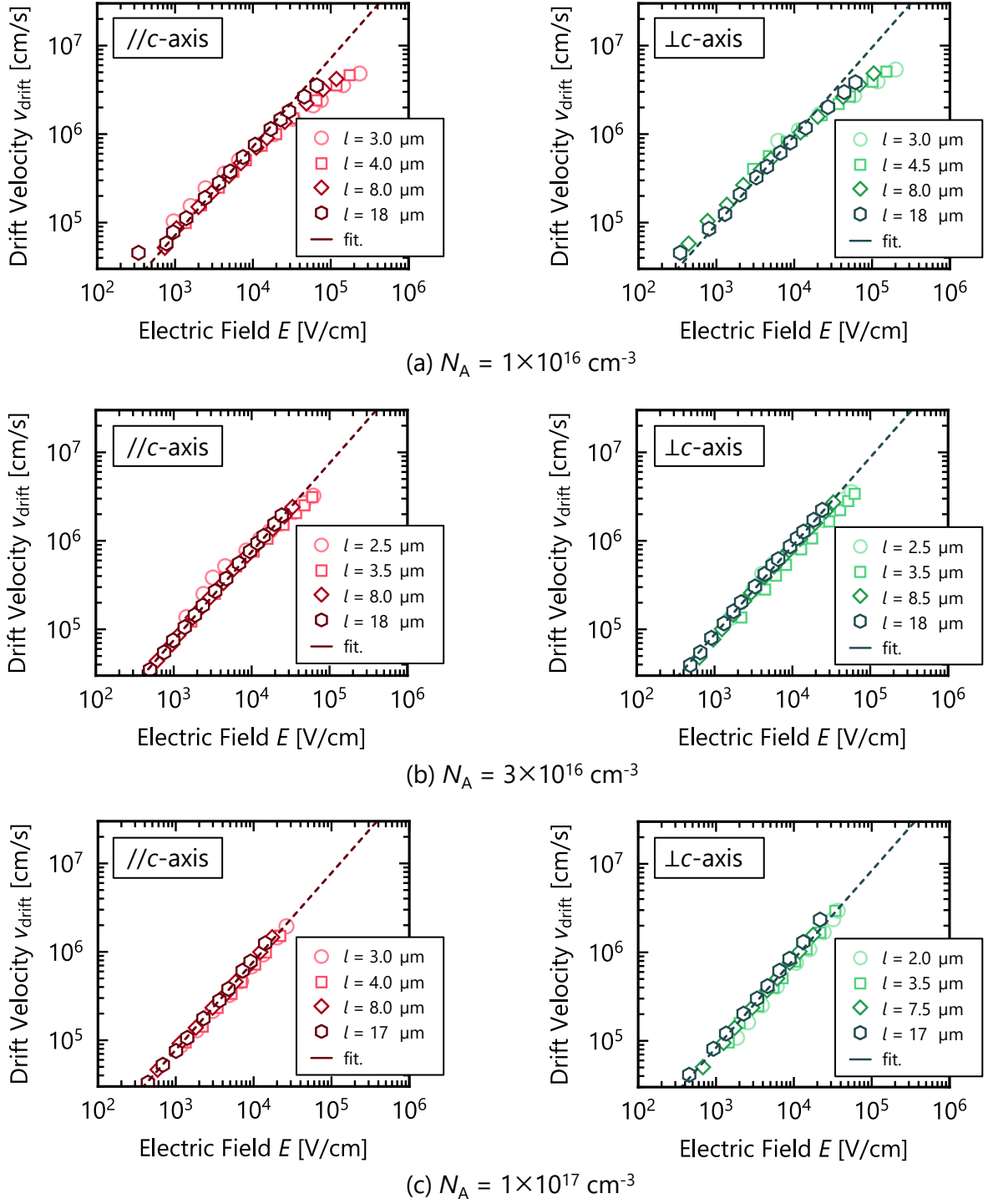


Figure 5.7: Drift velocity of holes versus electric field strength obtained from the test structures with different bridge lengths (l) along both directions for (a) $N_A = 1 \times 10^{16} \text{ cm}^{-3}$, (b) $N_A = 3 \times 10^{16} \text{ cm}^{-3}$, and (c) $N_A = 1 \times 10^{17} \text{ cm}^{-3}$. Dashed lines depict the fitting results obtained by linear extrapolation.

From the obtained v_d - E_{bridge} relationships, the low-field mobility (μ) was extracted by performing linear extrapolation in the low-field region ($E_{\text{bridge}} \leq 1 \times 10^4$ V/cm) for each acceptor concentration and direction. The hole mobilities are summarized, alongside the Hall hole mobilities obtained in Chapter 4 in Fig. 5.8 as a function of acceptor concentration, where the error bars include both the fitting error and the determination error of the bridge dimensions. The hole mobilities determined by conductance measurements are consistent with those from Hall effect measurements, indicating that the present measurements and analyses are reliable. Besides, it is also worth noting that the current waveforms remain nearly flat, even in the most heavily-doped sample under the highest electric field, suggesting minimal self-heating effects in the present measurements.

5.4 Discussion

First, the author investigated the reason why the saturation of hole drift velocity was not observed within the measured electric field range (1–200 kV/cm), whereas the electron drift velocity exhibited clear saturation around 100 kV/cm, as depicted again in Fig. 5.9. The low-field mobility of holes is almost one-tenth that of electrons [1–4] as also confirmed experimentally in this study in Chapters 2 and 4, while the saturated velocity (v_{sat}) of holes is expected to be approximately half that of electrons. This expectation is based on the equation $v_{\text{sat}} = \sqrt{8\hbar\omega/3\pi m^*}$ [5], where the energy of optical phonons ($\hbar\omega$) is identical for both electrons and holes, but the effective mass (m^*) of holes are 3–5 times heavier than that of electrons at room temperature, as seen from Fig. 2.25 and Fig. 4.14(d). Based on these considerations, the electric field at which velocity saturation occurs for holes is anticipated to shift toward higher fields – approximately five times higher – compared to the case of electrons. This shift is likely the primary reason why velocity saturation was not observed for holes in the measured electric field range, and rough estimation, derived by multiplying the electron saturation field by a factor of 5, suggests that the obvious saturation of hole drift velocity is expected to be observed around 500 kV/cm. Furthermore, velocity saturation might be observed at lower temperatures due to the enhanced hole mobilities under such conditions, as observed in Si [6]. Therefore, extending the measurement range to higher electric fields and lower temperatures is required for future studies.

Figure 5.10(a) compares the hole velocities along the directions parallel and perpendicular to the c -axis, which implies approximately 10% anisotropy in hole drift velocity is maintained even at high electric fields unlike in the case of electrons. This result can be extrapolated by the relationship between the effective mass anisotropy and the energy distribution of holes. The energy distribution of holes under a high electric field (1 MV/cm, parallel to the c -axis) [7] is depicted in Fig. 5.10(b), along with those under thermal equilibrium at several temperatures (300 K, 600 K, and 900 K), which indicates holes are distributed with higher energies under both higher electric fields and elevated temperatures. As calcu-

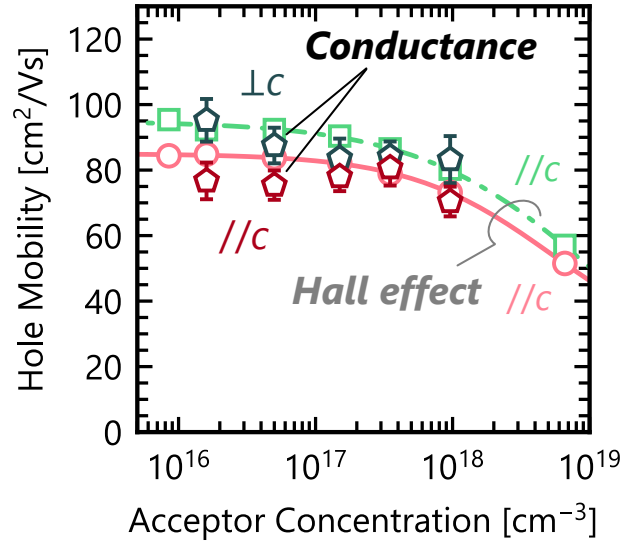


Figure 5.8: Low-field mobility of holes extracted from the drift velocity versus electric field relationship as a function of acceptor concentration.

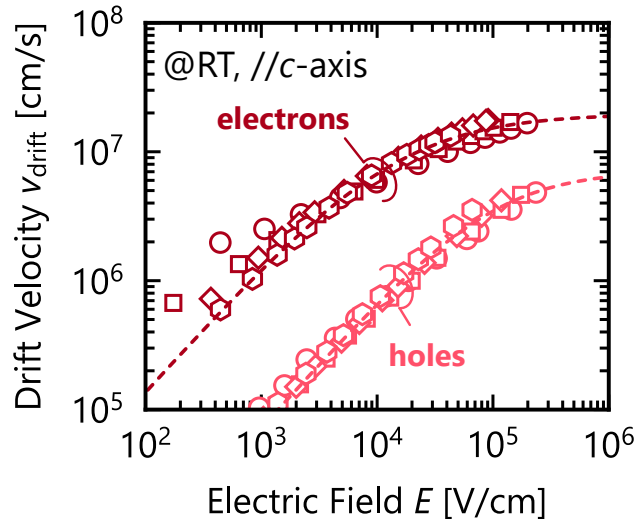


Figure 5.9: Electric field dependence of the drift velocity parallel to the c -axis of electrons ($N_D = 5 \times 10^{15} \text{ cm}^{-3}$) and holes ($N_A = 1 \times 10^{16} \text{ cm}^{-3}$). The ten times lower mobility (experimentally determined) and two times lower saturated velocity (estimated) of holes compared with those of electrons can explain that the electric field at which saturation occurs becomes greater and velocity saturation was not observed for holes in the measured electric field range.

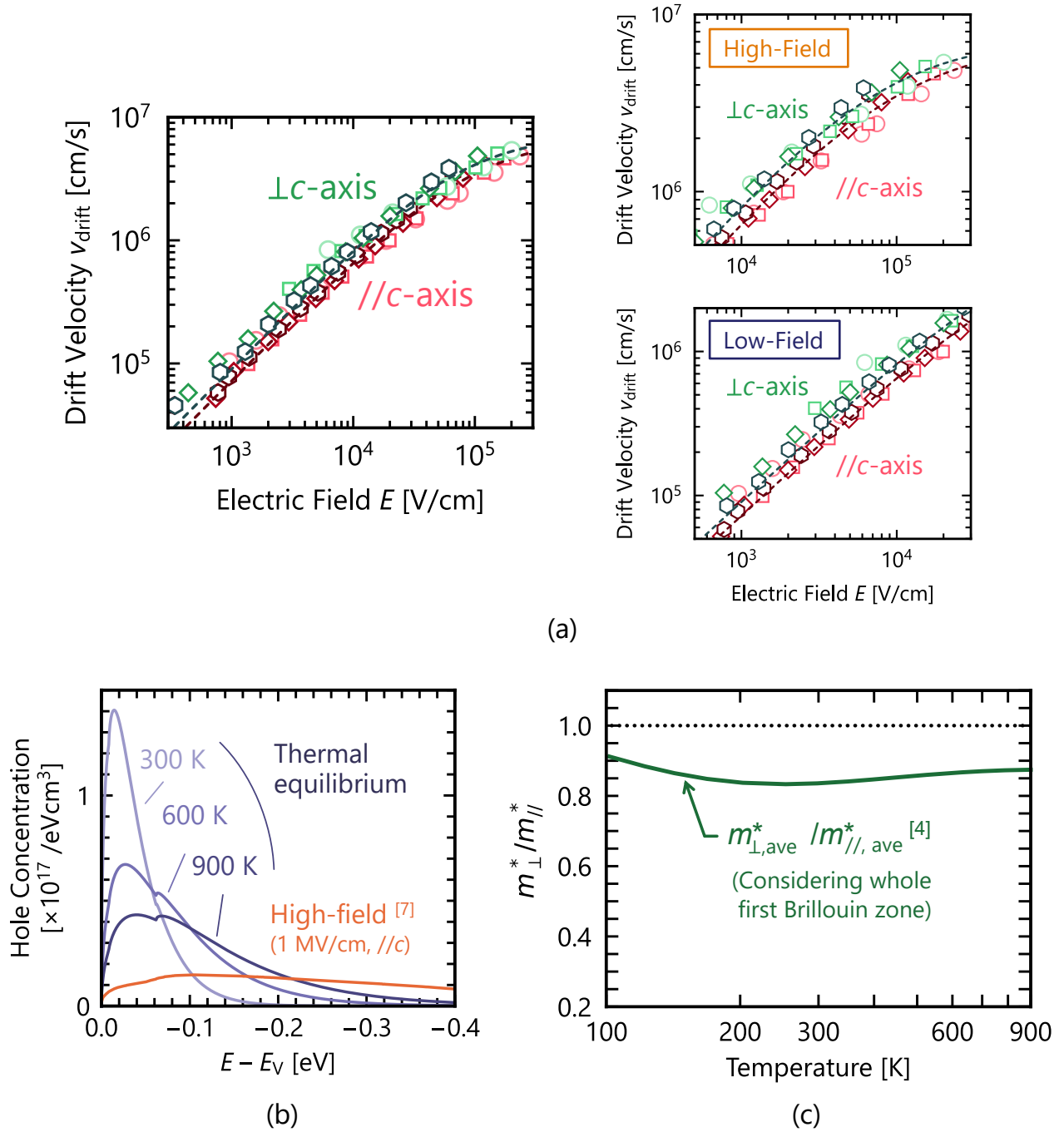


Figure 5.10: (a) Comparison between the hole velocities along the directions parallel and perpendicular to the c -axis obtained for the sample with $N_A = 1 \times 10^{16} \text{ cm}^{-3}$, where almost 10% anisotropy is preserved over the observed electric field range. (b) Hole distributions in the valence band under thermal equilibrium state at several temperatures and high electric field (1 MV/cm, $//c$ -axis) [7]. (c) Calculated anisotropy of hole effective mass ($m_{\text{ave}, \perp}^* / m_{\text{ave}, \parallel}^*$) considering the energy distribution of holes under thermal equilibrium state at several temperatures [4], which implies that the m_{ave}^* ratio is little influenced by the change in the hole distribution.

lated in Section 4.3, the averaged effective mass ratio ($m_{\text{ave},\perp}^*/m_{\text{ave},//}^*$) – which accounts for the energy dependence of effective mass – remains almost independent of temperature, and the calculated ratio is shown again in Fig. 5.10(c) [4]. This independence indicates that the energy distribution of holes has a limited effect on the anisotropy of effective mass, which is qualitatively consistent with the observation that the anisotropy in hole velocity is independent of the electric field strength. However, for a more accurate analysis, the average effective mass should be recalculated based on the energy distribution of holes under various electric fields and the valence band structure over the whole first Brillouin zone.

5.5 Summary

In this chapter, the high-field hole velocity was experimentally determined by conductance measurements on p-type SiC(11 $\bar{2}$ 0) epilayers over a wide range of electric fields (1–200 kV/cm). A measurement system including a negative high-voltage short-pulse source was established for accurate measurement and analysis, and test structures consisting of narrow and short bridge structures with p-type conduction were fabricated as the subject of measurements. As a result, the hole drift velocity exhibited an almost linear relationship with the electric field in the observed range, and velocity saturation was not observed even at a high electric field of 200 kV/cm, which was attributed to the low hole mobility in SiC. In addition, the 10% anisotropy in hole drift velocity was preserved over the wide electric field range (1–200 kV/cm), and this result was consistent with the minimal dependence of effective mass anisotropy on the energy distribution of holes.

References

- [1] J. Pernot, W. Zawadzki, S. Contreras, J. L. Robert, E. Neyret, and L. Di Cioccio, *J. Appl. Phys.* **90**, 1869 (2001).
- [2] H. Iwata and K. M. Itoh, *J. Appl. Phys.* **89**, 6228 (2001).
- [3] A. Koizumi, J. Suda, and T. Kimoto, *J. Appl. Phys.* **106**, 013716 (2009).
- [4] H. Tanaka, S. Asada, T. Kimoto, and J. Suda, *J. Appl. Phys.* **123**, 245704 (2018).
- [5] S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (John Wiley & Sons, 2006).
- [6] C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *Solid State Electron.* **20**, 77 (1977).
- [7] H. Tanaka, T. Kimoto, and N. Mori, *Mater. Sci. Semicond. Process.* **173**, 108126 (2024).

Chapter 6

Conclusions

6.1 Summary of This Thesis

In this dissertation, the author systematically studied the transport phenomena of both electrons and holes in SiC under low and high electric fields while considering its anisotropy by using SiC(11 $\bar{2}$ 0) wafers. The research was divided into four parts according to the carrier type and electric field strength; low-field electron mobility (Chapter 2), high-field electron velocity (Chapter 3), low-field hole mobility (Chapter 4), and high-field hole velocity (Chapter 5). The fundamental database of transport properties along the c -axis was established, which is particularly important for SiC-based power device applications. In addition, the anisotropy of carrier transport was discussed from the measurement results for directions parallel and perpendicular to the c -axis. Theoretical calculation, based on the conduction and valence band structures of SiC and energy distribution of carriers, revealed that the anisotropy in mobility and drift velocity of carriers can be explained by their anisotropic effective mass, including the temperature and electric field dependences. The main conclusions obtained by the present study are summarized as follows.

In Chapter 2, the anisotropic low-field electron mobility was investigated by using two approaches. First, the electron mobility along the c -axis was estimated by analyses based on capacitance–voltage (C – V) and current–voltage (I – V) measurements on SiC(0001) vertical Schottky barrier diodes (SBDs). By taking care of the current spreading and separation of resistance components, the electron mobility was obtained to be 1070 cm²/Vs with an accuracy of ± 290 cm²/Vs for the donor concentration (N_D) of 1×10^{15} cm⁻³. Despite of the relatively large error, the averaged value was close to the result by Hall effect measurement, which ensured the validity of the present method. As the second approach, the author performed Hall effect measurements on n-type SiC(11 $\bar{2}$ 0) epilayers and determined the electron mobility parallel and perpendicular to the c -axis over wide ranges of donor concentration ($N_D = 5 \times 10^{14}$ – 4×10^{18} cm⁻³) and temperature (120–600 K). A high mobility of 1210 cm²/Vs was obtained for the direction parallel to the c -axis, which is the highest value ever measured for SiC at room temperature. From the systematic experimental results, empiri-

cal equations describing the donor concentration and temperature dependences of electron mobilities were determined. In addition, the electron mobility along the c -axis was found to be 10–20% higher than that perpendicular to the c -axis, and the origin of the anisotropy was discussed by focusing on the anisotropy in electron effective mass. A comparison between the observed mobility anisotropy and effective mass reported at the conduction band minimum suggested the necessity to take into account the energy dependence of effective mass. Then, a theoretical calculation was performed considering the energy distribution of electrons and the conduction band structure of SiC, and it was clarified that the anisotropy in electron mobility is quantitatively explained only by that in effective mass. In addition, the temperature dependence of the electron mobility was calculated by assuming the isotropic relaxation time of scattering, which reproduced well the observed mobility for both directions.

In Chapter 3, the author determined the anisotropic high-field drift velocity of electrons using n-type SiC(11 $\bar{2}$ 0) epilayers. Conductance methods were adopted since it has no restriction for doping concentration of samples in principle and it is considered to be suitable for SiC, whose minimum doping concentration ($\sim 1 \times 10^{14} \text{ cm}^{-3}$) is relatively higher than that of other semiconductors such as Si and Ge ($\leq 1 \times 10^{11} \text{ cm}^{-3}$) at the present stage. The electron velocity was measured over a wide range of electric field from 1 to 200 kV/cm by combining the n-type bridge structures and a high-voltage short-pulse source. Saturation of electron drift velocity was observed around 100 kV/cm, with saturated drift velocities of $1.7 \times 10^7 \text{ cm/s}$ for both directions parallel and perpendicular to the c -axis. Careful consideration of the effects of transient current and self-heating ensured the accuracy of these results. In addition, the relaxation of velocity anisotropy at higher electric field was qualitatively explained by the change in the energy distribution of electrons.

In Chapter 4, the anisotropic low-field hole mobility was studied by Hall effect measurements on p-type SiC(11 $\bar{2}$ 0) epilayers with various acceptor concentrations ($N_A = 8 \times 10^{15} - 7 \times 10^{18} \text{ cm}^{-3}$) and temperatures (120–600 K). Empirical equations expressing the acceptor concentration and temperature dependences of mobilities were determined so that the systematic experimental results are well reproduced. Unlike electron mobility, the hole mobility along the c -axis was 10% lower than that perpendicular to the c -axis, and this anisotropy was discussed by focusing on the anisotropic hole effective mass. Similar calculation with the case of electrons was performed by considering the energy distribution of holes and the valence band structure of SiC with an important difference that the E - k dispersion over the whole Brillouin zone was taken into account accompanied by the complex structure of the SiC valence band. Consequently, the author revealed that the anisotropy in hole effective mass quantitatively explains the observed anisotropy in the hole mobility. Besides, the temperature dependence of the hole mobility was successfully reproduced well for both directions by the calculated hole mobility considering anisotropic effective mass and relaxation time.

In Chapter 5, the high-field hole velocity was determined by conductance measurements

on p-type SiC(11 $\bar{2}$ 0) epilayers under various electric fields up to 200 kV/cm. Velocity saturation of holes was not observed even at a high electric field of 200 kV/cm, and it was attributed to the low hole mobility in SiC. The 10% anisotropy in hole drift velocity was preserved across the observed electric field range, and that was consistent with the minimal dependence of calculated effective mass anisotropy on the energy distribution of holes.

The present data on the carrier transport properties in SiC bulk crystals, including (i) carrier type (electrons or holes), (ii) crystal direction (parallel and perpendicular to the c -axis), (iii) electric field strength, (iv) doping concentration, and (v) temperature dependences are essential for understanding what happens in the devices under any operation. These results enable us to predict the device performance with greater accuracy and make it easier to achieve an optimum design of SiC devices. In addition, the author believes that the theoretical analyses on the origin of the carrier transport anisotropy focusing on the band structure of the material can provide a deep insight into comprehensive understanding of physics in anisotropic semiconductor materials including GaN and Ga₂O₃.

6.2 Future Outlook

The author has investigated the fundamental transport properties of carriers in SiC bulk crystals and advanced the understanding of anisotropic carrier transport based on the anisotropic band structure of SiC. Stemming from the findings of this study, the following research topics are proposed for future exploration.

1. Determination of carrier transport properties under electric field exceeding 1 MV/cm

This study experimentally determined the drift velocities of electrons and holes over a wide electric field with a maximum value of 200 kV/cm. As the next step, expansion of the electric field range of measurement up to 1 MV/cm is essential for deeper understanding of carrier transport phenomena in SiC. The determination of drift velocity under such extremely high electric fields has not yet been reported, even for other semiconductor materials [1–11]. This limitation is primarily due to the constraints of the time-of-flight technique and breakdown of the materials themselves at high fields. For materials such as Ge, Si, and GaAs, which have critical electric fields on the order of hundreds of kV/cm [12–14], applying electric fields beyond 1 MV/cm is fundamentally impossible. In contrast, SiC, with its high critical electric field of approximately 2.5 MV/cm [15], offers the potential for measurements at much higher electric fields. Furthermore, conductance techniques are not fundamentally restricted in terms of the maximum electric field unlike time-of-flight methods, which are typically limited to a maximum electric field of around 100 kV/cm by the minimum flight time and maximum applied voltage allowed in measurement systems. Theoretical studies have predicted that under electric fields exceeding 1 MV/cm, carriers in SiC

may exhibit unique transport phenomena, such as Bloch oscillations caused by the narrow Brillouin zone of SiC along the $\langle 0001 \rangle$ direction, and these phenomena could result in negative differential drift velocity [16–18]. However, this intriguing prediction remains experimentally unverified, leaving it an open question in semiconductor physics. To achieve accurate measurements of carrier drift velocities in this unexplored high-field regime by conductance techniques, it is necessary to develop test structures capable of withstanding higher blocking voltages and incorporating shorter bridge regions. Alternatively, the design of novel test structures or the development of innovative measurement techniques could provide a pathway to advancing the boundaries of high-field carrier transport research in semiconductor materials.

2. Characterization of temperature dependence of high-field carrier transport

Although the high-field drift velocity of carriers was investigated in this study, the measurement temperature is limited to room temperature at the present stage. Changes in temperature are expected to influence the energy distribution of electrons and holes and their interactions with optical phonons, leading to variations in high-field drift velocity, as observed in other materials such as Si, GaAs, and heterostructures [1, 11, 19, 20]. Since power devices usually operate at elevated temperatures due to self-heating of devices, understanding the temperature dependence of high-field drift velocity is critical for accurate simulation. Moreover, investigating drift velocity at both low and high temperatures would provide valuable insights into the anisotropy discussed in this thesis, as temperature directly influences the energy distributions of carriers. Experimental determination of temperature dependence of anisotropic high-field drift velocity is therefore essential, both from the perspective of practical applications and for advancing the fundamental understanding of carrier transport physics.

3. Understanding the transport mechanism of minority carriers

The focus of this study was on the transport properties of majority carriers, namely electrons in n-type and holes in p-type SiC. However, the minority carrier transport is also important for device applications. For example, in SiC-based bipolar devices such as pin diodes and insulated-gate bipolar transistors (IGBTs), the drift or diffusion of injected minority carriers significantly impacts the device performance [21, 22]. The transport properties of minority carriers may be different from those of majority carriers due to additional scattering mechanisms, including electron-hole scattering, i.e., interactions with majority carriers [23]. Experimental determination of anisotropic transport properties of minority carriers using techniques such as time-of-flight measurement or photo-Hall effect measurement [24–28] would greatly contribute to a comprehensive understanding of carrier transport in SiC.

References

- [1] C. Jacoboni, C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *Solid State Electron.* **20**, 77 (1977).
- [2] C. B. Norris and J. F. Gibbons, *IEEE Trans. Electron Devices* **14**, 38 (1967).
- [3] V. Rodriguez, H. Ruegg, and M.-A. Nicolet, *IEEE Trans. Electron Devices* **14**, 44 (1967).
- [4] D. M. Chang and J. G. Ruch, *Appl. Phys. Lett.* **12**, 111 (1968).
- [5] R. D. Larrabee, *J. Appl. Phys.* **30**, 857 (1959).
- [6] J. G. Ruch and G. S. Kino, *Appl. Phys. Lett.* **10**, 40 (1967).
- [7] P. M. Smith, M. Inoue, and J. Frey, *Appl. Phys. Lett.* **37**, 797 (1980).
- [8] A. Neukermans and G. S. Kino, *Appl. Phys. Lett.* **17**, 102 (1970).
- [9] J. L. Heaton, III, G. H. Hammond, and R. B. Goldner, *Appl. Phys. Lett.* **20**, 333 (1972).
- [10] J. A. Cooper and D. F. Nelson, *J. Appl. Phys.* **54**, 1445 (1983).
- [11] K. Hirakawa and H. Sakaki, *J. Appl. Phys.* **63**, 803 (1988).
- [12] S. L. Miller, *Phys. Rev.* **99**, 1234 (1955).
- [13] Y. J. Chang and S. M. Sze, *J. Appl. Phys.* **40**, 5392 (1969).
- [14] R. Van Overstraeten and H. De Man, *Solid State Electron.* **13**, 583 (1970).
- [15] H. Niwa, J. Suda, and T. Kimoto, *IEEE Trans. Electron Devices* **62**, 3326 (2015).
- [16] H. Tanaka, T. Kimoto, and N. Mori, *Mater. Sci. Semicond. Process.* **173**, 108126 (2024).
- [17] H. Tanaka, T. Kimoto, and N. Mori, *Appl. Phys. Express* **13**, 041006 (2020).
- [18] L. Esaki and R. Tsu, *IBM J. Res. Dev.* **14**, 61 (1970).
- [19] C. Canali, G. Ottaviani, and A. Alberigi Quaranta, *J. Phys. Chem. Solids* **32**, 1707 (1971).
- [20] T. H. Windhorn, T. J. Roth, L. M. Zinkiewicz, O. L. Gaddy, and G. E. Stillman, *Appl. Phys. Lett.* **40**, 513 (1982).

- [21] B. J. Baliga, *Fundamentals of Power Semiconductor Devices* (Springer, 2nd edition, 2019).
- [22] T. Kimoto and Y. Yonezawa, *Mater. Sci. Semicond. Process.* **78**, 43 (2018).
- [23] D. K. Schroder, *Semiconductor Material and Device Characterization* (John Wiley & Sons, 3rd edition, 2006).
- [24] W. E. Spear, *Proc. Phys. Soc. B* **70**, 669 (1957).
- [25] D. D. Tang, F. F. Fang, M. Scheuermann, and T. C. Chen, *Appl. Phys. Lett.* **49**, 1540 (1986).
- [26] R. K. Ahrenkiel, D. J. Dunlavy, D. Greenberg, J. Schlupmann, H. C. Hamaker, and H. F. MacMillan, *Appl. Phys. Lett.* **51**, 776 (1987).
- [27] J. R. Lowney and H. S. Bennett, *J. Appl. Phys.* **69**, 7102 (1991).
- [28] O. Gunawan, S. R. Pae, D. M. Bishop, Y. Virgus, J. H. Noh, N. J. Jeon, Y. S. Lee, X. Shao, T. Todorov, D. B. Mitzi, and B. Shin, *Nature* **575**, 151 (2019).

List of Publications

A. Original Papers (Peer Reviewed)

1. R. Ishikawa, M. Hara, H. Tanaka, M. Kaneko and T. Kimoto,
“Electron mobility along $\langle 0001 \rangle$ and $\langle 1\bar{1}00 \rangle$ directions in 4H-SiC over a wide range of donor concentration and temperature,”
Applied Physics Express **14**, 061005 (2021).
2. R. Ishikawa, H. Tanaka, M. Kaneko, and T. Kimoto,
“Experimental and Theoretical Study on Anisotropic Electron Mobility in 4H-SiC,”
Physica Status Solidi B **260**, 2300275 (2023).
3. R. Ishikawa, H. Tanaka, M. Kaneko, and T. Kimoto,
“Origin of hole mobility anisotropy in 4H-SiC,”
Journal of Applied Physics **135**, 075704 (2024).
4. R. Ishikawa, H. Tanaka, M. Kaneko, and T. Kimoto,
“High-field anisotropic electron transport in 4H-SiC,”
in preparation.

B. Conference Proceedings (Peer Reviewed)

1. T. Kimoto, M. Kaneko, K. Tachiki, K. Ito, R. Ishikawa, X. Chi, D. Stefanakis, T. Kobayashi, and H. Tanaka,
“Physics and Innovative Technologies in SiC Power Devices,”
Technical Digest of 67th IEEE International Electron Devices Meeting, 36-1-1 – 36-1-4 (2021).
2. R. Ishikawa, M. Kaneko, and T. Kimoto,
“Estimation of Electron Drift Mobility along the c -Axis in 4H-SiC by Using Vertical Schottky Barrier Diodes,”
Solid State Phenomena **360**, 205 (2024).

C. International Conferences (Peer Reviewed)

1. R. Ishikawa, M. Hara, M. Kaneko, and T. Kimoto,
“High electron mobility along the *c*-axis in 4H-SiC,”
2020 International Conference on Solid State Devices and Materials,
Virtual, Sep. (2020), Oral, D-4-02.
2. R. Ishikawa, M. Hara, H. Tanaka, M. Kaneko, and T. Kimoto,
“Anisotropy of electron mobility in 4H-SiC over wide ranges of donor concentration and temperature,”
European Conference on Silicon Carbide and Related Materials 2020/2021,
Tours (France)/Virtual, Oct. (2021), Oral, Tu-4B.
3. T. Kimoto, M. Kaneko, K. Tachiki, K. Ito, R. Ishikawa, X. Chi, D. Stefanakis, T. Kobayashi, and H. Tanaka,
“Physics and Innovative Technologies in SiC Power Devices” (invited),
67th IEEE International Electron Devices Meeting,
Virtual, Dec. (2021), Oral, 36-1.
4. R. Ishikawa, H. Tanaka, M. Kaneko, and T. Kimoto,
“Anisotropy of hole mobility in 4H-SiC over wide ranges of acceptor concentration and temperature,”
International Conference on Silicon Carbide and Related Materials 2022,
Davos (Switzerland), Sep. (2022), Oral, Fr-2-A.3.
5. R. Ishikawa, H. Tanaka, M. Kaneko, and T. Kimoto,
“Anisotropic Electron and Hole Mobilities in 4H-SiC Bulk Crystals,”
65th Electronic Materials Conference,
Santa Barbara (USA), June (2023), Oral, S01. **[Selected as a finalist for the EMC Oral Presentation Award]**
6. T. Kimoto, H. Niwa, X. Chi, M. Hara, R. Ishikawa, H. Tanaka, and M. Kaneko,
“High-Field Phenomena in SiC Material and Devices” (invited),
Symposium on Silicon Carbide as Quantum-Classical Platform,
Erlangen (Germany), Sep. (2023), Oral, 4-1.
7. R. Ishikawa, M. Kaneko, and T. Kimoto,
“Estimation of electron drift mobility along the *c*-axis in 4H-SiC by using vertical Schottky barrier diodes,”
International Conference on Silicon Carbide and Related Materials 2023,
Sorrento (Italy), Sep. (2023), Poster, We.C.2.

8. R. Ishikawa, M. Kaneko, and T. Kimoto,
“Low-field and high-field anisotropic electron transport in 4H-SiC,”
International Conference on Silicon Carbide and Related Materials 2024,
Raleigh (USA), Sep. (2024), Oral, 21A.
9. T. Kimoto, R. Ishikawa, X. Chi, K. Mikami, K. Tachiki, and M. Kaneko,
“Impacts of Anisotropic Material Properties on Performance of SiC Power Devices”
(invited), *Pacific Rim Meeting on Electrochemical and Solid State Science 2024*,
Honolulu (USA), Oct. (2024), Oral, G03-2294.