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Kyoto University
Anisotropy in breakdown field of 4H–SiC

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The breakdown fields along the (1120) and (0338) directions in 4H–SiC have been measured. For the measurements, epitaxial p + n diodes with mesa structures were fabricated on the (1120) and (0338) faces, and they showed good rectification properties and avalanche breakdown. The breakdown fields along these directions calculated from the breakdown voltage were found to be about three quarters of that along the (0001) direction in 4H–SiC. The cause of the anisotropy in breakdown field is discussed. © 2002 American Institute of Physics. [DOI: 10.1063/1.1477271]

Silicon carbide (SiC) is one of the most promising semiconductor materials for power devices, owing to its superior electrical and thermal properties. In particular, breakdown field and impact ionization coefficients are the most important material properties in designing power devices. The breakdown fields1–3 as well as the impact ionization coefficients4,5 along the (0001) direction in both 6H– and 4H–SiC have been reported, and it was found that the impact ionization coefficient of holes along the (0001) direction is much larger than that of electrons, as contrasted with most of other common semiconductor materials. It was also reported that the breakdown field in 6H–SiC shows strong anisotropy:1 the breakdown field along the direction perpendicular to the (0001) direction is about two thirds of that along the (0001) direction. However, the anisotropy of breakdown field in 4H–SiC, a more attractive polytype for power devices, has not been reported. Recently, it was suggested that the use of other faces than (0001) in 4H–SiC, namely (1120) (Ref. 6) and (0338) (Ref. 7), may improve the performance of metal–oxide–semiconductor devices, and the breakdown fields along the directions perpendicular to these faces have emerged as critical issues. Even in 4H–SiC devices on off-axis (0001), the anisotropy in the breakdown field is an important property to design device structures, because the electric field distribution is always three-dimensional. In this letter, the breakdown fields along these directions are measured.

To measure the breakdown field, epitaxial p + n diodes were fabricated. By employing a mesa structure, we can assume parallel-plane breakdown, when the mesa is high enough for the depletion region not to reach the bottom of mesa. The substrates used in this work were heavily doped (more than 10^18 cm^-3) n-type 4H–SiC (0001) faces inclined by 8° toward (1120), and on-axis (1120) and (0338) faces. The epilayers were grown simultaneously in a horizontal cold-wall chemical vapor deposition reactor using SiH4 and C2H6 as source gases and H2 as a carrier gas. Nitrogen and trimethylaluminum were used as doping sources for n and p layers, respectively. The designed doping concentration for the n layer and the mesa height are summarized in Table I. The diameter of mesa was 60 or 100 µm. The p + layer actually consists of two parts: the first layer (adjacent to the n-layer) is a 1.3 µm-thick anode layer with an acceptor concentration of about 1×10^18 cm^-3, and the second layer is a 0.4 µm-thick contact layer, in which the acceptor concentration is much higher than the anode, in order to reduce the contact resistance. The mesa structure was formed by reactive ion etching using CF4 and O2, and then passivated by thermal oxides grown at 1150 °C for 1 h in a wet ambient and annealed at the same temperature for 30 min in an argon ambient. Ohmic contacts for the substrates and p + contact layers were nickel and titanium covered with aluminum, respectively, sintered at 800 °C for 10 min in an argon ambient.

The growth condition for the designed doping concentration was determined for 4H–SiC (0001), and the mesa height was designed to be larger than the maximum depletion width calculated from the breakdown field along 4H–SiC (0001) previously suggested by another group.4 In general, more nitrogen atoms are incorporated into other faces than (0001),9 which should not cause a premature breakdown at the bottom of mesa; because the higher the donor concentration is, the thinner the maximum depletion width is. However, an attention has to be paid to the fact that less aluminum atoms are incorporated into other faces than (0001).9 From the growth conditions,9 the acceptor concentrations in the p anodes are estimated to be 1×10^18 cm^-3, 5×10^17 cm^-3, and 7.5×10^17 cm^-3 for (0001), (1120), and (0338), respectively, which are not much higher than the donor concentrations.

For an abrupt but not one-sided p–n junction, the acceptor concentration in the p layer, Np, is not much higher than the donor concentration in the n layer, Nd. The depletion region extends to both of the n and p layers. Hence, from

<table>
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<th>Structure</th>
<th>Np (cm^-3)</th>
<th>h (µm)</th>
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<tr>
<td>1</td>
<td>1×10^16</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>1×10^17</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4×10^17</td>
<td>10</td>
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Table I. The designed donor concentration and device parameter of the n layer of fabricated diodes. The donor concentration is designed for 4H–SiC (0001).
capacitance–voltage \((C–V)\) measurements, the “reduced donor concentration” \(N_B\) is obtained, as \(N_d\) is for an one-sided \(p^n\) junction. \(N_B\) is expressed as \(N_d(N_a+N_d)^{-1}\), and approaches \(N_d\) when \(N_d\) is much higher than \(N_a\). The maximum electric field at breakdown, which we define the breakdown field, is given as \(\sqrt{2e(V_d^2+|V_B|)}N_B\varepsilon_{\text{SiC}}^{-1}\), where \(e\), \(\varepsilon_{\text{SiC}}\), and \(V_B\) are the magnitude of electronic charge, the permittivity of SiC, and the breakdown voltage, respectively. \(V_d\) is the built-in potential, to which we applied the value obtained from the \(C–V\) measurements.

The breakdown measurements were done with a protective resistance (100 kΩ) in series, and by applying a step voltage with a step width of 416 µs, which is short enough to be considered as a pulse operation. The breakdown voltage is defined as the intercept on the voltage axis of the line extrapolated from the region where the reverse current linearly increases with increasing reverse voltage.

Figure 1 shows the typical electrical properties of the diodes fabricated on 4H–SiC (1120) and (0338). The diodes show good rectification properties. The specific on resistances \(R_{\text{on}}\) were below 10 mΩ cm\(^2\), implying that parasitic resistances are negligible in determining the breakdown voltage. For (0338), the onset of breakdown is rather gentle and seems like soft breakdown. This may be attributed to relatively poor crystallinity of (0338) wafers currently available. The breakdown voltages for both (1120) and (0338) clearly increase with increasing temperature, suggesting avalanche breakdown. The calculated breakdown field also showed positive temperature coefficients of \(6 \times 10^2\) and \(4 \times 10^2\) V/cm K for (1120) and (0338), respectively. The diodes with structures 1 and 2 simultaneously fabricated on (0001) did not show reasonable breakdown voltages because the donor concentrations were accidentally so low as to extend the depletion layers beyond the bottom of mesa. However, the diodes with structure 3 agreed well with the breakdown field previously reported,\(^3,4\) and showed positive but smaller temperature coefficients (\(2 \times 10^2\) V/cm K).

Figure 2 shows the breakdown fields at room temperature along 4H–SiC (1120) and (0338) obtained in this work, and that along 4H–SiC (0001) suggested by literatures.\(^3–5\) The breakdown fields along 4H–SiC (1120) and (0338) were found to be about three quarters of that along 4H–SiC (0001) reported.\(^3,4\)

For 6H–SiC, it was reported\(^1\) that the breakdown field along \(\langle0001\rangle\) is larger than that along the direction perpendicular to \(\langle0001\rangle\), because the impact ionization coefficient of electrons along \(\langle0001\rangle\) is much smaller than that along the perpendicular direction, while those of holes are not very different. Similarly, the larger breakdown field along \(\langle0001\rangle\) in 4H–SiC should be attributed to the smaller impact ionization coefficient of electrons only along \(\langle0001\rangle\), explained as follows. In 4H–SiC and many other common polytypes of SiC except for 3C–SiC, the conduction band is split into minibands within the first Brillouin zone only along the \(\langle0001\rangle\) direction.\(^10\) The conduction band splitting comes from the long period along \(\langle0001\rangle\) just like splitting in phonon dispersion curve,\(^11,12\) but far stronger interactions between electron waves cause much wider splitting between the minibands. Assuming sinusoidal potential by the long period and the same potential from core electrons as in 3C–SiC, one-dimensional Schrödinger’s equation has been solved to estimate the miniband structure.\(^11\) The conduction band splitting between the first and second minibands in 4H–SiC along \(\langle0001\rangle\) was estimated\(^13\) to be about 1 eV as shown in Fig. 3, which is large enough to assume very few electrons in the higher miniband at thermal equilibrium. In addition, the conduction band splitting is large enough to neglect the Zener tunneling\(^14,15\) of electrons between the first and second minibands under a strong electric field.\(^16\) The splitting in the conduction band also prohibits the electrons in the first miniband to have enough energy to cause impact ionization: in the case of 4H–SiC, electrons in the first miniband can be accelerated to at most 1 eV along \(\langle0001\rangle\).\(^13\) Scattering into higher minibands by either phonons, crystal imperfections, or electrons themselves, is required for the electrons in the first miniband to be accelerated to cause impact ionization, when the electrons can be accelerated only along the \(\langle0001\rangle\) direction. Because the phonon energy is 120 meV or below,\(^12\) many scattering processes (not along \(\langle0001\rangle\)) have to occur.
in a very short period. Scattering by electrons themselves has been neglected in other materials due to its small probability. Therefore, the impact ionization by electrons along \( \langle 0001 \rangle \) is greatly suppressed. If the ionization coefficient of electrons along a direction is small, the breakdown field along the direction should be consequently large.

The conduction band splitting is not present along the directions perpendicular to \( \langle 0001 \rangle \) as shown in Fig. 3, and thus the breakdown field along \( \langle 0001 \rangle \) should be larger than those along \( \langle 1120 \rangle \) and \( \langle 0110 \rangle \). For an intermediate direction, the breakdown field should probably take an intermediate value between those along the \( \langle 0001 \rangle \) direction and along the direction perpendicular to \( \langle 0001 \rangle \), for example, \( \langle 0338 \rangle \) is between \( \langle 0001 \rangle \) and \( \langle 0110 \rangle \). However, as shown in Fig. 2, the breakdown fields along \( \langle 0338 \rangle \) and \( \langle 1120 \rangle \) are almost the same. This is possibly attributed to the lower breakdown field along \( \langle 0110 \rangle \) than along \( \langle 1120 \rangle \) (not confirmed yet).

In summary, the breakdown fields along the \( \langle 1120 \rangle \) and \( \langle 0338 \rangle \) directions in 4H–SiC have been measured using epitaxial \( p^+n \) diodes with mesa structures. They showed good rectification properties and avalanche breakdown. The breakdown fields along these directions calculated from the breakdown voltage were found to be about three quarters of that along the \( \langle 0001 \rangle \) direction in 4H–SiC. The cause of the anisotropy in the breakdown field can be explained by the split of the conduction band only along the \( \langle 0001 \rangle \) direction.

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\[16\] Assuming a triangular potential barrier with 1 eV in height, the barrier width under 1 MV/cm of electric field is 100 Å, which is large enough to neglect tunneling of electrons through the potential barrier.