Low-Loss, High-Voltage 6H-SiC Epitaxial p-i-n Diode

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***Abstract*—The p-i-n diodes were fabricated using 31-μm thick n^- – and p-type 6H-SiC epilayers grown by horizontal cold-wall chemical vapor deposition (CVD) with nitrogen and aluminum doping, respectively. The diode exhibited a very high breakdown voltage of 4.2 kV with a low on-resistance of 4.6 mΩcm^2. This on-resistance is lower (by a factor of five) than that of a Si p-i-n diode with a similar breakdown voltage. The leakage current density was substantially lower even at high temperatures. The fabricated SiC p-i-n diode showed fast switching with a turn-off time of 0.18 μs at 300 K. The carrier lifetime was estimated to be 0.64 μs at 300 K, and more than 5.20 μs at 500 K. Various characteristics of SiC p-i-n diodes which have an advantage of lower power dissipation owing to conductivity modulation were investigated.**

***Index Terms*—Minority carrier lifetime, on-resistance, p-i-n diode, power device, SiC.**

I. Introduction

SILICON CARBIDE (SiC) is a IV–IV semiconductor and possesses many outstanding properties, such as wide bandgap, high breakdown electric field strength (approximately one order of magnitude higher than Si), high thermal conductivity, high saturation drift velocity, high thermal stability, and chemical inertness. These properties are attractive for high-power, high-frequency, and high-temperature applications [1].

Owing to its high electric field strength, the layer thickness of the active base region of SiC power devices can be thinner (by a factor of ten) than that of Si devices with a similar breakdown voltage. Moreover, the doping level in the SiC layer can be made higher, roughly by two orders of magnitude than that in Si, because the depletion layer width changes inversely with the square root of the doping concentration. In the on-state of power devices, the base layer produces a series resistance called *on-resistance* which leads to power loss. Therefore, owing to the thinner base region and higher doping level, a greatly reduced on-resistance (by two and one-half orders of magnitude) can be realized with SiC compared to Si.

Considering demands for power devices such as low loss and high switching speed, majority carrier (unipolar) devices are strongly required. However, the on-resistance of Si majority carrier devices becomes very large for 200 V or higher voltage ratings, while for SiC, a smaller on-resistance can be realized, as described above.

To realize high-voltage power devices, high-purity and thick layers are needed. In the last few years, there has been significant progress made in the quality of SiC wafer and epitaxial growth technology. Through recent efforts on SiC device development, high-performance SiC unipolar devices such as Schottky diodes with a breakdown voltage of 2.0 kV and an on-resistance of 5 mΩcm^2 [2] have been reported. Whereas, above 3 kV, even SiC unipolar devices will have a large on-resistance. In this rating, bipolar devices can realize a higher breakdown voltage with a lower on-resistance than unipolar devices owing to conductivity modulation. So far, several high-voltage SiC p-i-n diodes with a breakdown voltage up to 6.2 kV have been reported [3]–[9]. However, such advantages of SiC bipolar devices have not been fully investigated. In this paper, the authors report on high-performance and high-voltage ($>$3 kV) 6H-SiC epitaxial p-i-n diodes.

II. Diode Fabrication

6H-SiC epitaxial p-i-n diodes were fabricated on $p^+/p/n^-/n$ homoepitaxial layers grown on highly doped (5×10^{18} cm^{-3}) n-type substrates. Epitaxial growth was performed by atmospheric-pressure chemical vapor deposition (CVD) in a SiH_4-C_3H_8 -H_2 system at 1500 °C for 11 h [10] in our group. In order to prevent the depletion region from expanding to the substrate, nitrogen-doped double n-layers for field stopping were grown. The net donor concentration and thickness of the first layer were designed to be 6×10^{16} cm^{-3} and 1.8 μm, and the second layer 2×10^{16} cm^{-3} and 0.8 μm, respectively. The aluminum acceptor concentration and thickness of the p-layer were designed to be 1×10^{18} cm^{-3} and 1.2 μm thick, and the p^+-layer 1×10^{20} cm^{-3} and 0.2 μm, respectively. From the capacitance–voltage ($C-V$) measurements of the diodes, the net donor concentration of n^--layer and the built-in voltage were estimated to be 1×10^{15} cm^{-3} and 2.68 V, respectively. The measured built-in voltage was in good agreement with the theoretical value (2.61 V) calculated from the Fermi-level difference between p- and n^--layers. The thickness of n^--layer was determined to be 31 μm by scanning electron microscope (SEM) observation.

Mesa structures with different areas (60 $\sim$ 1200 μm in diameter) were formed by reactive ion etching (RIE) to a depth of about 12 μm using $CF_4 + O_2$ gases with an Al/Ni mask. The surface was passivated with 15-nm thick thermal oxides grown by dry oxidation at 1100 °C for 6 h. Al/Ti and Ni were evaporated as ohmic contacts onto the top p^+-layers and the back-side

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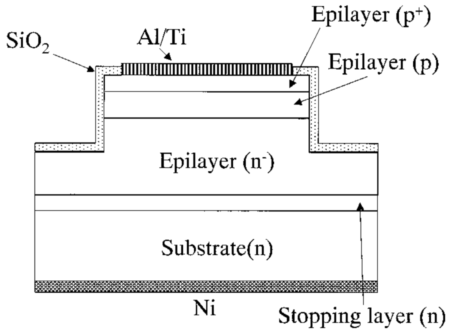

Fig. 1. Schematic view of SiC p-i-n diode.

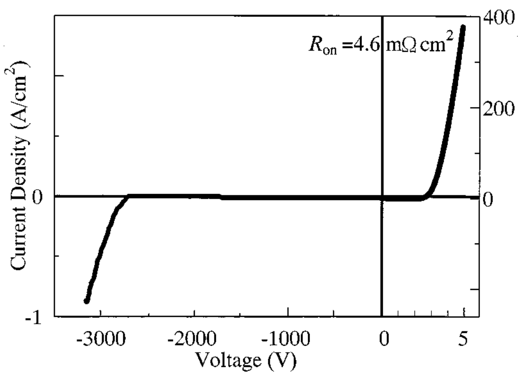

Fig. 2. Linear $J-V$ characteristics of SiC p-i-n diode at room temperature.

n-type substrates, respectively, and were annealed at 800 °C in Ar to improve contact resistance and adhesion. A schematic view of the diode is shown in Fig. 1.

4H-SiC p-i-n diodes were also fabricated in the same process. They showed a relatively high performance, but were inferior to 6H-SiC diodes, e.g., they had a lower breakdown voltage and higher on-resistance (6H-SiC: 4.2 kV, 4.6 mΩcm^2; 4H-SiC: 3.2 kV, 7.9 mΩcm^2). Therefore, only 6H-SiC diodes are discussed in this paper. 6H-SiC has disadvantages of lower electron mobility and higher substrate resistance, especially in the $\langle 0001 \rangle$ direction, compared to 4H-SiC. However, the minority carrier lifetime is usually longer in 6H-SiC than in 4H-SiC [5], which may compensate the low electron mobility in 6H-SiC for bipolar-type power device applications. Furthermore, the quality and size of 6H-SiC are still more advanced in spite of recent efforts in bulk growth of 4H-SiC.

III. Results and Discussion

Fig. 2 represents the linear current density–voltage ($J-V$) plot by a curve tracer for a 100 μm diameter diode at room temperature. The forward voltage drop at a current density of 100 A/cm^2 was 3.75 V, in spite of the large built-in voltage of SiC p-n junction. In the high-current region, the forward conduction is governed by a series resistance as low as 4.6 mΩcm^2. More than 45% of this resistance is ascribed to the substrate resistance. The low on-resistance indicates that the conductivity of n$^-$-layer is significantly modulated by minority carrier injection. The on-resistance decreases with decreasing the size of diodes because of an anisotropy in electron mobility which has an effect on current spreading. Due to the smaller mobility in the $\langle 0001 \rangle$ direction, the region where current flows becomes gradually large. Thus, the smaller diode is leading to estimation of smaller on-resistance. A metal resistance with a thin anode contact is also a cause of this phenomenon, and larger diodes are influenced by the metal resistance while current spreading in metal.

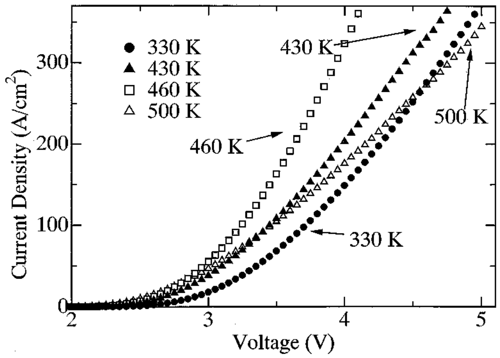

Fig. 3. Linear forward $J-V$ characteristics of SiC p-i-n diode at different temperatures.

Most diodes showed a sharp increase in reverse current at a breakdown voltage, which corresponds to the onset of avalanche breakdown. The diode did not show destructive breakdown up to a high reverse current density of 0.88 A/cm^2 at a high voltage of 3.2 kV. This means that the diode can withstand at least a high peak power density of 2.8 kW/cm^2. The smaller diodes tend to achieve a higher breakdown voltage, probably owing to the lower possibility of containing defects. Some large diodes exhibited a high breakdown voltage such as 2.6 kV for a 1200 μm diameter diode and 3.2 kV for a 800 μm diameter diode.

Due to the limitation of measurement range of curve tracer, a high-voltage dc supply was used to measure blocking voltages above 3.2 kV. A small (200 μm in diameter) diode achieved the highest breakdown voltage of 4.2 kV. This value is about 70% of the theoretical value, which may be attributed to the lack of proper junction termination, resulting in the electric field crowding at the corners of mesa structure. To achieve a nearly ideal value, junction termination extension (JTE) by utilizing ion implantation [8] is required.

The present SiC p-i-n diode exhibited a high breakdown voltage of 4.2 kV with a low on-resistance of 4.6 mΩcm^2, showing a better performance than the theoretical value of SiC unipolar devices (80 mΩcm^2) with a similar breakdown voltage, owing to the effective conductivity modulation. Moreover, compared to a Si p-i-n diode with a similar breakdown voltage, a low on-resistance by a factor of five was obtained. The forward voltage drop of 3.75 V and the low on-resistance, which are important factors in a practical on-state, are low or similar compared to those of previously reported p-i-n diodes with similar breakdown voltages (100 A/cm^2 at $\sim$6 V, 140 mΩcm^2) [4], (100 A/cm^2 at 4.2 V, 4.1 mΩcm^2) [9].

The linear forward $J-V$ plots for a 100 μm diameter diode at different temperatures are shown in Fig. 3. The turn-on voltage decreases slightly with the increase of temperature, because the built-in potential becomes lower at higher temperatures due to the decrease of bandgap. The on-resistance becomes smaller at temperatures from 300 K (4.6 mΩcm^2) to 460 K (2.7 mΩcm^2). This result may be attributed to the increased minority carrier lifetime and thereby the longer diffusion length at high temperatures which brings more effective conductivity modulation,

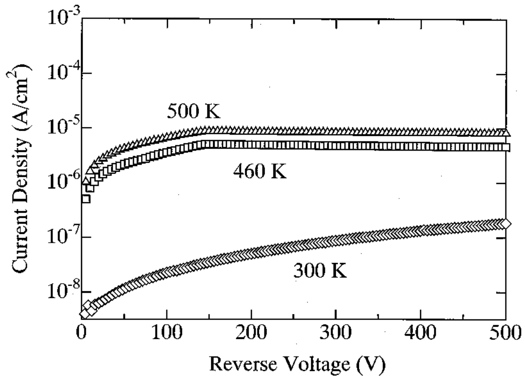

Fig. 4. Semi-logarithmic reverse $J-V$ characteristics of SiC p-i-n diode at different temperatures.

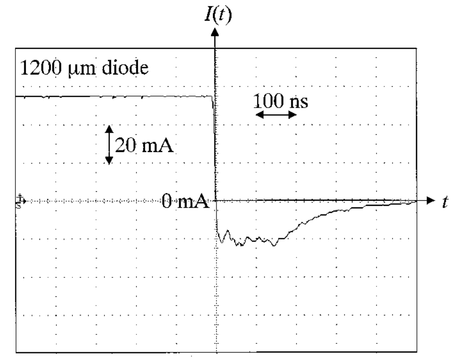

Fig. 5. Typical turn-off switching waveform for 1200 μm diameter SiC diode at 300 K.

as confirmed later. The reduced contact resistance at high temperatures might also contribute to this phenomenon. At 500 K, however, the on-resistance becomes high (6.0 mΩcm^2), probably due to the increase of the substrate resistance because the electron mobility decreases and the electron concentration is almost constant in this temperature range for SiC.

The semi-logarithmic reverse $J-V$ characteristics at different temperatures are demonstrated in Fig. 4. At room temperature, a low leakage current density of 1.8×10^{-7} A/cm^2 was obtained at 500 V. Even up to a high voltage of 1 kV, the leakage current was 5.8×10^{-7} A/cm^2. With the increase of temperature, the leakage current increases slightly. However, at 500 K, the leakage current was still low, 8.1×10^{-6} A/cm^2 at 500 V. This is very attractive for low-loss, high-power applications at a high operating temperature.

In order to determine the minority carrier lifetime, a turn-off switching characteristic was investigated. In a turn-off switching waveform of p-i-n diodes, a storage time of τ_s was observed, due to carrier storage in the lightly doped n$^-$-layer. The effective carrier lifetime τ_p is given as follows [11]:

$$\tau_p = \frac{\tau_s}{\left\{\mathrm{erf}^{-1}\left(1+\frac{1}{\frac{I_r}{I_f}}\right)\right\}^2}. \quad (1)$$

Here, I_r and I_f are the reverse current during storage time and the forward on-state current, respectively, and erf is the error function.

A typical turn-off switching waveform for a 1200 μm diameter diode is illustrated in Fig. 5. The diodes were switched from the on-state with a forward bias voltage of 5 V ($I_f = 5$ A/cm^2) to the off-state with a reverse bias voltage of -1 V ($I_r = -3.5$ A/cm^2). In the on-state, the concentration of injected minority carriers p_n can be estimated by using [11]

$$p_n = p_{n0}\exp\left(\frac{qV}{kT}\right) \quad (2)$$

where

- p_{n0} equilibrium hole concentration in the n$^-$-side;
- q electric charge;
- V bias voltage at the p-n junction;
- k Boltzmann constant;
- T temperature.

In the on-state with a forward bias voltage of 5 V, the diodes are under high-level injection, because the injected minority carrier concentration is well above the majority carrier concentration in the n$^-$-side of the junction ($p_n > 10^{19}$ cm^{-3} $\gg$ equilibrium electron concentration $\sim 10^{13}$ cm^{-3}). Therefore, the obtained carrier lifetime is an ambipolar lifetime. The effective carrier lifetime τ_p was determined to be 0.4 μs calculated from the storage time of 0.18 μs at 300 K. Also, at 500 K, τ_p of 5.2 μs was obtained from τ_s of 1.0 μs.

Since recombination occurs at a perimeter as well as the bulk of a diode, the effective (measured) carrier lifetime can be given by [12]

$$\frac{1}{\tau_p} = \frac{1}{\tau} + s_p\frac{P}{A} \quad (3)$$

where

- τ intrinsic carrier lifetime determined by bulk recombination;
- s_p surface recombination velocity;
- P perimeter length;
- A diode area.

The P/A ratio dependence of the inverse of effective carrier lifetimes ($1/\tau_p$) at 300 K and 500 K is shown in Fig. 6. The clear P/A ratio dependence reveals that perimeter recombination is dominant. From the intercept of the plot, the intrinsic carrier lifetime was estimated to be 0.64 μs at 300 K. For an accurate determination of the minority carrier lifetime, the intrinsic carrier lifetime was calculated with the different ratios of I_r/I_f by changing the forward bias voltage. The deviation in the values was less than 10%. At 500 K, a long intrinsic carrier lifetime of 11.0 μs was obtained. More careful investigation is required to determine the accurate lifetime, because the smaller slope of the plot at 500 K brings a larger error in the estimation. It can be said, however, that the intrinsic carrier lifetime is longer than the effective carrier lifetime of 5.2 μs at 500 K at least.

The intrinsic carrier lifetime significantly increases with the increase of temperature suggesting that the carriers occupying traps are released as the temperature rises [13]. From the intrinsic carrier lifetime, the diffusion length L can be given by

$$L = \sqrt{D\tau} \quad (4)$$

where D is the ambipolar diffusion constant (2.02 cm^{2}s^{-1}) [14] calculated from the Einstein relationship [15], electron mobility, and hole mobility (80 cm^2/Vs) [16]. Using this equation, the diffusion length at 300 K was calculated to be 11 μm which is one-third of the n$^-$-layer thickness. The extremely important phenomenon of p-i-n diode, called conductivity modula-

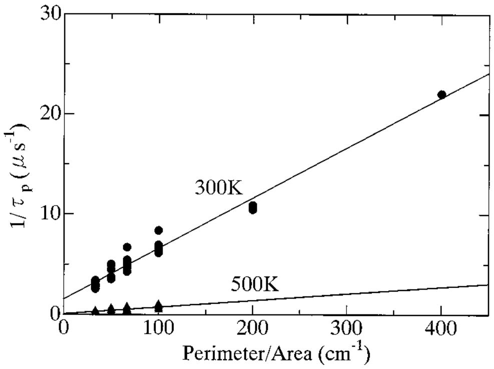

Fig. 6. P/A ratio dependence of $1/\tau_{\rm P}$ for SiC p-i-n diodes.

tion, is that the concentration of injected minority carriers becomes much greater than the background doping level, resulting in a large decrease in the on-resistance. When the diffusion length is half of the n^{-}-layer, the conductivity of the layer is most effectively modulated [17]. Thus, with the present diffusion length, the low on-resistance was realized.

One-tenth thinner SiC n^{-}-base layer thickness to support the same blocking voltage as the Si counterpart indicates roughly the one-tenth less amount of the stored minority carriers, leading to much faster switching speed, and much smaller switching loss of SiC bipolar power devices, compared to Si devices. Although, an introduction of proper recombination centers is required to control the switching speed for Si bipolar devices, fast switching speed can be realized without such lifetime control in SiC bipolar devices.

IV. Conclusion

High-purity and thick SiC epilayers have enabled us to fabricate a high-performance 4.2 kV p-i-n diode. The on-resistance was 4.6 mΩcm^2, and about 45% of this resistance was produced by the resistance of the substrate. A forward current density of 100 A/cm^2 was obtained at 3.75 V. At 500 V, the leakage current density were 1.8×10^{-7} A/cm^2 at 300 K, and 8.1×10^{-6} A/cm^2 at 500 K. For a 1200 μm diameter diode, a fast switching time of 0.18 μs was realized without lifetime control. The minority carrier lifetime was estimated to be 0.64 μs at 300 K, and more than 5.2 μs at 500 K.

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