Supplementary Materials: Promise and Challenges of High-Voltage SiC Bipolar Power Devices

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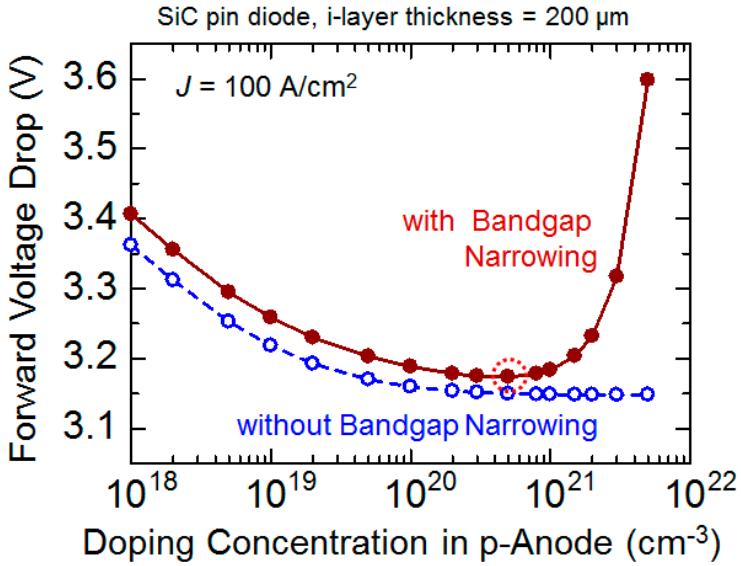

Figure S1. Forward voltage drop at 100 A/cm^2 vs. doping concentration in the p-anode simulated with and without the bandgap narrowing effect in SiC pin diodes. The i-layer thickness is 200 μm. The optimum doping concentration can be determined as 5×10^{20} cm^{-3}, taking account of the bandgap narrowing effect.

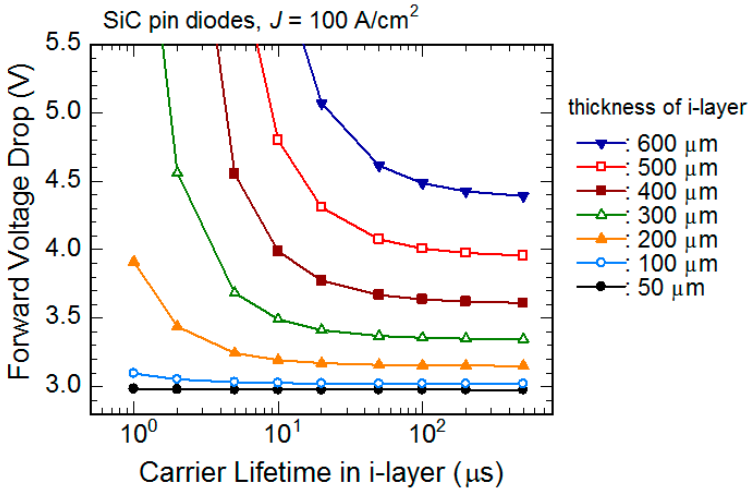

Figure S2. Forward voltage drop at 100 A/cm^2 vs. carrier lifetime in the i-layer simulated for SiC pin diodes having different i-layer thicknesses. In each case, the forward voltage drop shows saturation when the carrier lifetime is long enough. The saturated voltage drop significantly increases with increasing the i-layer thickness.

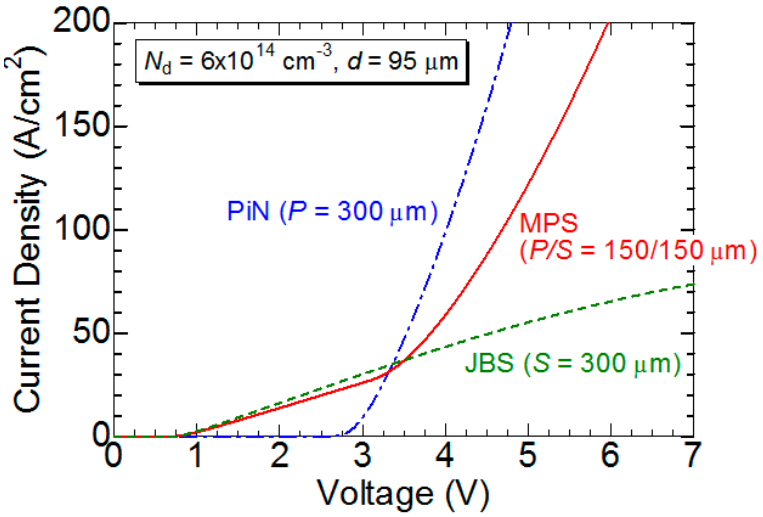

Figure S3. Forward characteristics of the epitaxial MPS diode, pure pin diode, and pure JBS diode fabricated in this study. The proposed MPS diode exhibited a lower voltage drop than the pin diode at low current density and did than the JBS diode at high current density.

Note for Figure S1:

Analytical expressions for the current-voltage characteristics of a pin diode

An analytical expression for the current-voltage characteristics of a pin diode, actually the voltage-current characteristics as a function of carrier lifetime, is described below (References [13,28] in the manuscript):

The forward voltage drop of a PiN diode (V_F) is given by the sum of the junction voltage (V_j) and the voltage drop in the i-layer (V_i):

$$V_F = V_j + V_i \tag{S1}$$

The junction voltage (V_j) is the sum of that at the p$^+$-anode/i-layer and that at the n$^+$-cathode/i-layer junctions, and is given by the following equation, taking account of carrier injection and recombination in the anode and cathode regions.

$$V_j = \frac{2kT}{q}\ln\left[\frac{2\sqrt{\eta}}{1+\eta}\times\left\{\frac{w/2L_a}{\tanh(w/2L_a)}\right\}\times\frac{\langle p\rangle}{n_i}\right] \tag{S2}$$

where n_i is the intrinsic carrier concentration, q the elementary charge, k the Boltzmann constant, T the absolute temperature, respectively. L_a and w are the ambipolar diffusion length and the i-layer thickness, respectively. η is the ratio of the carrier concentration in the i-layer near the p$^+$-anode boundary and that near the n$^+$-cathode boundary. <p> is the mean carrier concentration inside the i-layer, which is given by

$$\langle p\rangle = \left(\frac{2\tau J}{qw}\right)\times\left\{1+\sqrt{1+\frac{2H\tau J}{qD_a\tanh^2(w/2L_a)}}\right\}^{-1} \tag{S3}$$

here, τ is the carrier lifetime and D_a is the ambipolar diffusion constant. The diffusion constants can be calculated from mobility values by using the Einstein relation. H is the normalized emitter parameter, which can be expressed by

$$H = 2\frac{\eta^2 h_p + h_n}{(\eta+1)^2} \tag{S4}$$

where h_p and h_n are the emitter parameters at the p^+-anode/i-layer and that at the n^+-cathode/i-layer junctions, respectively [28].

The voltage drop in the i-layer (V_i) is approximately expressed by the following equation.

$$V_i = \frac{w^2}{2(\mu_n + \mu_p)\tau}\left\{1 + \sqrt{1 + \frac{2H\tau J}{qD_a \tanh^2(w/2L_a)}}\right\} \quad \text{(S5)}$$

here, μ_n and μ_p are the electron and hole mobilities, respectively. By combining these equations, one can calculate the forward voltage drop (V_F) as a function of current density (J).

In the equation shown above, the carrier injection efficiencies at the p/i and n/i junctions are taken into account, but the injection-level dependence of SRH lifetime are not considered. By using these equations, one can roughly calculate the current-voltage characteristics of pin diodes if the diode structure and basic material properties such as mobilities are given.

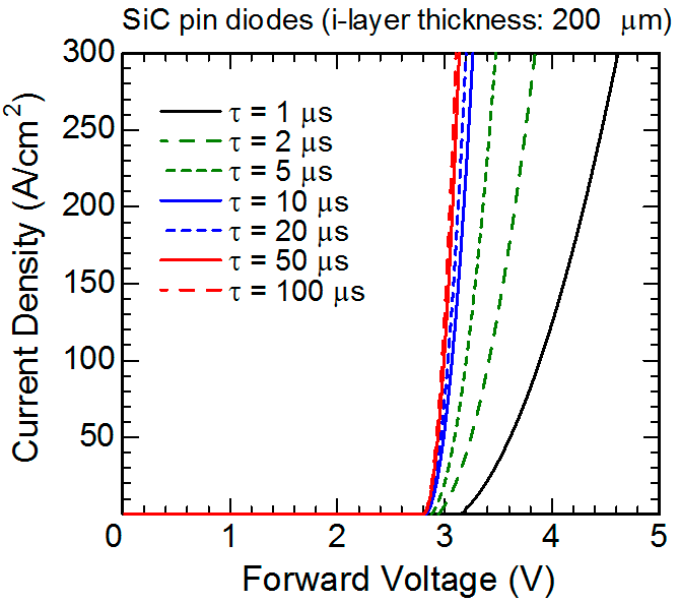

Figure S4. Forward characteristics of SiC pin diodes having an i-layer thickness of 200 μm (28 kV class). The carrier lifetime in the i-layer was changed from 1 μs to 100 μs.

Figure shown above depicts the forward characteristics of SiC pin diodes having an i-layer thickness of 200 μm (28 kV class). The carrier lifetime in the i-layer was changed from 1 μs to 100 μs. The diode structure and the range of carrier lifetime considered are the same as those for Figure 3, and thus it is of interest to compare the above result with Figure 3. The present analytical approach is less accurate than the device simulation, because it is assumed that the mobilities and ambipolar diffusion length are constant inside the thick i-layer (In the device simulation, these parameters are dependent on the location, taking account of their dependence on the carrier concentration). Furthermore, the conductivity modulation of the i-layer is simplified in the analytical approach. Nevertheless, the characteristics obtained by the analytical approach show relatively good agreement with those obtained by the device simulation. Thus, the analytical approach is useful when a quick analysis or rough optimization of a device structure is required.