12.9 kV SiC PiN diodes with low on-state drops and high carrier lifetimes

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Abstract. Sharp avalanche breakdown voltages of 12.9 kV are measured on PiN rectifiers fabricated on 100 µm thick, 3 x 10^{14} cm^{-3} doped n- epilayers grown on n+ 4H-SiC substrates. This equates to 129 V/µm. Optimized epilayer, device design and processing of the SiC PiN rectifiers result in a > 60% blocking yield at 10 kV, ultra-low on-state voltage drop and differential on-resistance of 3.75 V and 3.3 mΩ-cm^2 at 100 A/cm^2 respectively. Open circuit voltage decay (OCVD) measured carrier lifetimes in the range of 2-4 µs are obtained at room temperature, which increase to 14 µs at 225 °C. Excellent stability of the forward bias characteristics within 10 mV is observed for a long-term forward biasing of the PiN rectifiers at 100 A/cm^2. A PiN rectifier module consisting of five parallel large area 6.4 mm x 6.4 mm 10 kV PiN rectifiers is connected as a free-wheeling diode with a Si IGBT and 1100 V/100 A switching transients are recorded. Data on the current sharing capability of the PiN rectifiers is also presented.

Introduction

At 10 kV -20 kV voltage ratings, 4H-SiC PiN rectifiers offer the best trade-off between on-state voltage drop, switching losses and high-temperature performance as compared to Si PiN and SiC Schottky/JBS rectifiers. Optimized 2.4 mm x 2.4 mm (active area = 0.79 mm^2) and large-area 6.4 mm x 6.4 mm (active area = 25 mm^2) were designed and fabricated at GeneSiC with 10 kV – 13 kV blocking voltage capabilities. A detailed investigation of the on-wafer and packaged forward bias, blocking voltage, switching, carrier lifetime and long-term forward bias stability of these PiN rectifiers is presented in this paper.

Device Design and Fabrication

SiC PiN rectifiers with 2.4 mm x 2.4 mm chip size (active area = 0.79 mm^2) were fabricated on 100 µm thick, 3 x 10^{14} cm^{-3} doped n- 4H-SiC epilayers. Large-area 6.4 mm x 6.4 mm (active area = 25 mm^2) PiN rectifiers were fabricated on 90-95 µm thick, 7-9 x 10^{14} cm^{-3} doped n- 4H-SiC epilayers. The epilayer growth was performed on 4° off-axis SiC substrates. The p+ emitter layers were 1.5 µm thick and doped to 1 x 10^{19} cm^{-3}. Optimized edge termination for the PiN rectifiers was provided by a combination of negative beveled mesa etching and p-type ion-implantation followed by high-temperature annealing for implant activation. Ohmic contacts to the p+ Anode and n+ Cathode layers was formed by Al-based and Ni- based metallization. Thick Al overlayers were deposited on the top and a solderable Au-based metallization was provided on the bottom for die-attaching to Cu baseplates. After on-wafer testing, selected die were assembled in custom-designed packages for detailed high-current, switching and long-term measurements.

On-state and blocking voltage characteristics

Blocking voltage yields in excess of 56% at 10 kV (leakage current limit = 39 µA) can be noted from histograms and a wafer map of blocking voltages (see Figure 1) measured on a 3" SiC wafer populated with 0.79 mm^2 PiN diodes. A sharp onset of avalanche breakdown at 12.9 kV can be clearly observed from representative reverse I-V characteristics measured on a couple of

packaged 0.79 mm^2 rectifiers (see Figure 2a). The achievement of 12.9 kV blocking voltages corresponds to record-high 129 V/µm and ≈ 90% of the avalanche breakdown limit for the 100 µm thick n- epilayers used for device fabrication. On-state voltage drops as low as 3.75 V at 100 A/cm^2 and differential specific on-resistance as low as 3.3 mΩ-cm^2 are extracted from on-state I-V characteristics (Figure 2b) of packaged 0.79 mm^2 PiN rectifiers indicating a high-level of conductivity modulation of the n-base layer. A negative differential co-efficient of on-state voltage drop is also observed from Figure 2(b), which is due to the reduction of knee voltage at higher temperatures.

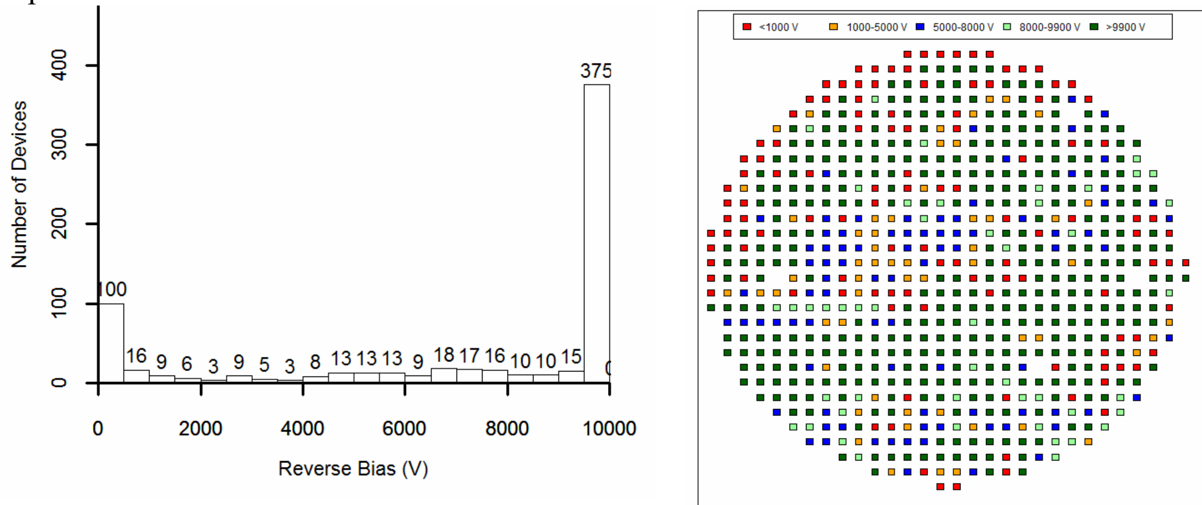

Figure 1: (Left, a) Histogram and (Right, b) Wafer Map of blocking voltages measured on a 3” SiC wafer populated with 0.79 mm^2 PiN rectifiers under a leakage current threshold of 39 µA.

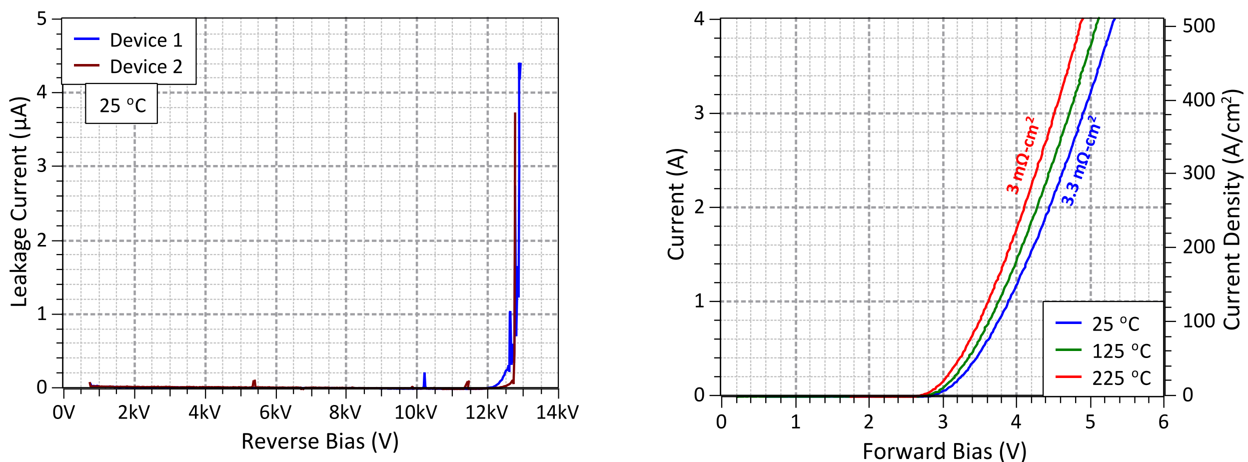

Figure 2: (Left, a) Reverse I-V characteristics and (Right, b) Forward I-V characteristics measured on representative 0.79 mm^2 PiN rectifiers fabricated on 100 µm thick n- SiC epilayers.

High-current, on-state characteristics measured on a representative 25 mm^2 PiN rectifier and a module consisting of five, 25 mm^2 PiN rectifiers connected in parallel are shown in Figure 3. A slightly higher differential on-resistance of 5.75 mΩ-cm^2 is extracted from the I-V characteristics measured on the 25 mm^2 rectifier as compared to 3.3 mΩ-cm^2 reported for the 0.79 mm^2 rectifier. This extra resistance may be due to either (A) Higher n-base doping concentration on the wafers used for fabricating the 25 mm^2 rectifier resulting in lower emitter injection efficiency and/or (B) metal spreading resistance on the large-area rectifiers.

Carrier Lifetime measurements

Open circuit voltage decay (OCVD) measurements were performed on packaged 0.79 mm^2 and 25 mm^2 PiN rectifiers to extract the high-level carrier lifetime (t_{HL}) in the thick n-base layer at

various temperatures. Voltage decay waveforms measured on representative 25 mm^2 PiN rectifiers are shown in Figure 4(a). A record-high room-temperature carrier lifetime of 4 µs is extracted from the slope of the linear portion of the voltage decay transients, which surpasses the 3.7 µs carrier lifetime reported by Ivanov et al. [1] on 10 kV SiC PiN diodes. The carrier lifetime increases to 14 µs at 225 °C (Figure 4(b)). A carrier lifetime of 4 µs at 25 °C corresponds to a large ambipolar diffusion length, $L_a = (D_a t_{HL})^{1/2}$ = 48 µm. L_a remains relatively constant with temperature, since the increase in carrier lifetime at higher temperatures is countered by a corresponding decrease in carrier mobilities. The temperature dependence of the carrier mobilities was calculated using the procedure detailed in [2] and [3]. The high values of L_a relative to the n- base thickness is the reason for the high level of observed conductivity modulation in the base layer, as evidenced by the low differential on-resistance obtained from the I-V characteristics shown in Figure 2 and Figure 3.

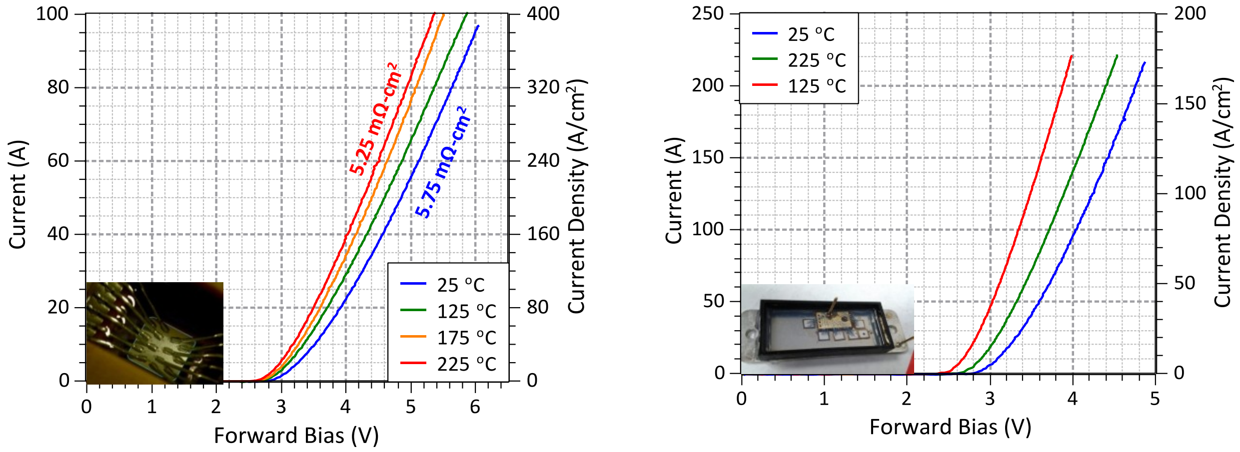

Figure 3: High-current forward bias characteristics measured on (Left, a) A packaged 25 mm^2 PiN rectifier and (Right, b) Five 25 mm^2 PiN rectifiers co-packaged in parallel. Photographs of the discrete and the multi-device diode module are shown as insets in the respective graphs.

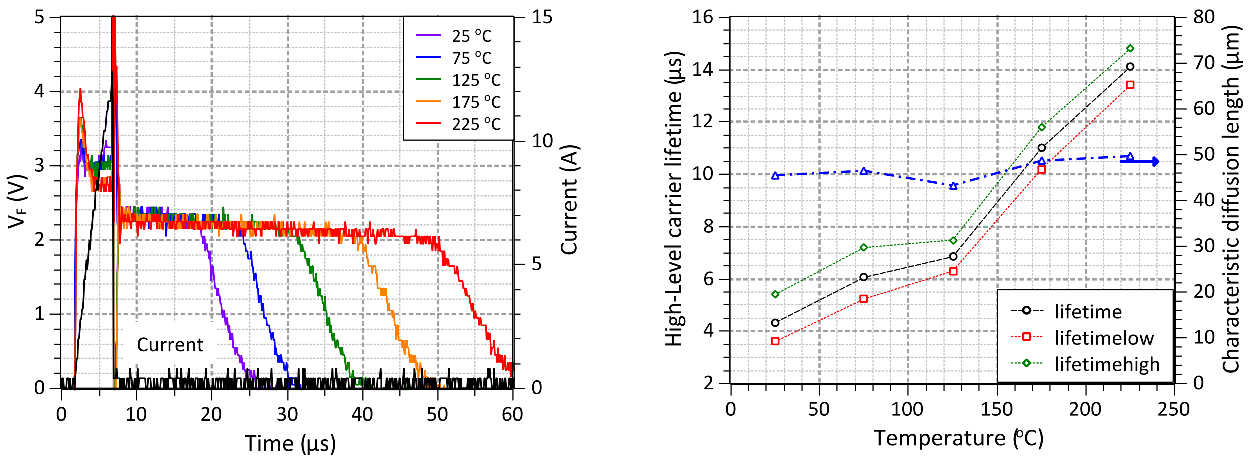

Figure 4: (Left, a) OCVD Forward Current and Voltage transients measured at different temperatures on a packaged 25 mm^2 PiN rectifier and (Right, b) Extracted high-level carrier lifetime and characteristic diffusion length as a function of temperature. The error bars correspond to the uncertainty in extracting the slope of the linear portion of the voltage decay transients.

Switching characteristics

A module consisting of five parallel-connected 25 mm^2 SiC PiN rectifiers was connected as free-wheeling diode (FWD) with a 1200 V/300 A Si IGBT to evaluate the high-current switching performance of the SiC PiN rectifiers at different temperatures. The well-known double-pulse technique was used to switch 1100 V and 100 A through the Si IGBT/SiC PiN rectifier module at a FWD turn-off dI/dt of 432 A/µs at temperatures up to 225 °C. The current and voltage transients measured during the free-wheeling diode turn-off are shown in Figure 5(a). Due to a positive temperature co-efficient for the injected carrier lifetime in the n-base, the peak reverse recovery

current (I_{rr}) is observed to increase from – 48 A at 25 °C to -120 A at 225 °C, while the reverse recovery time (t_{rr}) increases from 168 ns at 25 °C to 528 ns at 225 °C (see Figure 5(b)).

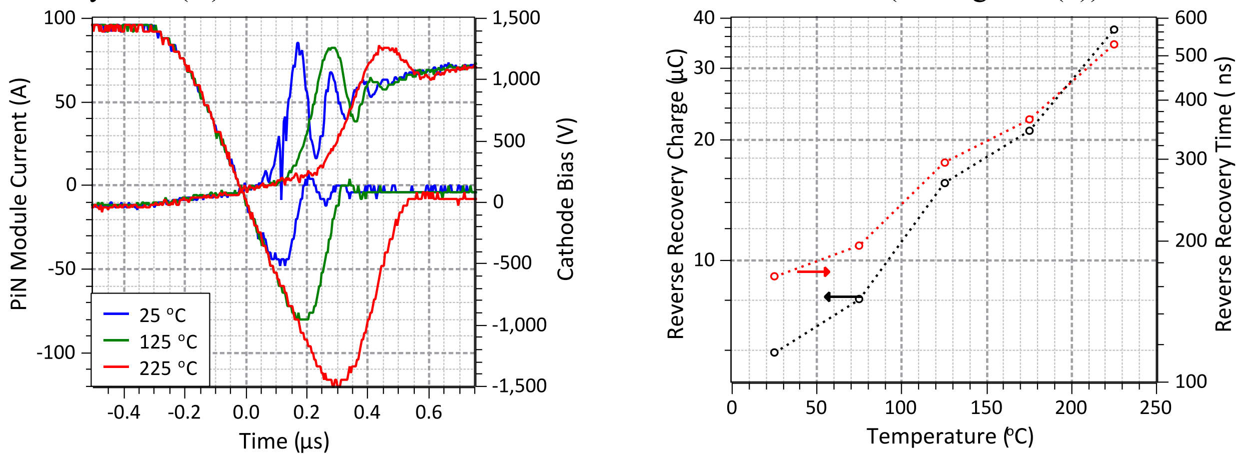

Figure 5: (Left, a) Voltage and Current transients measured during FWD turn-off of a 1200 V/300 A Si IGBT connected in anti-parallel with a PiN rectifier module consisting of five 25 mm^2 PiN rectifiers connected in parallel. (Right, b) Reverse Recovery current and Reverse Recovery Charge extracted from the turn-off current transients at different temperatures.

Long-term Stability of on-state characteristics

As seen in Figure 6(a), the voltage drop across a packaged 0.79 mm^2 PiN rectifier is remarkably stable (within 10 mV) under a constant 100 A/cm^2 DC bias, indicating that the SiC epilayers and process used for fabricating these PiN rectifiers is free from bipolar degradation. The current sharing capability of the PiN rectifiers was investigated by passing a DC current of 30 A through two parallel connected 25 mm^2 PiN rectifiers mounted on a common heat sink for 90 min. As seen in Figure 6(b), the current is unequally shared as ≈ 17.2 A through the PiN rectifier with the lower Von and ≈ 12.6 A through the PiN rectifier with the slightly higher Von. Initially, the PiN rectifier with the lower specific on-resistance draws increasingly more current, due to the negative temperature co-efficient of Von. The currents through the rectifiers stabilize after ≈ 30 min into the test due to the thermal coupling between the paralleled diodes.

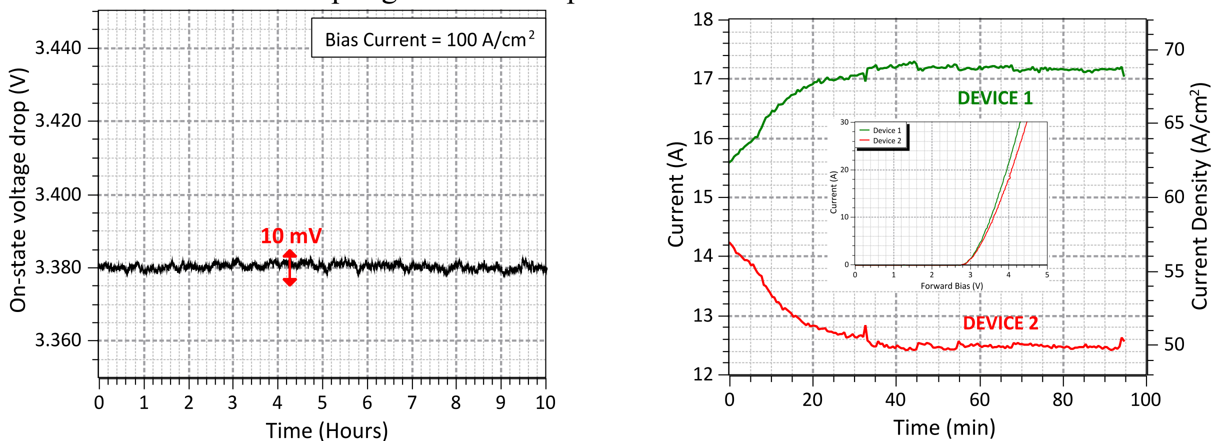

Figure 6 (Left, a) Time evolution of Von under a constant DC bias of 100 A/cm^2 (0.8 A) applied to a 0.79 mm^2 PiN rectifier (Right, b) Current sharing between two 25 mm^2 PiN rectifiers with the forward I-V characteristics of the individual PiN rectifiers shown as an inset in the graph.

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