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Unifying Concepts for Ion-Induced Leakage Current Degradation in Silicon Carbide Schottky Power Diodes

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Abstract— The onset of ion-induced reverse leakage current in SiC Schottky diodes is shown to depend on material properties, ion LET, and bias during irradiation, but not the voltage rating of the parts. This is demonstrated experimentally for devices from multiple manufacturers with voltage ratings from 600 V to 1700 V. Using a device with a higher breakdown voltage than required in the application does not provide increased robustness related to leakage current degradation, compared to using a device with a lower voltage rating.

Index Terms—Schottky diodes, Silicon carbide, single-event effects, vertical MOSFET

I. INTRODUCTION

SILICON carbide (SiC) has favorable material properties for high-power applications. It has an inherently higher thermal conductivity and breakdown field relative to silicon. These characteristics allow for device designs with higher current ratings, lower on-state resistance, and higher breakdown voltages for a given die size compared to silicon device equivalents [1].

However, SiC power diodes and metal oxide semiconductor field-effect transistors (MOSFETs) have been shown to be susceptible to both heavy-ion leakage current degradation (defined as increases in leakage current owing to ion strikes), with damage occurring at biases as low as 20% of

their rated breakdown voltage [2], [3]. This degradation has been characterized as two voltage controlled current sources in series which are together in parallel with a pristine Schottky structure [4]. Single-event burnout (SEB) has also been observed in SiC diodes using pulsed-lasers [5] and high energy protons have been shown to induce both SEB [6] and breakdown due to displacement damage [7]. Both SiC diodes and MOSFETs may experience SEB in the presence of high-energy neutrons [8], [9]. Single event leakage current degradation is also a problem in Schottky diodes in silicon [10] and gallium nitride (GaN) [11], [12] when exposed to heavy-ions.

This paper develops a model for single-event induced leakage current in SiC Schottky and junction-barrier Schottky (JBS) power diodes based on earlier work by Kuboyama *et al.* [13]. The model is used to explain new experimental data from this work and two other experiments, involving four different SiC Schottky diodes and three manufacturers, with three different voltage ratings. Results show the onset of degradation depends only on SiC material properties, LET, and irradiation bias and does not depend on rated breakdown voltage (Fig. 1). The model predicts that using diodes with higher breakdown voltage (greater epitaxial depth or lower epitaxial doping density) provides no benefit for preventing degradation compared to using a part with a lower breakdown voltage.

II. EXPERIMENTAL DETAILS

A. New Experiment

Two different Wolfspeed SiC JBS power diodes were tested. One of the devices is the 4th generation CPW-1200-S020B bare die and C4D020120A packaged version, which have a 1200 V blocking voltage and are rated for 20 A maximum current. The second device is the 5th generation CPW5-1700-Z050B bare die packaged in TO-3 cans without lids. This second device has a 1700 V blocking voltage and is rated for 50 A maximum current. Both diodes are made of 4H SiC with an epitaxial layer approximately 10 μm thick (1200 V device) or 14 μm thick (1700 V device).

1) C4D020120A and CPW-1200-S020B

Heavy ion testing was conducted at the Texas A&M University Cyclotron facility. Each device was characterized before and after each heavy-ion irradiation run by generating a reverse-bias current-voltage (IV) sweep using an Agilent B1505A parameter analyzer. The IV sweeps were run from an

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unbiased state to the power compliance of the parameter analyzer, typically 35% greater than the rated 1200 V for initial tests before irradiation. Each irradiation consisted of a total fluence of 10,000 ions/cm² using a flux of approximately 100 ions/(s*cm²). The device current was monitored and recorded during each experiment.

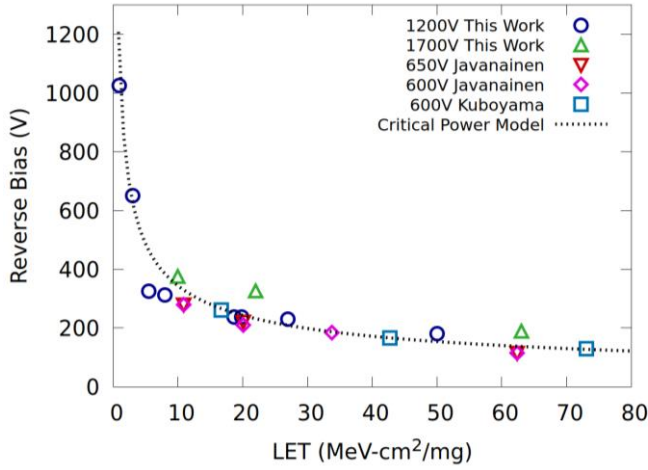


Fig. 1. Average observed reverse bias voltage thresholds for onset of heavy-ion-induced leakage current degradation in SiC JBS and Schottky diodes at various heavy ion LETs in silicon. New data from the experiments described here are included, as well as data from work done by Kuboyama et al. [13] and Javanainen et al. [14].

2) CPW51700Z050B

Heavy ion testing was conducted at the Lawrence Berkeley National Laboratory (LBNL) in vacuum. Each device was characterized before and after each heavy-ion irradiation run by generating a reverse-bias IV sweep using a Keithley 2410 source meter. These tests were run from zero bias to the power compliance of the source meter or to 1100 V if power compliance was not reached. Each run consisted of a total fluence of 10,000 ions/cm² using a flux of approximately 100 ions/(s*cm²). The device current was monitored and recorded during each experiment.

B. Experimental Results

Initial experiments determined the relationship between ion LET and reverse bias for the onset of leakage current degradation. After establishing a lower boundary for degradation events, devices were biased above this boundary but below the experimentally-observed threshold for SEB for these devices.

Fig. 2 shows a typical example of degradation of leakage current due to heavy-ion exposure. Degradation consisted of discrete increases in leakage current of varying magnitude as previously reported in [13], [14]. At a given bias, the average increase in leakage current with respect to total fluence converged to a constant value as total fluence per run increased. This observation held true regardless of the amount of prior degradation in the device.

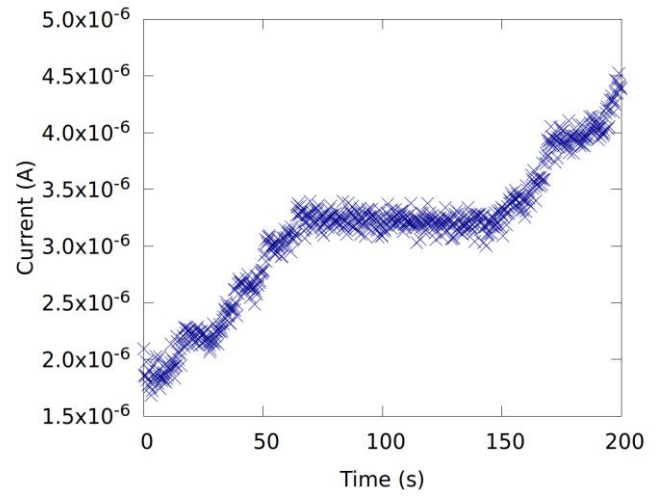


Fig. 2. Example strip chart showing discrete increases in leakage current increases over time for a single device during irradiation. This data was taken from a test run of a 1200V Wolfspeed part.

C. Comparison to Existing Data

TABLE I

SILICON CARBIDE SCHOTTKY DIODE DEVICE PROPERTIES

Part Number	Mfr.	Rated Breakdown	Epitaxial Depth
CPW5-1700-Z050B This work	Wolfspeed	1700 V	14 μm
C4D020120A This work	Wolfspeed	1200 V	10 μm
STSPSC10H065DY Ref. [14]	STMicro	650 V	6 μm
STPSC1006D Ref. [14]	STMicro	600 V	6 μm
SDP06S60 Ref. [13]	Infineon	600 V	3.7 μm

Fig. 1 shows leakage current degradation thresholds using our new data (see Section IIA and IIB) and data presented in Kuboyama et al. [13] and Javanainen et al. [14]. This figure plots the average between the lowest irradiation bias at which measurable degradation occurs and the highest irradiation bias at which no measurable degradation is observed vs. ion LET. For the data obtained from Kuboyama et al. [13] and Javanainen et al. [14], the average values are estimated from plots. Due to this, there are no meaningful error bars that can be applied equally to the entire data set. Each point represents a single device, as the data is used in a linear regression further in the paper to determine the parameters of the critical power model as it is plotted both in Fig. 1 and Fig. 3. The devices measured vary in breakdown voltages, epitaxial depths, and epitaxial doping, yet fall along the same curve for the threshold of leakage degradation, indicating that these properties do not determine the onset of degradation. Table I gives the device type, rated breakdown voltage, and epitaxial thickness for all devices.

III. MODEL DEVELOPMENT

A. Kuboyama *et al.* Model

Kuboyama *et al.* [13] hypothesized that degradation is caused by local heating due to peak regions of power dissipation during a strike, and introduced (1) as a model for the peak power (P_p) dissipated within the device. The constant k contains the electric charge in Coulombs (q), the material density in mg/cm^3 (ρ), the ambipolar semiconductor mobility (μ) in $\text{cm}^2/(\text{V}\cdot\text{s})$, and the electron-hole pair creation energy (E_i) in eV/pair . In Kuboyama's model, the quantity X is the active layer thickness in cm and the only device parameter in the equation. The voltage V_R is the diode reverse voltage in units of volts and LET in silicon is in units of $\text{MeV}\cdot\text{cm}^2/\text{mg}$. Note that using this set of units requires a unit conversion with the LET (in $\text{MeV}\cdot\text{cm}^2/\text{mg}$) and the electron-hole pair creation energy (in eV/pair) for silicon carbide.

$$P_p[W] = V_R \cdot I_p = V_R^2 \cdot \text{LET} \cdot \frac{k}{X} \quad (1)$$

$$k = \frac{q\rho\mu}{E_i}$$

B. Application of Model

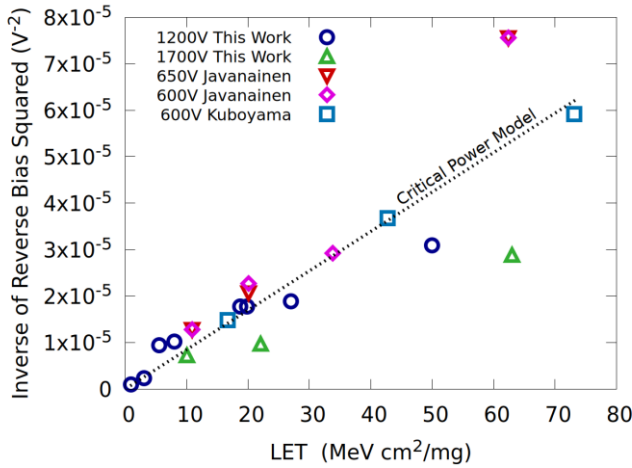


Fig. 3. Distribution of degradation onset reverse bias values for various LETs for the data presented here as well as other works [13], [14]. Fitted to this data is a linear regression of the function shown in (2) and detailed in Table II, treating the onset of degradation as crossing a critical power threshold.

Equation (1) can be used to model the critical power needed to produce measurable degradation. By rearranging (1) and identifying P_p as the critical power (P_c) needed to produce degradation, it is possible to linearize (1) with respect to LET, in the form shown here as (2). This modification can be applied to the data sets in Fig. 1. The intercept should be approximately zero for any data set if the model is an accurate representation of the mechanisms at play. The results of the regression analysis of each individual set are similar enough to justify applying the modified model to the collective data set, with the implication that the device parameters that differentiate the tested devices are not significant variables in the resulting model. This regression and the degradation data are shown in Fig. 3. Since the vertical axis is inversely related to the square of reverse bias voltage, equivalently-sized

deviations from the regression line (i.e. a 25 V difference) appear much larger at lower biases and higher LET values.

$$\frac{1}{V_R^2} = \frac{k}{P_c \cdot X} \cdot \text{LET} \quad (2)$$

TABLE II

LINEAR REGRESSION OF THE THRESHOLD LET FOR HEAVY-ION-INDUCED LEAKAGE CURRENT ON THE INVERSE SQUARE OF BIAS VOLTAGE.

Dependent Variable	LR Slope $P_c \cdot X/k$	LR Intercept (LET)	R ² Value
$1/V_R^2$	8.48×10^{-7}	9.66×10^{-7}	0.78

As shown in Fig. 3, the critical power for the onset of leakage current degradation appears to be inversely proportional to any variation in device parameters present in (1), as $P_c \cdot X/k$ is constant. Since these devices are all 4H SiC Schottky diodes and k is a constant, the implication is that $P_c \cdot X$ is also a constant. As the epitaxial depth increases, critical power has to decrease for (2) to balance at a given LET and bias. However, the data imply that there is no dependence on epitaxial depth, suggesting that the parameter, X , should be a constant value. Yet the devices all have different epitaxial depths. In the following section, these assumptions are explored using TCAD simulations to provide insight into the relationship between power dissipation and device parameter variants.

IV. TCAD SIMULATION

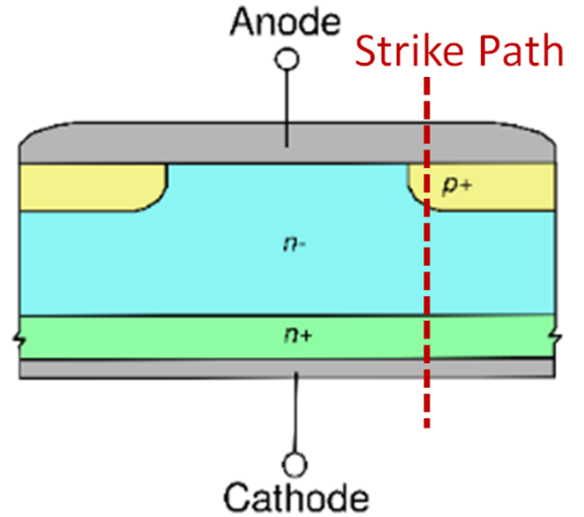


Fig. 4. Diagram showing the device structure as well as the worst-case strike path, used in the presented TCAD simulations.

2D TCAD models were developed in the Synopsys Sentaurus suite of TCAD tools [15] and used to explore the similarities of the heavy ion response between the SiC JBS Schottky diode device variants listed in Table I. Information for the 1200 V diode is primarily from published literature [16]–[19]. We have estimated the epitaxial depth and doping density from the breakdown voltage rating. Fig. 4 shows the

strike path relative to the structure of the diode, and Fig. 5 shows simulated device structure variation, with epitaxial thicknesses of 4 μm , 6 μm , and 10 μm . Heavy ion simulations were performed for an ion with LET = 10 $\text{MeV}\cdot\text{cm}^2/\text{mg}$ and the diode reverse biased at 300 V, to match one of the conditions shown in Fig. 1. The carriers generated during the ion strike create a uniform conductive path across the epitaxial region, shown in Fig. 5, resulting in a resistive shunt across the device. As presented in [19], the damage to the device has likely occurred during or immediately following (within 100 ps) the strike.

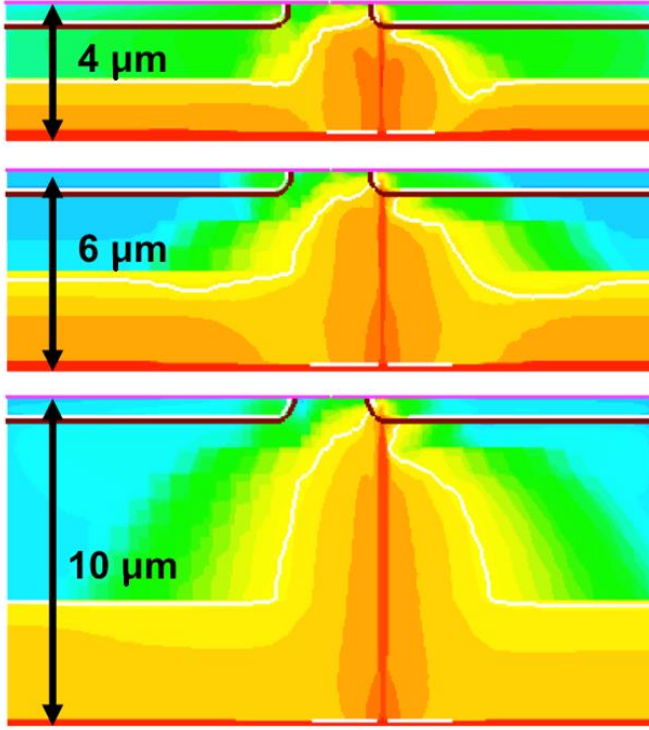


Fig. 5. TCAD simulation showing carrier density in a Schottky diode just after an ion strike, resulting in a resistive shunt through the epitaxial layer.

The power dissipation during the ion strike can be analyzed by taking 1D cut-lines along the ion track at various times following the strike. Figure 6 shows the internal electric field across the epitaxial layer for each device variant. For the pre-strike condition, the devices are reverse biased at 300 V, and the electric fields show the classic shape described by Poisson's equation, governed by the doping and epitaxial thickness. However, at 15 ps following the strike, the electric fields have been modified due to the ion-induced charge, and the shape and magnitude of each curve are identical, differing only in the location of the peak electric field, which, in each case, is at the epi/n+ junction. Further, the peak electric field at the epi/n+ junction is significantly higher than the electric field required for avalanche breakdown, generating additional carriers that can contribute to device damage [19]. As noted in Fig. 6, the regions where the electric field varies rapidly are high resistance regions along the strike path (shown as L_{FRONT} at the surface and L_{BACK} at the epi/n+ interface), and denoted as L_{ION} in [19]. The current density is high in these regions, resulting in high power dissipation. In each of the device

variants, most of the potential is dropped over the back interface, which is identical in structure for all three device variants. Due to this, the electric field distributions are similar and L_{ION} is approximately a constant value, independent of epitaxial thickness and doping.

Power density ($J\cdot\epsilon$) is a function of current density and the electric field, and is shown in Fig. 7, with the left y-axis representing power density as a function of position through the epitaxial region, and the right y-axis representing the total instantaneous power. More than 50% of the total power dissipated during the strike is in the high resistance regions described as L_{ION} , and for all three device variants, the power dissipation is identical at a given bias and particle LET.

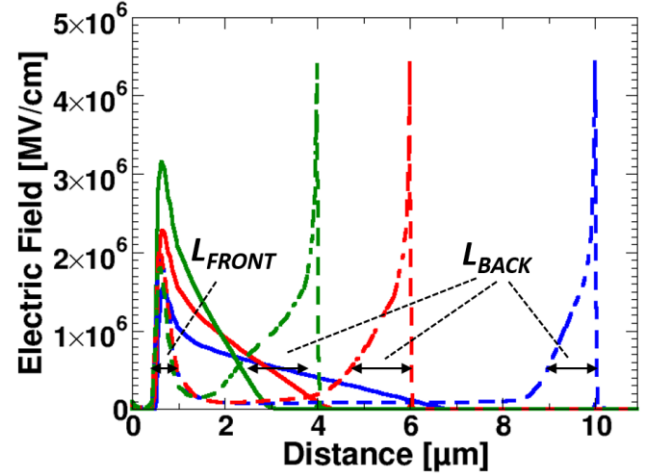


Fig. 6. Electric field as a function of distance from the surface of the SiC JBS Schottky diode to the epi/n+ interface for each of the device variants. The green lines correlate to the 4 μm device, the red to the 6 μm device, and the blue to the 10 μm device. Solid lines represent an initial condition, while dashed lines indicate the redistribution of the electric field 15 ps following the ion strike. L_{FRONT} plus L_{BACK} give L_{ION} , which is the region where the electric field gradient is high.

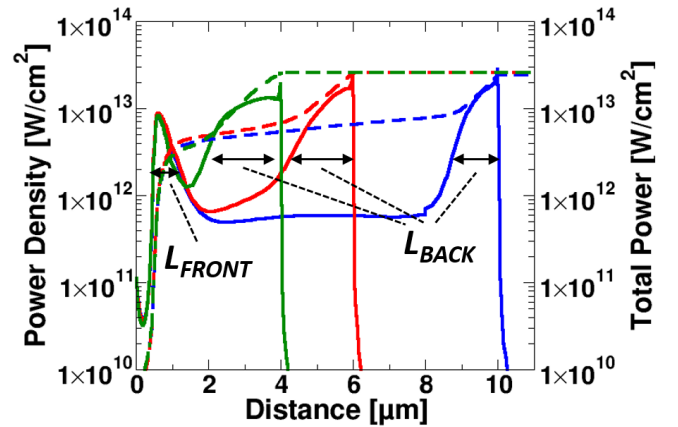


Fig. 7. Heavy ion-induced power density for the three SiC JBS Schottky diode variants, with LET = 10 $\text{MeV}\cdot\text{cm}^2/\text{mg}$ and reverse-biased at 300 V. The green lines correlate to the 4 μm device, the red to the 6 μm device, and the blue to the 10 μm device.

V. DISCUSSION

Since, as shown in Fig. 6, there is a small portion of the potential dropped in the ion track outside of L_{ION} , the power

within this region can be neglected and the bias voltage V_R across the resistive length L_{ION} can be used as an adequate approximation of P_C . By altering (2) to be in terms of resistance rather than current, the interpretations of the effects of bias voltage and ion LET are isolated. Let R_S be the total resistance of the plasma shunt that forms in the device just after the ion strike, which depends on the LET of the strike and the material properties contained within k , as shown in (3) and (4). The power dissipated within this shunt, for a specific value of R_S , is determined by the reverse bias of the device during the strike. Since most of the voltage is depleted over the length L_{BACK} and the average electric field in the shunt is highest in L_{BACK} , R_S is approximately equal to the total resistance over this length. The terms introduced are ρ_S and A_{ION} , which are the average resistivity and area of the plasma shunt.

$$P_C[W] \cong \frac{V_R^2}{R_S} = V_R^2 \cdot LET \cdot \frac{k}{L_{ION}} \quad (3)$$

$$R_S = \frac{L_{ION}}{LET \cdot k} \cong \frac{L_{BACK} \cdot \rho_S}{A_{ION}} \quad (4)$$

In Section IV, critical power for the threshold of degradation was shown to be constant for all device variants because the high-field lengths within the ion-induced resistive shunt are constant for a given bias and LET. Equation (1) can be rewritten as (3) in such a way to be generically applicable for a range of 600 V – 1700 V SiC Schottky diodes as a function of ion-induced high resistance, rather than for epitaxial thickness. In this way, the degradation threshold can be defined as a function of material properties, LET, and bias, and independent of device parameters. Therefore, there exists a critical power in the ion shunt that must be exceeded for degradation to occur.

The operating bias and LET curve for the onset of degradation shown in Fig. 1 depends exclusively on the material properties of the semiconductor used, specifically the material density, the ionization energy, and the ambipolar carrier mobility of the plasma during an ion event. As the result is independent of epitaxial depth and epitaxial doping, the model suggests that de-rating parts with higher breakdown voltage (greater epitaxial depth or lower epitaxial doping density) provides no benefit for preventing degradation compared to using a part with a lower breakdown voltage. Based on the results shown in Fig. 2, if operating in an environment where degradation must be avoided and particles with LETs below 29 MeV-cm²/mg are the only concern (a critical value known as the “iron knee” beyond which flux quickly falls off [20]), device operation limits can be obtained. The reverse voltage of 4H-SiC Schottky diodes must stay at or below approximately 180 V to avoid leakage current increases due to heavy-ions.

VI. CONCLUSIONS

A model for heavy-ion induced leakage current in SiC Schottky diodes is applied to the onset of degradation for several silicon carbide device types and rated breakdown voltages. The degradation threshold is found to be independent of device parameters, including the epitaxial

depth, epitaxial doping density, and breakdown voltage. The model suggests that an ion strike produces a resistive shunt between the cathode and anode of the device as long as the ion has sufficient range to pass through the entire epitaxial depth. De-rating based upon device blocking voltage yields no benefit when attempting to prevent any single-event induced leakage current, as the threshold for degradation is representative of the characteristics of 4H-SiC itself. The model provides a general criterion for designers of space systems to predict the bias conditions under which silicon carbide power diodes will accrue increased leakage currents due to heavy ions in space environments.

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