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**ANALYSIS OF HIGH FIELD EFFECTS ON THE STEADY-STATE CURRENT-VOLTAGE
RESPONSE OF SEMI-INSULATING 4H-SiC FOR PHOTOCONDUCTIVE SWITCH
APPLICATIONS**

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Analysis of high field effects on the steady-state current-voltage response of semi-insulating 4H-SiC for photoconductive switch applications

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A model-based analysis of the steady-state, current-voltage response of semi-insulating 4H-SiC is carried out to probe the internal mechanisms, focusing on electric field driven effects. Relevant physical processes, such as multiple defects, repulsive potential barriers to electron trapping, band-to-trap impact ionization, and field-dependent detrapping, are comprehensively included. Results of our model match the available experimental data fairly well over orders of magnitude variation in the current density. A number of important parameters are also extracted in the process through comparisons with available data. Finally, based on our analysis, the possible presence of holes in the samples can be discounted up to applied fields as high as ~ 275 kV/cm.

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I. INTRODUCTION

The physical properties of silicon carbide (SiC), such as a large bandgap (3.1–3.35 eV), high avalanche breakdown field (~ 3 MV/cm), and large thermal conductivity (4–5 W/cm K) with superior radiation hardness and resistance to chemical attack, make SiC an attractive candidate for high voltage, high temperature, and high power device applications.^{1–4} An important advantage of SiC is the ability to grow a stable thermal oxide, enabling fabrication of MOS-based device structures. Silicon carbide has a number of different polytypes, and 4H-SiC, which is a wurtzite material with a hexagonal Brillouin Zone (BZ), is favored (for example, over 6H-SiC) because of the higher and more isotropic bulk mobility. The latter translates to lower on-resistance in power devices and higher current density (J) capability.

Since the early studies by Auston,⁵ photoconductive semiconductor switches (PCSSs) have been investigated intensively for many applications owing to their unique advantages over conventional gas and mechanical switches. In particular, PCSSs are low-jitter compact alternatives to traditional gas switches in pulsed power systems.⁶ The advantages of PCSSs make them a perfect choice for many important applications where switching accuracy and high electric field (E) capability are required, such as in microwave and millimeter wave generation, impulse radar, and pulsed power systems, high-voltage pulse generation, and electron-beam pumped lasers.⁷ Though most PCSSs have been fabricated using Si or GaAs, these materials have critical intrinsic limitations for operation at high fields, high temperatures, and high radiation levels.^{8,9} Hence, there has been a great deal of interest in the development of SiC power switches.^{10,11} Besides, SiC is the only technology currently available that can achieve MegaWatt output power and MegaHertz repetition rates which are of practical interest.^{12,13} For the same breakdown voltage, the on-state

resistance of a SiC device is expected to be lower by two orders of magnitude than that for Si because smaller layer thicknesses and/or higher doping levels can be used.¹⁴ A small on-state resistance, which is a critical parameter for reduced power dissipation, not only depends on the semiconductor material used but also on the contact properties. The contact problems are exacerbated by the need for high-temperature high power operation expected of SiC devices. However, the use of n^+ -GaN subcontact current spreading layers for 4H-SiC PCSS devices has been shown¹⁵ to alleviate this potential problem.

This contribution focusses on an analysis of the steady-state, current-voltage response of semi-insulating 4H-SiC to probe the internal mechanisms and transport processes. There appears to be a relative dearth of reports in the literature pertaining to the high field electronic behavior in semi-insulating SiC devices barring a few studies,¹⁶ as compared to the well-studied GaAs material system. Furthermore, a good physical understanding of the inherent physics is essential if one hopes to predict and tailor the electrical response of SiC photoconductive switches at high fields. Internal traps and defects in the SiC devices are known to play an important role in shaping the observed J - E response.¹⁷ For instance, experimental steady-state curves obtained by our group and shown in Fig. 1 are for a set of 4H-SiC samples with Ohmic contacts deposited by sputtering 50 nm Nickel-Chrome on 10 nm Titanium. The area of the SiC samples was roughly 6.35 mm $\times$ 6.35 mm of which the contact areal dimensions were 4.826 mm $\times$ 4.826 mm. The distance between the top and bottom electrodes was 0.454 mm, with many of the other device details as discussed elsewhere.¹⁸ Some of the SiC samples (e.g., SiC1 as shown in Fig. 1) were irradiated with a high-energy electron beam (1 MeV) for 3.5 h with a total fluence of 2×10^{18} electrons/cm² to add additional deep trap states that allowed the device to be operated at high electric fields with low leakage currents.^{19,20}

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FIG. 1. The experimental J - F characteristics obtained for semi-insulating 4H-SiC photoconductive devices. Solid line is for sample SiC1, taken from a set of samples that were electron-beam irradiated, while dashed line is for sample SiC2 that was not irradiated.

The experimental J - E curves indicate a nonlinear response, with space charge limited currents^{21–23} expected to play an important part in molding the device characteristics. A cursory examination of the results of Fig. 1 reveal the following features: (a) With negligible irradiation (sample SiC2), i.e., low levels of externally created traps, the current is seen to rise quite sharply by about three orders of magnitude at relatively low electric fields around 18 kV/cm. This trend is suggestive of a Mott-Gurney like behavior,²⁴ which is generally characteristic of space-charge transport in the absence of traps. However, at moderately higher electric fields (above ~ 22 kV/cm), the J - E curve of Fig. 1 is seen to exhibit a small, yet nearly constant, slope. Due to the semi-logarithmic plot, this translates into a near exponential growth in current up to a field of about 130 kV/cm. At higher fields, a change in the slope is visible and suggests the onset of another contributory process. (b) The samples in Fig. 1 subject to irradiation (denoted by SiC1), which can be assumed to have a much higher density of internal traps, exhibit much lower currents by comparison. This is expected based on the theory of space-charge currents with electron trapping.^{21–23} However, at fields just beyond 180 kV/cm, the measured currents rise sharply, a feature that is a likely signature of trap-filled conduction. More interestingly though, current densities at much higher electric fields (i.e., values in excess of 225 kV/cm) seem to exhibit a slower rise at a nearly constant slope. This suggests an exponential-type current increase and marks the transition to another conduction regime.

Here, steady-state current conduction in semi-insulating SiC samples meant for high power photoconductive switches is probed based on a one-dimensional (1D) model. A number of relevant processes such as multiple defects, repulsive potential barriers to electron trapping, band-to-trap impact ionization, and field-dependent detrapping are evoked and included in a comprehensive model analyses. The role of the various mechanisms and their respective electric field ranges of applicability are simulated. Our numerical results agree with the data for both the irradiated and non-irradiated 4H-SiC samples.

II. MODEL ANALYSIS

An analytical theory of space-charge-limited current in high resistivity semiconductors with discrete trapping levels was discussed several years ago by Lampert *et al.*^{21–23} The term “relaxation semiconductor” has often been used to define such semiconductors for which the dielectric relaxation time can exceed the recombination lifetime. A more complete description of the current transport was based on computer modeling approaches.^{25,26} In the Mark and Lampert model, trapping of the injected carriers causes the current to remain well below the value in a trap-free insulator, until the applied voltage is high enough to inject enough excess carriers to fill the traps. At this point, called the trap-filled-limit-voltage (V_{TFL}) by Lampert, a rapid increase of current with voltage is predicted until the current reaches a value corresponding to the trap-free space-charge-limited current and varies as the square of the voltage. A number of investigations were carried out on semi-insulating materials, particularly CdS and GaAs, but as pointed out by Bube,²⁷ they have generally yielded values for trap densities, which were much lower than determined by other experimental methods. It was, therefore, suggested²⁷ that the sudden increase in current does not take place at V_{TFL} , but at a lower voltage due to contributions from impact ionization. A similar suggestion has been that impact ionization of impurities, rather than band-to-band ionization, is responsible for the observed I - V characteristics.^{28–30} Various regimes and additional processes have been identified.³¹ Experimental results by Willing and Maan in semi-insulating GaAs³² have revealed an onset of field-enhanced trapping at lower fields. Furthermore, they observed³² that the capture coefficient did not saturate at high fields, but instead decreased at high fields, thus yielding a local maxima.

We begin a simple analysis under steady-state, equilibrium conditions, based on a 1D rate equation for electrons. For one trap at low electric fields, one obtains

$$dn/dt = e_{n0}N_T^- - c_n n (N_T - N_T^-) = 0, \quad (1)$$

where n , N_T , and N_T^- are the electron, total trap, and occupied traps densities, respectively, while e_{n0} represents the electron emission rate and c_n is the electron capture cross-section. Thus, $e_{n0} = c_n n (N_T - N_T^-)/N_T^- \equiv c_n P_0$. In equilibrium, the value of $n(N_T - N_T^-)/N_T^- = N_C \exp[(E_T - E_c)/(k_B T)]$, where E_T and E_c are the energy levels of the trap and the conduction band edge, respectively, T is the temperature in Kelvin, and k_B is the Boltzmann constant. With an electric field F applied, c_n can become field-dependent and hence symbolically changes as $c_n(F) \rightarrow c_n R_C(F)$, where $R_C(F)$ represents a field-dependent ratio factor. Field-dependent enhancements of the capture coefficient are possible if the trapping process entails a repulsive potential barrier. This occurs because in such a situation, an applied external field increases the average kinetic energy of the electrons, making it easier for them to surmount the potential barrier. Alternatively, on the basis of the Lucovsky model,³³ increased quantum mechanical tunneling of electrons through the potential barrier would also increase the capture coefficients. Thus, electron capture rates could increase with field, as long as the field

magnitudes were not very large. Such electric field dependence of electron trapping is important and has been shown to lead to domain formation and current oscillations in semiconductor materials.³⁴ This was later supported by the work of Sacks and Milnes.³⁵ However, at much higher electric fields, carrier heating would cause the capture rate to decrease, since a long sequence of phonon emissions would then be required for the eventual and successful trapping of mobile electrons. Such a lowering of the capture rate at high fields has been probed in the literature^{36–39} and should lead to a maxima for the field-dependent $R_C(F)$ function. It may be mentioned in this context that such behavior would not be valid for hydrogenic traps. However, since one expects deeper defect energies in the wide bandgap SiC material, the existence of such repulsive deep levels is a possibility.

At higher fields, the simple Eq. (1) should be modified to incorporate a field-dependent factor $R_C(F)$ as: $e_{n0} N_T^- = c_n R_C(F) n (N_T - N_T^-)$. This would then yield the following expression for the occupied trap density: $N_T^- = R_C(F) n N_T / [P_0 + R_C(F) n]$. Using the expression for N_T^- in the Poisson equation leads to

$$\begin{aligned} dF/dx &= -q[n + N_T^-]/\epsilon_s \\ &= -qn\{1 + R_C(F)N_T/[P_0 + R_C(F)n]\}/\epsilon_s. \end{aligned} \quad (2a)$$

At low electric fields, $R_C(F)$ is expected to be very small due to the repulsive potential barrier for trapping, and so $dF/dx \sim -q n/\epsilon_s$ which represents a Mott-Gurney-like behavior, leaving the traps with virtually little influence on the current conduction. Such could be the case for the SiC2 sample curve (of Fig. 1) that leads to a quick current increase at low fields. For high electric-fields, $R_C(F) > I$, and one roughly gets $dF/dx = -(q n/\epsilon_s) R_C(F) N_T/[P_0 + R_C(F) n]$. So a high field (and hence strong voltage drop) would appear across the device. As a result, the J - E curve with traps would shift to higher fields (i.e., move to the right of Mott-Gurney curve) and have smaller current values. Equation (1) can easily be extended for the case of N multiple traps at different energies to yield

$$dF/dx = -qn_{i=1}^N \{1 + R_{Ci}(F)N_{Ti}/[P_{0i} + R_{Ci}(F)n]\}/\epsilon_s. \quad (2b)$$

Additionally, emission from traps can also be field-dependent. In the direction of the applied field, the potential barrier is lowered, and hence an electron requires less energy to escape from the trap. This field-assisted emission is known as the Poole-Frenkel effect,^{40,41} and the barrier decreases by an amount $\Delta\phi_{PF}$. In a simple one-dimensional treatment $\Delta\phi_{PF} = [(q^3 F)/(\pi\epsilon)]^{1/2}$. As a result, the rate of electron emission from a trap is enhanced by the field, with $e_n(F) \sim e_n(F=0) \exp[\Delta\phi_{PF}/(kT)]$. A more rigorous three-dimensional analysis of emission^{42,43} leads to the following, slightly modified expression of the emission rate: $e_{n3D}(F) \sim e_n(F=0) \{1/2 + [(\gamma - 1) \exp(\gamma) + 1]/\gamma^2\}$, where $\gamma = \Delta\phi_{PF}/(kT)$. In addition, the applied field increases the probability for trapped electrons to escape into the conduction band via both elastic and inelastic tunneling.^{44,45} Hence, high field

effects on electron emission need to be included in the rate equation analysis, especially in the context of high power devices. This is easily accomplished through the inclusion of a field dependent ratio factor, i.e., $e_n(F) \sim R_E(F) e_n(F=0)$, and leads to $N_T^- = R_C(F) n N_T/[R_E(F) P_0 + R_C(F) n]$. Hence, the spatial dependence of the electric field from Poisson's equation is

$$\begin{aligned} dF/dx &= -qn \sum_{i=1}^N \{1 + R_{Ci}(F)N_{Ti}/ \\ &\quad [R_{Ei}(F)P_{0i} + R_{Ci}(F)n]\}/\epsilon_s. \end{aligned} \quad (2c)$$

In a situation involving a defect with a repulsive potential and trap density N_{T1} , and another with an attractive potential (i.e., a shallow hydrogenic trap) at a density N_{T2} , the above is modified to

$$\begin{aligned} dF/dx &= -qn\{[1 + R_{C1}(F)N_{T1}/[R_{E1}(F)P_{01} + R_{C1}(F)n]] \\ &\quad + N_{T2}/[P_{02} + n]]\}/\epsilon_s. \end{aligned} \quad (2d)$$

The above treatment can be extended to include both attractive and repulsive traps, field-dependent emission and band-to-trap impact ionization. Algebraic manipulation leads to the following general equation for the case of a semi-insulating semiconductor with N different repulsive defects and M separate attractive traps, and trap-to-band ionization

$$\begin{aligned} dF/dx &= -(qn/\epsilon_s) \left\{ 1 + \sum_{k=1}^N c_k R_{Ci}(F) N_{Tk} / [c_k P_{k0} R_{ek}(F) \right. \\ &\quad \left. + c_k R_{Ck}(F) n + n R_{iik}(F)] \right. \\ &\quad \left. + \sum_{l=1}^M c_l N_{Tl} / [c_l P_{l0} R_{el}(F) + c_l n + n R_{iil}(F)] \right\}, \end{aligned} \quad (3)$$

where $R_{iik}(F)$ and $R_{iil}(F)$ are field dependent impact-ionization factors for electron collision-induced impact ionization from traps with a repulsive- and attractive potentials, respectively.

Here, the field dependent impact-ionization factors $R_{iip}(E)$ were taken to be a function of the local electric field. A similar approach had been used for band-to-trap processes in SiO₂,⁴⁶ another wide-bandgap material. Conceptually, the process is similar to that of electron ionization from the subbands of quantum well superlattices.⁴⁷ Strictly, computations of the threshold energy for impact-ionization require momentum and energy conservation, taking into account of the detailed bandstructure.^{48–51} However, for simplicity, the threshold values were taken to be fitting parameters. Similarly, empirical forms were assumed for the impact-ionization factors $R_{iip}(F)$ of the type $R_{iip}(F) \sim R_{0p} \exp(\alpha_p |F|)$, and values of R_{0p} and α_p extracted from comparisons to the data. A more exact approach could perhaps include details of the electron distribution function at each location (i.e., discretized position within a device) via a Monte Carlo (MC) scheme with inclusion of internal scattering processes and the bandstructure. For example, the energy-dependent ionization rates discussed by Robbins⁵² could be folded into a MC simulation.

Finally, for completeness, a brief discussion of carrier drift velocity is presented, since it influences the current density, in addition to the local electron density. For 4H-SiC material, the electron drift velocity v_{dr} was taken to be⁵³

$$v_n(F) = [\mu_{n1}|F| + \mu_{n0}|F|(|F|/F_0)^\theta + v_{sat}(|F|/F_1)^\eta] / [1 + (|F|/F_0)^\theta + (|F|/F_1)^\eta], \quad (4)$$

where $\eta = 3$, $\theta = -1.95$, $F_1 = 2.8 \times 10^7$ V/m, $F_0 = 3.05 \times 10^6$ V/m, $\mu_{n0} = 4 \times 10^{-3}$ m²/V s, and $\mu_{n1} = 0.68 \times 10^{-3}$ m²/V s.

III. RESULTS AND DISCUSSION

Simulation results were obtained for the current density J through the 4H-SiC samples as a function of the applied bias based on the theory presented in Section II. In performing the calculations, values of the current density J and electric field $F(0)$ at the cathode (as a boundary condition) were chosen and held fixed. Diffusion was neglected, so the entire current was assumed to arise from electron drift. Equation (4) was then used to obtain the spatial profile of the internal electric field for a set of chosen J , $F(0)$, and the other parameters selected for trap densities, cross-sections, field-dependent functions $R_{iip}(F)$, $R_{ci}(F)$, $R_{ek}(F)$, etc. The electron density n needed for the numerical evaluation of Eq. (3) was obtained from the chosen current density J as $n = J/[q v_n(F)]$, with Eq. (4) being used for computations of the drift velocity $v_n(F)$. Vertical contacts at the top and bottom ends on opposite surfaces at a distance of 0.454 mm were assumed in keeping with the experimental data from the samples.

Figure 2 shows results of the J - F calculations, with F being the average electric field across the device. In addition to numerical simulations, the actual experimental data for the SiC2 sample is also included. The two curves appear to be in fairly good agreement with the electric field spanning values from about 10 kV/cm to 170 kV/cm. The boundary condition for the electric field at the cathode worked out to be $|F(0)| = 0.1$ V/m. The current density J ranges over several orders of magnitude from roughly 5×10^6 A/m² to 1 A/m². The fit between the data and the simulation results was achieved by using three sets of traps in the 4H-SiC material

with densities of $N_{T1} = 4.5 \times 10^{19}$ m⁻³, $N_{T2} = 6.5 \times 10^{20}$ m⁻³, and $N_{T3} = 4.5 \times 10^{18}$ m⁻³. Of these, traps 1 and 3 were assumed to have a repulsive potential. Trap energy values derived from the comparison between simulation results and the data were 0.263 eV, 0.333 eV, and 0.383 eV, below the conduction band-edge. The low-field electron capture cross-sections for the traps were taken to be 10^{-17} m². The factor R_C was taken to have the form $[exp(a|F|) - 1]$, with $a = 8 \times 10^{-7}$ m/V, while a field dependence of $exp(b|F|)$ for R_E yielded $b \sim 8 \times 10^{-7}$ m/V as well. Values obtained for the threshold field for band-to-trap ionization for the three defect levels were 1.4×10^7 V/m, 1.65×10^7 V/m, and 1.75×10^7 V/m. For simplicity, the local field-dependent expression for the ionization factor was assumed to be $a_I exp(b_I |F|)$, and the curve fitting to the data yielded $a_I = 10^8$ and $b_I = 10^{-6}$ m/V for traps 1 and 3, and $a_I = 5 \times 10^8$ and $b_I = 10^{-6}$ m/V for trap 2.

Results obtained for the internal electric fields within the SiC2 sample are discussed next. Two different device current densities from Fig. 2 were chosen; a relatively low value of -4.54×10^{-3} A/m² (for average 50 kV/cm field) and a higher current density of -7.29×10^{-2} A/m² (at an average field of 150 kV/cm). The negative sign is simply the result of our chosen orientation with the anode at $x = 0.454$ mm and cathode at $x = 0$. The internal electric field profile is indirectly indicative of the spatial electron distribution and influenced by internal processes such as band-to-trap ionization. Going towards the anode, the electric field magnitude shown in Fig. 3 increases and reflects the decreasing free electron density with position. Electrons are injected from the left (cathode) side and gradually reduce in density towards the anode side due to capture by one of the three trap sites. The condition of a spatially constant current density $J [=n q v_n(F)]$ value in the steady-state for a given bias, requires reductions in free electron density n as the electric field magnitudes (and hence the drift velocities) increase. Furthermore, for the -4.54×10^{-3} A/m² curve in Figure 3, the slope of the electric field progressively becomes larger with distance implying a higher charge density towards the anode. The higher charge density is associated with a larger population of occupied traps. Since two repulsive defects were assumed here with their capture rates increasing with

FIG. 2. Comparison between the simulation J - F results and the experimental data for semi-insulating 4H-SiC for sample without irradiation.

FIG. 3. Calculated internal electric field profiles for the SiC2 sample at two steady-state current densities of -4.54×10^{-3} A/m² and -7.29×10^{-2} A/m².

local electric field, more of such traps would be filled by electrons towards the anode side due to the higher driving fields. Thus, for this scenario, the contribution of negative charge at the filled traps towards the anode side outweighs the smaller free electron density in this region, to yield an overall higher net charge density. This situation is representative of low levels of electron flow in a trap-filled, semi-insulating semiconductor.

At the higher current density of $-7.29 \times 10^{-2} \text{ A/m}^2$, on the other hand, the values and shape of the electric field profile are somewhat different. The electric field magnitude is again an increasing function of distance from the cathode. As before, the free electron densities are lower over regions of higher field magnitudes, since the drift velocities are higher. However, a sharp change in slope is seen at around the 150 micron location, when the electric field reaches $-1.65 \times 10^7 \text{ V/m}$. This field corresponds to the threshold for the trap-to-band impact ionization chosen in our model for trap N_{T2} which is the most populous. Beyond this spatial point, the free electron density begins to increase as trap-to-band ionization begins to contribute. Also, as shown in Fig. 3, the electric field crosses the chosen threshold for trap-to-band ionization from N_{T3} at about $220 \mu\text{m}$, for this applied bias. As a collective result, the current density in the SiC sample begins to increase dramatically at high biasing, and leads to a high sample conductance. In addition, at this high applied biasing level, the electric field profile ceases to increase extensively beyond $220 \mu\text{m}$. Upon increasing the applied bias (result not shown), the threshold for the trap-to-band ionization begins to be reached closer to the cathode and the “knee” in the spatial field distribution shifts to the left. As a result, while the electric field values below the knee increase, the spatial integral of the electric field beyond the knee has a relatively modest or incremental change. The overall result is that increases in the voltage drop across the sample at biasing are significantly slower, while the current density rises quickly. The net effect is the rapid upswing in the J - F characteristic seen in Fig. 2 beyond an average field of 130 kV/cm .

Though the simulations were in good agreement with the data (as shown in Fig. 2) and were used to extract important parameters, it must be stressed that the values obtained are not entirely unique. Due to the relatively large number of parameters involved, it would be possible to obtain slightly different sets of values that could also yield a relatively close agreement with the steady-state J - F curve for the SiC sample. A sensitivity analysis could be carried out to determine the robustness of the results and to identify the model parameters that have the most significant effect on the electrical response. However, the intent here was more to develop a comprehensive physics-based model that would include a variety of processes and mechanisms spanning a large range of electric fields. Furthermore, since a simple one-dimensional model was used, a more rigorous and accurate two-dimensional approach would probably lead to slight differences in the parameter set needed to curve fit the data.

Finally, simulations for the irradiated SiC1 sample were carried out to probe and understand the response. Current densities are expected to be much lower due to the higher

trap densities caused by the 3.5 h, 1 MeV electron irradiation. Results comparing the predictions from the simulations with experimental data are shown in Fig. 4. Four different cases were simulated, two of which used the full velocity-field characteristic of Eq. (4) denoted by $v(F)$ in the figure, and two were obtained on a simpler mobility-based, linear $v(F) = \mu F$ characteristic. Additionally, two of the four calculations shown did not include field-dependent detrapping [denoted by $R_E(F) = 1$ in Figure 4], while two remaining curves included this process [denoted by $R_E(F)$]. Figure 4 shows reasonably close agreement with the data for the SiC1 sample based on two deep trap levels having energies E_{T1} and E_{T2} of 1.07 eV and 1.09 eV, respectively, below the conduction band edge. The corresponding densities used for the calculations were $N_{T1} = N_{T2} = 2.55 \times 10^{19} \text{ m}^{-3}$. Of the four simulation results, the plot that incorporated both a field-dependent drift velocity and carrier detrapping provided the best match with the data. Use of the simpler linear drift-velocity model without any high-field saturation resulted in excessively higher currents. Using the field dependent velocity alone was also not adequate. Without inclusion of carrier detrapping, the predicted currents were much lower than the observed data.

A significant feature for the irradiated sample SiC1 is the presence of a near-constant low-level current density of around 10^{-5} A/m^2 for fields below $\sim 80 \text{ kV/cm}$. Electrically active defects are known to strongly enhance the leakage currents,⁵⁴ and it has been speculated that trap-assisted tunneling (TAT)^{55,56} can be an important transport process in such situations. TAT of electrons through a two-step process^{57,58} has previously been used to study the capture and emission times near interface traps⁵⁹ in ultrathin MOSFETs and erasable programmable read only memories,⁶⁰ and in gate dielectric stacks.⁶¹ In addition, the multi-phonon tunneling process⁶² can also be expected to be operative and contribute to the leakage current at low voltages. In the present analyses for the SiC1 sample, both elastic trap-assisted-tunneling and the multi-phonon processes were included using

FIG. 4. Comparison between the simulation J - F results and experimental data for semi-insulating 4H-SiC SiC1 sample subjected to the 1 MeV irradiation. Simulation results were obtained for different cases as discussed in the text.

the theory described in detail in one of our previous reports.⁶³ The deep levels in the irradiated sample SiC1 facilitated electronic transfers to the semiconductor via the trap states. However, for SiC2, the shallow levels meant a much larger tunneling distance would be needed, at any given electric field, for the cathode Fermi level to be energetically line up close to the trap, thereby facilitating the transition.

The present analysis shows that the main difference in the electrical response upon irradiation stems from the deep levels generated by the electron-beam bombardment. Though the trap densities for the irradiated SiC1 sample were not excessively large, a significant reduction in current over the SiC2 sample was nonetheless predicted. Furthermore, processes such as the trap-to-band ionization were insignificant and played no role in shaping the J - F characteristic for the sample with deep traps. This is understandable since much stronger electric fields would likely be required to produce the requisite high energy tail in the electron distribution function for impact ionization.

A final comment pertains to the phenomenon of double-injection and bipolar transport which have been well studied in the past.⁶⁴ These processes are known to be associated with filamentary currents, instabilities, and S-shaped negative differential characteristics.⁶⁵ However, since such detrimental effects were not observed in the SiC samples, at least up to the ~ 11.5 kV voltage range studied, the prospect of double-injection and bipolar transport would appear improbable. Physically, the latter could arise from band-to-band impact ionization. However, this would seem unlikely since the SiC bandgap is too large to facilitate band-to-band impact ionization over the range of the electric fields applied in the experiments. A more rigorous and definitive assessment though would require calculations of the electron distribution function at the fields used here for SiC either through Monte Carlo or Boltzmann schemes. The possibility of hole-injection at the anode contact, which could be an alternative route to bipolar transport, requires that barrier heights at the contacts for electrons and holes are roughly similar. In the situation of comparable barrier heights, electrons collected at the anode thermalize and exchange energy with the metallic reservoir. As a result, colder electrons in the metal contact could transition above the Fermi level by acquiring energy, and effectively create a hole for injection back into the semiconductor. However, the barrier height for electrons (ϕ_{Bn}) has been reported to be in around 0.8 eV for Ohmic contacts,⁶⁶ from which an estimate of ~ 2.5 eV can be made for the hole barrier height ϕ_{Bp} . Since these two values are quite dissimilar, hole injection at the contacts is unlikely for the SiC samples with Ohmic contacts. Nonetheless, as a simple test, forced hole injection was included into the simulations. The results (not shown) led to s-shaped negative differential J - E characteristics. Since this behavior is not observed in the experimental data, the presence of holes can be rejected.

IV. CONCLUSIONS

A model-based analysis of the steady-state, current-voltage response of semi-insulating 4H-SiC was carried out to

probe the internal mechanisms and transport phenomena. Relevant physical processes such as multiple defects, repulsive potential barriers to electron trapping, band-to-trap impact ionization, and field-dependent detrapping were evoked for comprehensive numerical analyses. The goal was to make comparisons with available experimental data obtained from SiC samples with and without exposure to electron irradiation. The focus was on understanding specific details of the observed J - E curve (e.g., variations in the slopes over different regimes), and identifying mechanisms over appropriate regimes potentially responsible for the electrical conduction.

Results of our model matched the experimental data fairly well over orders of magnitude variation in the current. A number of important parameters were also extracted in the process through comparisons with the data. The measured results were well explained with three relatively shallow defects for the non-irradiated SiC sample. However, several details such as traps with a repulsive potential, field dependent emission, and trap-to-band ionization controlled by the local electric field were necessary to adequately explain the characteristics over the entire range. For the irradiated sample, two deep traps were found to be necessary to fit the data, along with field-dependent emission. Furthermore, trap-assisted tunneling was an important process at low voltages. Also, for this case, impact ionization was shown to be insignificant, at least over the range of electric field values used in the experiments. However, this does not discount the possibility of impact ionization or even hole-generation during exposure of such photoconductive samples to low wavelength laser radiation. Finally, the possible presence of holes in the samples was rejected for the experimental voltage range. Though not shown here explicitly, the results of our simulations with the forced inclusion of hole injection resulted in negative differential conductance. Since this feature is not observed in the data, the possibility of hole conduction becomes unlikely.

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