Impact of Electron Irradiation on the ON-State Characteristics of a 4H–SiC JBS Diode

Jan Vobecký, Senior Member, IEEE, Pavel Hazdra, Senior Member, IEEE, Stanislav Popelka, Student Member, IEEE, and Rupendra Kumar Sharma

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Impact of Electron Irradiation on the ON-State Characteristics of a 4H–SiC JBS Diode

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Abstract—The ON-state characteristics of a 1.7-kV 4H–SiC junction barrier Schottky diode were studied after 4.5-MeV electron irradiation. Irradiation doses were chosen to cause a light, strong, and full doping compensation of an epitaxial layer. The diodes were characterized using Deep Level Transient Spectroscopy, C–V(T), and J–V measurements without postirradiation annealing. The calibration of model parameters of a device simulator, which reflects the unique defect structure caused by the electron irradiation, was verified up to 2000 kGy. The quantitative agreement between simulation and measurement requires: 1) the Shockley–Read–Hall model with at least two deep levels on the contrary to ion irradiation and 2) a new model for enhanced mobility degradation due to radiation defects. The diode performance at high electron fluences is shown to be limited by the doping compensation at the epitaxial layer.

Index Terms—Numerical simulation, radiation effects, Schottky diodes, wide-bandgap semiconductors.

I. INTRODUCTION

 Junction barrier Schottky (JBS) diodes are the most commercially used SiC devices, because they have much lower failure rate compared with bare Schottky diodes. This is given by the epitaxial layer with alternating n-type (Schottky diode) and implanted p-type (p–n junction) regions (Fig. 1), which bring a low leakage current and high avalanche ruggedness. At high current densities, the p-type regions can provide conductivity modulation to reduce the high forward voltage drop (VF) of bare Schottky diodes [1].

As the SiC devices may be suitable for the operation in space applications, the behavior of JBS diode in a radiation environment assumes importance. This paper quantitatively evaluates the impact of electron irradiation on the ON-state characteristics, which are the most sensitive ones. The range of the investigated electron irradiation doses goes beyond the standardized performance requirements for semiconductor devices, which are usually defined for neutron irradiation.

Our analysis is based on experimentally calibrated device simulation at the Sentaurus Device platform from Synopsys [2]. For this purpose, a detailed knowledge of the radiation damage is needed. The defect structure of an electron-irradiated 4H–SiC JBS diode was published in [3] for doses up to 400 kGy. We extended their measurements to 2000 kGy [4] and calibrated the device simulator to provide a quantitative agreement with measured ON-state characteristics.

The calibration of a proton-irradiated SiC Schottky diode can be found in [6]. The difference between the protons and electrons consists in the following:

1) The forward I–V curves of proton irradiated diodes can be modeled by a single deep level with parameters independent of device operating temperature. The simulation of the electron irradiation is more complicated due to the existence of at least one shallower deep level (in terms of its impact on the forward I–V curves) with temperature-dependent parameters. Consequently, a more complex model has to be used.

2) The defects produced by the proton irradiation typically influence the few micrometers of an epitaxial layer close to the proton range. The defects from the electron irradiation modify the whole epitaxial layer and substrate as well. As a result, the whole device cross section has to be simulated. This allows us to quantitatively analyze the changes of the conductivity of both the epitaxial and substrate layers and explain their role in the modification of forward I–V curves.

II. EXPERIMENT

A. Device Under Test

Commercial 14 A/1700 V JBS diodes C3D10170H from Cree were used for the experiment [5]. The diode has about a
TABLE I

<table>
<thead>
<tr>
<th>Concentration of Detected Deep Levels up to 300 kGy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose (kGy)</td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>300</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>700</td>
</tr>
<tr>
<td>2000</td>
</tr>
</tbody>
</table>

Deep level E0 and doses 500 and 700 kGy are from fitting of C-V(T).

TABLE II

<p>| Free Carrier Concentration from (C-V) Measurements at 300 and 160 K |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|</p>
<table>
<thead>
<tr>
<th>Dose (kGy)</th>
<th>n(300K) (\text{cm}^{-3})</th>
<th>n(300K) (\text{cm}^{-3})</th>
<th>n(300K) (\text{cm}^{-3})</th>
<th>N(_{\text{Ea}}) (\text{cm}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.80 \cdot 10(^{15})</td>
<td>0</td>
<td>0</td>
<td>7.0 \cdot 10(^{12})</td>
</tr>
<tr>
<td>60</td>
<td>3.68 \cdot 10(^{15})</td>
<td>1.2 \cdot 10(^{14})</td>
<td>1.8 \cdot 10(^{14})</td>
<td>2.4 \cdot 10(^{14})</td>
</tr>
<tr>
<td>100</td>
<td>3.60 \cdot 10(^{15})</td>
<td>2.0 \cdot 10(^{14})</td>
<td>3.0 \cdot 10(^{14})</td>
<td>3.3 \cdot 10(^{14})</td>
</tr>
<tr>
<td>200</td>
<td>3.36 \cdot 10(^{15})</td>
<td>4.4 \cdot 10(^{14})</td>
<td>8.0 \cdot 10(^{14})</td>
<td>8.5 \cdot 10(^{14})</td>
</tr>
<tr>
<td>300</td>
<td>3.15 \cdot 10(^{15})</td>
<td>6.5 \cdot 10(^{14})</td>
<td>1.1 \cdot 10(^{15})</td>
<td>1.3 \cdot 10(^{15})</td>
</tr>
<tr>
<td>500</td>
<td>2.50 \cdot 10(^{15})</td>
<td>1.3 \cdot 10(^{15})</td>
<td>1.9 \cdot 10(^{15})</td>
<td>2.3 \cdot 10(^{15})</td>
</tr>
<tr>
<td>700</td>
<td>4.0 \cdot 10(^{15})</td>
<td>3.4 \cdot 10(^{15})</td>
<td>&gt; 3 \cdot 10(^{15})</td>
<td>4.0 \cdot 10(^{15})</td>
</tr>
<tr>
<td>2000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Estimated concentrations of shallow (E0) and deep levels (E1 + E2 + E3) giving the best agreement with C-V(T).

B. Electron Irradiation

The diodes were irradiated by 4.5-MeV electrons using the electron linear accelerator LINAC 4-1200. The irradiation doses (fluences) were chosen in the range between 60 kGy (2.2 \cdot 10\(^{15}\) \(\text{cm}^{-2}\)) and 2000 kGy (7.2 \cdot 10\(^{15}\) \(\text{cm}^{-2}\)) to achieve a light, strong, and total compensation of the epitaxial layer (Tables I and II). To eliminate excessive heating during irradiation, the samples were irradiated by repetitive exposure at 6-kGy steps.

C. Deep Level Transient Spectroscopy

The radiation defects were characterized by capacitance Deep Level Transient Spectroscopy (DLTS) using the spectrometers DLS-82E and DLS-83D from SEMILAB, Inc. Fig. 2 compares the DLTS spectrum of unirradiated device with that of the device irradiated with 200-kGy electrons (as-irradiated) and subsequently annealed at 325 °C for defect stabilization (annealed). The spectrum of the unirradiated diode shows peaks connected with deep levels typical for as-grown SiC, namely, the Z1/Z2 centers [3], which have total concentration of 7 \cdot 10\(^{12}\) \(\text{cm}^{-3}\). The DLTS spectrum measured on the as-irradiated sample shows that the electron irradiation introduces different defects evidenced by broad and dominant features labeled E0/E1, E2, and E3, which are most likely given by a superposition of several peaks (defects) with close activation energies. These defects form deep acceptor levels in the SiC bandgap, which compensate for the nitrogen shallow donors and cause carrier (electron) removal in the lightly doped epitaxial layer. The DLTS spectra obtained on as-irradiated samples were used for the calibration of deep-level concentration for device simulation, because this corresponds to typical operation conditions.

The spectrum measured after annealing at 325 °C for 60 min illustrates the instability of deep levels generated by the electron irradiation at room temperature, which is described in [3] and [4]. Annealing in the temperature range of device operation (below 175 °C) results in the transformation of E0/E1, E2, and E3 features to S1, Z1/Z2, and S2 centers. However, this transformation has a minor effect on the ON-state characteristics (the change in \(V_F\) at 10 A is below 1%). The S1 and S2 centers then disappear after annealing above 300 °C.

D. Capacitance-Voltage Measurements

Tables I and II show energetic positions of deep levels E0–E3 and their concentrations received from the DLTS and temperature-dependent capacitance to voltage C–V(T) measurements at \(f = 1\) MHz. The C–V(T) measurements revealed one additional deep level E0, which is not clearly visible in the presented DLTS spectra. This acceptor level is located 0.22 eV below the conduction band and its electron capture cross section is approximately two orders of magnitude lower than those of levels E1–E3. A capture of carriers on the level E0 is therefore very slow and the DLTS peak of this level is covered by the feature E1 in the spectra for the doses lower than 300 kGy (see the inset of Fig. 2). Fig. 3 shows the measured profiles for lower doses and illustrates the way of their comparison with the simulated ones, which are based on the data summarized in Tables I and II.
dose while the embedding of defects E0 grows sharply for the doses above 200 kGy. The epitaxial layer is fully compensated for the dose of 2000 kGy and therefore not measurable. For 700 kGy, the epitaxial layer is at the threshold of compensation and the measurements are questionable. Therefore, the defect concentrations for these two levels can be only estimated from fitting the measured and simulated forward I–V curves. The defect distribution in the heavily doped substrate is estimated as identical to the epitaxial layer.

The levels E1–E3 are deep enough to be fully ionized (negatively charged) in the temperature range of device operation (−50 °C to 150 °C). On the contrary, the lower activation energy of the E0 center (E_C=−0.22 eV) causes that this center changes its charge state from negative to neutral in this temperature range. The high introduction rate and lower activation energy of the E0 then cause a strong temperature dependence of electron concentration in the n-type epitaxial layer, when irradiated to higher doses. As this level is shallow in terms of its impact on the forward I–V curves (partial ionization), it is simulated separately from the levels E1–E3 from Table II. Their concentrations are counted up into a single level with deep energetic position, because they are fully ionized at room temperature contrary to the level E0.

III. CALIBRATION OF DEVICE SIMULATION

A. Simulation Approach

The device simulator Sentaurus Device from Synopsys was used [2]. The relevant equations, models, and their parameters are summarized in Appendix A. The models for electron irradiated 4H-SiC are based on the following assumptions:

1) homogeneous distribution of introduced deep levels;
2) two-level model with nonlinear embedding of the level E0 with growing irradiation dose;
3) incomplete ionization of the level E0 at room temperature;
4) carefully calibrated enthalpy factors of electrons and holes.

B. Modeling of Deep Levels

Because of the nonlinear introduction and incomplete ionization of the E0, the single-level model [6] cannot be used. At least a two-level model must be applied. The first level has parameters of the level E0 (nonlinear introduction, acceptor character, and incomplete ionization), while the second level E1 + 2 + 3 emulates the characteristics of all deeper and fully ionized acceptor levels E1, E2, and E3. In the calibration, the activation energy of 0.6 eV and capture cross section of electrons of 6·10^{-14} cm^{-2} were used for the level E1 + 2 + 3 [7]. The concentration of E1 + 2 + 3 was then given by the sum of concentrations of E1, E2, and E3 levels measured for particular doses (see Tables I and II). For the level E0, the activation energies of 0.22 eV and 0.33 eV, respectively, were chosen for the doses up to 500 kGy and above. The capture cross section of electrons was chosen at 4·10^{-17} cm^{-2} from the DLTS [4]. While the on-state characteristics are sensitive to the concentrations of E0 and E1 + 2 + 3 levels and the energetic position of the E0 center, the magnitudes of capture cross sections of holes are irrelevant since the injection of holes into the epitaxial layer is negligible under our operation conditions.

A proper choice of the enthalpy factors of electrons and holes X_{ni} and X_{pi} from (A8) and (A9) is crucial for the simulation. The choice of X_{ni} > 1, namely, that of X_{ni} = 4 from [11], is the necessary condition for a quantitative agreement between the simulation and measurement after high-dose electron irradiation.

C. Modeling of Carrier Mobility

We use the anisotropic mobility model, which accounts for a different values along the (1120) and (0001) planes. In addition, the saturation of electron mobility at high electric field and the degradation of mobility due to the doping according to [8] are modeled (A12). For the initial parameter settings of the Caughey–Thomas formula, we took the ones for 4H-SiC from [9] and modified them to account for the total concentration of radiation defects N_T = N_{E0+1+2+3} by fitting the I–V curves. The resulting model is represented by (A12) of Appendix C. Fig. 7, present in the Appendix, shows how the mobility for different irradiation doses in the epitaxial layer is calculated. Fig. 6(a) and (b) shows the difference between the epitaxial layer and substrate. It turned out that the mobility degradation due to the radiation defects can be modeled by the modified Caughey–Thomas relation. However, the effect of radiation defects is much more pronounced than that of the doping. As a result, the mobility degrades sharply at relatively low concentrations of the introduced defects, as evidenced by different values of parameters C_I and β.

D. Modeling of Schottky Barrier

The agreement between the measured and simulated forward I–V curve at low currents was achieved by adjusting the barrier height φ_B at the Schottky contact. For the unirradiated diode, we received φ_B = 1.239 ± 0.003 eV from the I–V measurements. This fits well to the range presented
TABLE III
CALIBRATION PROCEDURE

<table>
<thead>
<tr>
<th>Not Irradiated</th>
<th>Input Method</th>
<th>Calibration parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLTS measured</td>
<td>Forward I-V simulated</td>
<td>Z1/2 concentration</td>
</tr>
<tr>
<td>Geometry and doping</td>
<td>Electron mobility</td>
<td>Barrier height</td>
</tr>
<tr>
<td>E₀ to E₁ energetic position</td>
<td>Electron mobility</td>
<td>Concentration of E₀ relative to E₁+E₂+E₃</td>
</tr>
<tr>
<td>E₀ to E₁ capture cross-section</td>
<td>Electron mobility</td>
<td>Enthalpy factors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electron irradiated</th>
<th>C-V measured</th>
<th>Electron conc. at epi-layer simulated</th>
<th>Concentration of E₀ relative to E₁+E₂+E₃</th>
</tr>
</thead>
</table>

Fig. 4. Concentration of deep levels versus irradiation dose as used in the simulation.

Fig. 5. Simulated and measured forward I–V curves. Electron irradiation dose is a parameter.

for titanium [10]. The received scatter of the JBS diode under study is significantly lower than that of the Schottky diode [6]. This allowed us a more precise calibration compared with the bare Schottky diodes [6]. Since we did not observe any significant influence of electron irradiation on $\phi_B$, no modification of $\phi_B$ with irradiation dose has been made. The measured reverse $I–V$ curves that showed a minor variation in breakdown voltage (below 1%) confirm this behavior.

**E. Simulation Domain**

The simulation domain comprises the whole device, i.e., contacts, epitaxial layer, and the complete substrate, except for junction termination (see Fig. 1). As the substrate is part of the simulation domain, no additional series resistance is needed. To account for different sizes of the anode and cathode contacts, trapezoidal shape of the simulated domain has been chosen.

**F. Calibration Procedure**

The unirradiated and subsequently the irradiated diode is calibrated on the parameters summarized in Fig. 1 using the top-down sequence in Table III. The concentration profile of deep levels is simulated by constant concentration of deep levels $E₀$ and $E₁+E₂+E₃$ with $n_{E₀} = 4 \cdot 10^{-17}$ cm$^{-2}$ and $n_{E₁+E₂+E₃} = 6 \cdot 10^{-14}$ cm$^{-2}$. The defect introduction rate is then calibrated by comparing the simulated profile of free electron concentration in the epitaxial layer with that from the C–V measurement. The deep-level concentrations leading to agreement between the simulated and measured electron concentrations are shown in Fig. 4. The final agreement between the measured and simulated high-current parts of forward $I–V$ curves is achieved by calibrating the parameters of the enhanced mobility degradation model (A12) in Fig. 7, as shown in the Appendix.

**IV. DISCUSSION**

Fig. 5 confirms the quantitative agreement between the measurement and simulation up to 2000 kGy and shows a high sensitivity of the ON-state characteristics to the electron irradiation. Undoubtedly, the biggest contribution comes from the low-doped epitaxial layer. However, the extent to which the highly doped substrate contributes is worth analyzing. Fig. 6(a) and (b) compares the dependencies of simulated electron mobility and concentration on the total concentration of deep levels in the epitaxial layer and substrate. The substrate features a very low electron mobility due to its high doping concentration. This value is close to $140$ cm$^2$/V.s already without irradiation, which is about six times less than in the epitaxial layer. Conditions in the substrate and epitaxial layers equalize at high doses when the doping compensation of the epitaxial layer takes place. The electron mobility becomes very small in both the epitaxial and substrate layers.

The relative decrease in free electron concentration is negligible in the substrate. The electron concentration lowers there only due to the incomplete ionization of impurities. The effect of radiation defects is relatively small, because the defect concentration is small in comparison with that of the doping even for the highest irradiation doses. On the contrary, the electron concentration drops several orders of magnitude in the epitaxial layer after the high-dose irradiation.
The changes of electron mobility and concentration are brought together in Fig. 6(c), where the conductivities of the substrate and epitaxial layers versus deep-level concentration are compared. While the substrate conductivity drops to one-third at high doses, that of the epitaxial layer drops practically to zero. The conductivity of the epitaxial layer can be five to six orders of magnitude lower than that of the substrate, when the full compensation in the epitaxial layer takes place (see the doses $\geq 700$ kGy). This means that the drastic increase in diode series resistance at high irradiation doses causes modification of the epitaxial layer, while its increase due to the substrate is only partial, although not negligible.

V. CONCLUSION

A new procedure for the calibration of simulation of the 4H-SiC JBS diode subjected to electron irradiation has been demonstrated by way of the example of deteriorated forward $I$–$V$ curves. This allowed us to carry out a quantitative analysis of conductivity changes between the epitaxial and substrate layers after the irradiation. For SiC devices, it implies that the low-doped epitaxial layer represents a principal limitation in the environment with high electron fluences.

APPENDIX

A. Poisson Equation

$$\text{div} \ \text{grad} \ \phi = \frac{e}{\epsilon} \cdot \left( n - p - N_D + N_A - \sum_{i=1}^{m} N_{ti}(x) \right) \times (z_i^{\text{emp}} \cdot (1 - f_i) + z_i^{\text{occ}} \cdot f_i) \quad (A1)$$

where $z_i^{\text{emp}}$ is the charge state of empty $i$th deep level, $z_i^{\text{occ}}$ is the charge state of occupied $i$th deep level, $N_{ti}(x)$ is the concentration profile of $i$th deep level ($i = 1$ – $m$), and $f_i$ is the occupation probability of the $i$th deep level

$$f_i = \frac{n_{ti}(x)}{N_{ti}(x)} \quad (A2)$$

calculated for every deep level from balance equation

$$\frac{df_i}{dt} = c_{ni} \cdot n \cdot (1 - f_i) - e_{ni} \cdot f_i + e_{pi} \cdot (1 - f_i) - c_{pi} \cdot p \cdot f_i. \quad (A3)$$

B. Continuity Equations for Electrons and Holes

The continuity equations (A4) and (A5) collect the contribution from all deep levels in the total g–r rate of electrons $R_n$ and holes $R_p$

$$R_n = \sum_{i=1}^{m} \left[ c_{ni} \cdot n \cdot N_{ti} \cdot (1 - f_i) - e_{ni} \cdot N_{ti} \cdot f_i \right] \quad (A4)$$

$$R_p = \sum_{i=1}^{m} \left[ c_{pi} \cdot p \cdot N_{ti} \cdot f_i - e_{pi} \cdot N_{ti} \cdot (1 - f_i) \right] \quad (A5)$$

where $e_{ni}$ and $e_{pi}$ are, respectively, the emission coefficients of electrons and holes of $i$th deep level and $c_{ni}$ and $c_{pi}$ are, respectively, the capture coefficients of electrons and holes of $i$th deep level, which are given by

$$c_{ni} = v_{thn} \cdot s_{ni} \quad (A6)$$

$$c_{pi} = v_{thp} \cdot s_{pi} \quad (A7)$$

where $v_{thn}$ and $v_{thp}$ are the thermal velocities of electrons and holes, respectively, $s_{ni}$ is the electron capture cross section of
ith deep level obtained from the DLTS [3], [4], and sp is the hole capture cross section of ith deep level estimated from [7].

The relation between the emission and capture coefficients reads

\[ e_{ni} = \frac{sn_i}{X_{ni}} \exp\left(\frac{E_{ti} - E_F}{kT}\right) \]  
\[ e_{pi} = \frac{sp_i}{X_{pi}} \exp\left(\frac{E_{ti} - E_F}{kT}\right) \]

where \( X_{ni} \) and \( X_{pi} \) are the enthalpy factors of electrons and holes, respectively, \( E_F \) is the energetic position of ith deep level, and \( E_F \) is the Fermi level.

For the stationary case of the \( C-V \) and \( I-V \) curves, the \( g-r \) rate with \( m \) deep levels results in the Shockley–Read–Hall model [12]

\[ R_{SRH} = \sum_{i=1}^{n} \frac{1}{v_{th}^E v_{pi}^H (x)} \cdot \left( \frac{n + n_i}{X_{ni}} + \frac{n + n_i}{X_{ni}} \cdot \frac{n_i}{v_{th}^E v_{pi}^H (x)} \right) \cdot (p + p_i) \]

\[ n_{i0} = N_C \left( \frac{\exp(E_v - E_C)}{kT} \right) \cdot p_{i0} = N_V \left( \frac{\exp(E_F - E_{ti})}{kT} \right) \]

C. Mobility Degradation Model

\[ \mu_n = \mu_{min} + \mu_{max} - \mu_{min} \]

where \( N_D \) is the total doping concentration, \( N_T \) is the total concentration of deep levels, \( C_r = 2 \cdot 10^{17} \text{ cm}^{-3} \), \( \alpha = 0.76, C_f = 2.3 \cdot 10^{15} \text{ cm}^{-3} \), \( \beta = 2.9 \), plane (1120):

\[ \mu_{max} (1120) = 920 \text{ cm}^2/\text{V} \cdot \text{s} \] and \( \mu_{min} = 10 \text{ cm}^2/\text{V} \cdot \text{s} \), and plane (0001):

\[ \mu_{max} (0001) = 830 \text{ cm}^2/\text{V} \cdot \text{s} \] and \( \mu_{min} = 10 \text{ cm}^2/\text{V} \cdot \text{s} \).

REFERENCES


Jan Vobecký (M’92–SM’01) received the M.Sc. degree from Czech Technical University, Prague, Czech Republic, in 1981, the Ph.D. degree in microelectronics in 1988, and the DrSc. degree in 1999, the Associate Professor degree in 1992, and the Full Professor degree in 2000. He has been the Principal Engineer with ABB Switzerland Ltd. Semiconductors, Lenzburg, Switzerland, since 2007.

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