Simulation and Characterization of 4H-SiC JBS Diodes Irradiated by Hydrogen and Carbon Ions

Rupendra Kumar Sharma, Pavel Hazdra, and Stanislav Popelka

Abstract—**This paper presents the development and application of simulation models for proton and carbon irradiated 4H-SiC junction barrier Schottky (JBS) diodes. Commercial JBS diode chips were irradiated to the identical depth with different doses of hydrogen and carbon ions. The resulting defects were then identified by deep level transient spectroscopy (DLTS). Comprehensive I-V and C-V measurement performed prior to and after ion irradiation was used for calibration of simulation models. Results show that compared to protons, heavier carbon ions introduce more defects with deeper levels in the SiC bandgap and more stable damage. For the first time, the free carrier concentration profile extracted from CV simulations for irradiated JBS diode has been compared with experimental data. The simulation of irradiated JBS diodes exhibit excellent matching with experimental data and can be very useful for the optimization of SiC power devices. Furthermore, it is shown that the developed model can be used for prediction of the effect of ion irradiation on both the static and dynamic characteristic of PiN diode.**

Index Terms—**4H-SiC, characterization, JBS diode, PiN diode, simulation.**

I. INTRODUCTION

THE unique properties of silicon carbide (SiC) material have the potential of an excellent semiconductor for the development of high-power, high-voltage, and high-temperature electronic devices [1]. 4H-SiC junction barrier Schottky (JBS) rectifiers as a key device in power conversion applications have been widely investigated in recent years [2]-[3]. The JBS diodes have a Schottky rectifier structure with p-n junction grids integrated into the drift region and thus behave similar to Schottky diodes in the on-state and switching characteristics while show reverse characteristics similar to PiN diodes [4]. The understanding of electrically active defects induced by ions is very important since they cause performance degradation of SiC devices working in space applications [5].

In our previous study, we have developed simulation models for proton irradiated 4H-SiC JBS diode [6]. This analysis was limited to the impact of proton irradiation on forward and reverse characteristics and C-V analysis was not presented. In the present paper, we have analyzed the influence of defects induced by irradiation with carbon ions together with hydrogen ions on the electrical performance of 1700 V 4H-SiC JBS diodes including C-V characteristics and temperature dependence. The developed simulation models for proton irradiation can easily be adopted for JBS diodes irradiated with carbon ions. This analysis is quite valuable and can be used for prediction of the effect of ion irradiation on both the static and dynamic characteristic of JBS and PiN diodes.

II. EXPERIMENTAL

Devices under test (DUTs) were CPW3-1700-S010B chips of 10 A/1700 V JBS power diodes produced by Cree™ [7]. Diodes were fabricated on 4H–SiC epilayers grown on heavily doped nitrogen n^+ (0.025–0.028 Ω cm) 360 µm thick SiC substrates. Thickness of the N-epilayer was 20 µm and the level of nitrogen doping about 4×10^{15} cm^{-3}. Diode has an active region of 6.72 mm^2 composed from titanium Schottky contact combined with implanted p^+ aluminum strips.

The diodes were irradiated from the anode side with 670 keV protons or 9.6 MeV C^{4+} ions using 3MV Tandetron accelerator. The irradiation fluences varied from 3×10^9 to 6×10^{10} cm^{-2} and formed a damaged region peaking 2.5 µm below the surface of the SiC epilayer. Radiation defects and their influence on diode characteristics were then characterized by capacitance deep level transient spectroscopy (DLTS), C-V profiling and I-V measurements. TCAD simulation on an equivalent JBS structure (Fig. 1) has been carried using the simulator ATLAS from SILVACO Inc. to develop and calibrate simulation models of ion irradiated SiC devices.

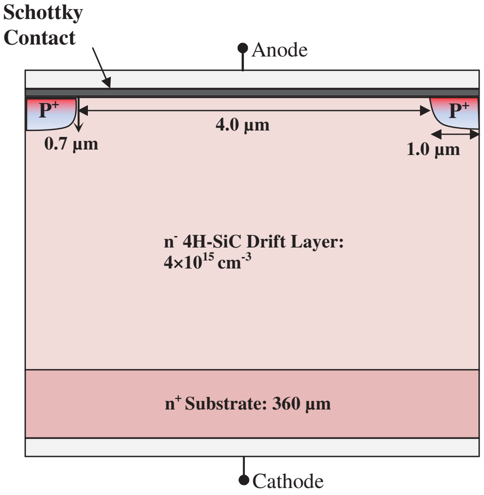

Fig. 1. Schematic device cross section of the simulated 4H-SiC JBS diode.

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R. K. Sharma, P. Hazdra, and S. Popelka are with Department of Microelectronics, Faculty of Electrical Engineering, Czech Technical University in Prague, Prague 16627, Czech Republic. Phone: +420-224352052; fax: 420-224310792; e-mail: sharmrup@fel.cvut.cz, hazdra@fel.cvut.cz.

III. RESULTS AND DISCUSSION

Concentration profiles of dominant deep levels for proton irradiated JBS diode are presented in Fig. 2. Profiles, which were obtained by DLTS measurement in double-DLTS mode, show that radiation defects, which are localized close to the ion's projected range R_P, follow well the distribution of primary damage (vacancies) obtained by simulation using the code SRIM [8] (dashed). Compared to protons, heavier carbon ions (not shown here) generate a larger number (50x) of primary defects (vacancies). However, the introduction rate of secondary (stable) defects is substantially lowered due to increased recombination of primary defects inside the denser cascade of recoiled atoms produced by carbon ions. We have noticed that the total number of stable defects produced per one introduced primary vacancy decreases from 0.3 (protons) to 0.03 (carbon) defect/vacancy.

Device simulation using ATLAS software was used to analyze underlying effects. Physical models accounting for the electric-field-dependent carrier mobility with velocity saturation, Shockley–Read–Hall (SRH) recombination / generation (g-r) with doping-dependent carrier life-timeand Auger recombination along with Fermi-Dirac statistics were applied [9]. The Schottky thermionic emission model accounts for field-dependent barrier- lowering along with universal Schottky tunneling (UST) model is activated. Lindefelt bandgap narrowing model for doping induced bandgap narrowing and incomplete ionization model for relatively large ionization energies in SiC poly types are taken into consideration. For doping-and temperature-dependent low-field mobilities, Caughey and Thomas mobility model is used.

$$\mu_n = \mu_{\min}\left(\frac{T}{300}\right)^{\alpha} + \frac{\mu_{\max}\left(\frac{T}{300}\right)^{\beta} - \mu_{\min}\left(\frac{T}{300}\right)^{\alpha}}{1+\mu_{\min}\left(\frac{T}{300}\right)^{\gamma}\left(\frac{N}{N_{CRIT}}\right)^{\delta}} \qquad (1)$$

where N is the local (total) impurity concentration and T is the temperature. The same model is applied for the degradation of mobility due to radiation defects from the proton irradiation by including concentration of all deep levels N_{ti} to the total impurity concentration (N) and T is the temperature. The parameters used for the calibration are given in Table I. For impact ionization, anisotropic impact ionization models are taken into account for direction dependent electric field magnitude.

The following equations describe the ionization rate.

$$\alpha\left(E_xE_y\right) = a\exp\left(-c\sqrt{1-A^2C^2\left(\frac{E_xE_y}{b_xb_y}\right)^2}\right) \qquad (2)$$

where

$$c = \left(\frac{E_x^2}{b_x^2}+\frac{E_y^2}{b_y^2}\right)^{-1/2} \qquad A = \ln\left(a_y / a_x\right) \qquad a = a_x^{\frac{c^2E_x^2}{b_x^2}}\, a_y^{\frac{c^2E_y^2}{b_y^2}}$$

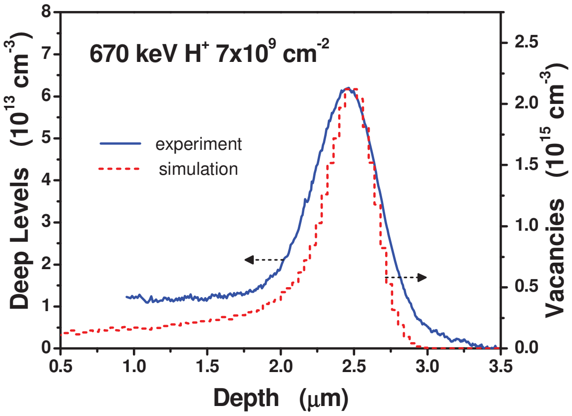

Fig. 2. Profile of deep level T285 measured in the 4H-SiC JBS power diode after irradiation with 670 keV protons to fluence of 7x10^9 cm^{-2} together with the simulated profiles of primary vacancies (dashed).

Here, E_x and E_y are the electric field magnitude in the x and y directions. The parameters a_x, a_y, b_x and b_y depend upon the crystal orientation. In the present analysis crystal orientation 0001 is selected and the parameters used are given in Table I.

Furthermore, band-to-band tunneling model is activated to take care of very high electric field in JBS diode. The tunneling generation rate is as follows:

$$G_{BBT} = D\alpha E^{\gamma}\exp\left(-\frac{\beta}{E}\right) \qquad (3)$$

where E is the magnitude of the electric field, D is a statistical factor, and α, β, and γ are fitting parameters (Table I).

For irradiated devices, an approach accounting for introduction of one dominant deep level into the Schottky-Read-Hall model of carrier generation/recombination (g/r) was used. For both ions, the model uses the g/r parameters of the Z1/Z2 centre (acceptor level E_C – 0.69 eV with electron/hole capture cross section of 9x10^{-14} cm^2) and above mentioned introduction rates (the number of defects produced per primary vacancy) which re-scales the simulated profile of primary vacancies to the profile of Z1/Z2 centers [10]. Identification parameters of registered deep levels and their identity are shown in Table II.

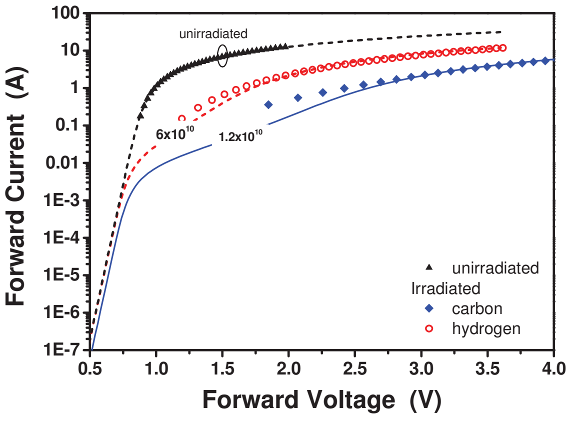

Fig. 3. Forward I-V characteristics of unirradiated and irradiated with proton (6x10^{10} cm^{-2}) and carbon (1.2x10^{10} cm^{-2}) 4H-SiC JBS diode.

Experimental and simulated forward I–V characteristics of irradiated 4H-SiC JBS diode are shown in Fig. 3. The donor doping is compensated close to the projected range of incoming ions because of acceptor character of the majority of introduced defects. This results in higher forward voltage drop (V_{FWD}) for irradiated diodes. In spite of lower fluences of carbon, the V_{FWD} for carbon irradiated diode is much larger than the proton irradiated devices. This is because, carbon ions are heavier than hydrogen, thus create more damage in the epi-layer.

The simulated models have also been verified for reverse characteristics of both the unirradiated and irradiated JBS diode (Fig. 4). Note that the introduction of acceptor traps by proton irradiation increases the breakdown voltage of the JBS diode. This is because of decrease in fixed positive charge of the space charge region in the damaged region of the epilayer in the blocking regime. The lower built-in charge implies lower electric field in the epi-layer and allows applying higher reverse bias. The introduced defects also decrease the rate of impact generation and slightly reduce the leakage current of the irradiated JBS diode at higher reverse voltages (> 2kV). Due to the wide SiC bandgap, the charge generation on introduced defects lying in the space charge region is negligible and we observe only a small increase of leakage at lower voltages (< 150V). It is observed that the breakdown voltage (not shown here) for JBS diode irradiated with carbon ($1.2\text{x}10^{10}$ cm^{-2}) is marginally (~ 30 V) higher than the proton irradiated ($6\text{x}10^{10}$ cm^{-2}) device, however, lower than the device irradiated with proton fluence of $9\text{x}10^{10}$ cm^{-2}.

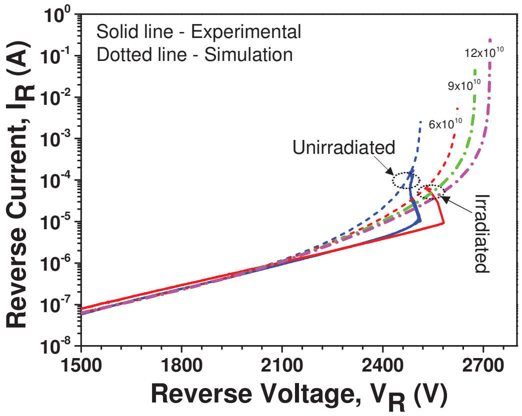

Fig. 4. Reverse I-V characteristics of 4H-SiC JBS power diode irradiated with 670 keV H^+ for $6\text{x}10^{10}$ cm^{-2}, $9\text{x}10^{10}$ cm^{-2} , $1.2\text{x}10^{11}$ cm^{-2} fluences.

The developed simulation models have the advantage to be used for the analysis of free carrier concentration profiles obtained from C-V measurements. In Fig. 5, we have compared experimental profiles obtained by C-V measurements with simulated ones. The method used for calculation of free carrier concentration from C-V measurements is as stated by Kimerling [15].

$$N(W) = \frac{-C^3}{q\varepsilon A^2 \frac{d}{dV}(C)} = \frac{2}{q\varepsilon A^3 \frac{d}{dV}\left(\frac{1}{C^2}\right)} \qquad (4)$$

The depletion width (W) of a reverse biased p-n junction, when considered as a parallel plate capacitor is $W = \varepsilon A / C$. It is very clear from Eq. (4) that the device area be precisely known for accurate doping profiling.

Note that the distribution obtained from C-V does not correspond to reality (flat without acceptor defects Fig. 2). Simulation results nearly perfectly show this effect. The difference between simulated and experimental curves is given by the different depletion profiles of Schottky and p-n junction regions, unknown levels, and their exact positions.

TABLE I

TCAD CALIBRATED PHYSICAL MODEL PARAMETERS FOR 4H-SIC JBS DIODE

Simulation Models	**Physical Parameters**			
Caughey and Thomas mobility model	$\mu n_{max} = 947$ cm^2/V.s $\mu n_{min} = 40$ cm^2/V.s N_{CRITN} = 1.94e17 cm^{-3}	$\delta_n = 0.61$ $\gamma_n = 2.4$ $\alpha_n = -0.5$ $\beta_n = -2.9$	$\mu p_{max} = 124$ cm^2/V.s $\mu p_{min} = 15.9$ cm^2/V.s N_{CRITP} = 1.76e19 cm^{-3}	$\delta_p = 0.34$ $\gamma_p = 2.3$ $\alpha_p = -0.5$ $\beta_p = -2.9$
Anisotropic Impact Ionization	a_e=1.86×10^8 cm^{-1} b_e=2.8×10^7 cm^{-1}	-	a_h=3.01×10^8 cm^{-1} b_h=2.05×10^7 cm^{-1}	-
Band-to-Band Tunneling	$\alpha = 9.66\times10^{12}$ (cm^{-1}V^{2}s^{-1})	$\beta = 1.5\times10^7$ (V/cm)	γ=1.67	D =1.0
SRH model	Z1/2, E.level = 0.68	SIGN = 5×10^{-14} cm^{-2}	SIGP = 5×10^{-14} cm^{-2}	$\eta_t = 0.3$
Thermionic Emission	me.tunnel = 0.7	mh.tunnel = 1.2	mass.tunnel = 0.76	

TABLE II

PHYSICAL MODEL PARAMETERS FOR 4H-SIC JBS DIODE

Ion	**Bandgap position [eV]**	**Capture cross section [cm^2]**	**Identity**
H/C	$E_C - 0.60$	$4\text{x}10^{-14}$	? [11,12,13]
H/C	$E_C - 0.69$	$9\text{x}10^{-14}$	Z1/Z2 [12,13,14]
H/C	$E_C - 0.72$	$7\text{x}10^{-14}$	? [11,12,13]
H/C	$E_C - 0.88$	$3\text{x}10^{-14}$	$RD_{1/2}$ [8,13]
H/C	$E_C - 1.04$	$6\text{x}10^{-14}$	EH4 [12]
H/C	$E_C - 1.10$	$5\text{x}10^{-15}$	EH5 [12]
C	$E_C - 1.45$	$8\text{x}10^{-14}$	RD_4 [8,13]
H	$E_C - 1.64$	$3\text{x}10^{-13}$	EH6/7 [12]

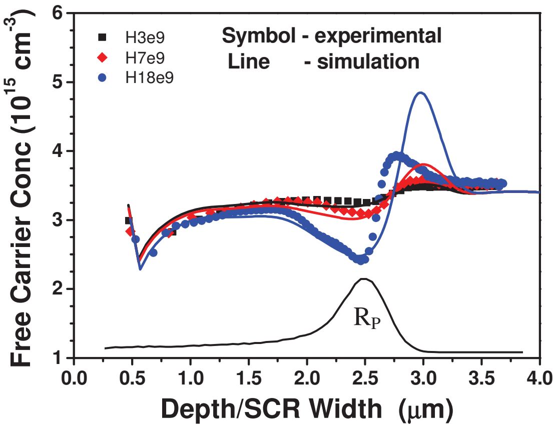

Fig. 5. Free carrier (electron) profiles measured in 4H-SiC JBS power diode irradiated with 670 keV H^+ together with the profile simulated for proton irradiated JBS (dashed).

Since majority of introduced defects exhibit acceptor character, the donor doping is compensated close to the projected range R_P of incoming ions and thus decreases the free carrier concentration. This drop in the concentration of free carrier increases with increasing proton fluences (acceptors) because of the growing compensated region in the n-type epi-layer. Note that the non-homogeneous distribution of deep acceptor traps creates a sharp increase in the concentration of free carriers at the edge of the damage region. The similar behavior with higher peak concentration is also observed in the simulation. This peak is clearly anomalous and has no real relation to net donor behavior of any kind. Usually, in the case of non-homogeneous distribution of deep centers these profiles are subjected to significant artifacts [15].

The developed simulation models accounting for local introduction of deep levels into SiC structures by ion irradiation can be further used for investigation of the effect of local lifetime control in bipolar power devices. Fig.6. shows the simulated variation of carrier lifetime profile in the epi-layer irradiated from the left side with different fluences of centers introduced by penetrating protons decrease strongly 670 keV protons. As can be readily seen, recombination the lifetime of excess carriers in the region close to their range (2.5μm), however, noticeable reduction can be also observed in the so-called tail region extending from the damage peak to the irradiated surface (left). Our simulation shows that a significant lifetime reduction occurs already at very low irradiation fluences (below 10^{10}cm^{-2}).

The effect of 670 keV proton irradiation on static and dynamic characteristics of the 1700V SiC PiN diode is shown in Figs. 7 to 9. The investigated PiN diode was identical to the structure of the 1700V JBS diode described above (Fig.1), only the P^+ region covered the whole area of the anode junction, i.e., there were no Schottky contacts. The region of the maximal lifetime reduction produced by 670 keV proton was than located approx. 1.8μm below the anode junction. Fig. 7 shows the effect of increasing proton fluence on diode forward characteristics. Simulation shows that irradiation gradually increases the forward voltage drop due to the reduction of the ON-state electron-hole plasma concentration in the n-base region of the diode which is given by the increased carrier recombination in the damaged region. Simultaneously, the recombination current in the subthreshold region increases. On the other hand, proton irradiation substantially speeds up the reverse recovery of the PiN diode and reduces the turn-OFF losses. This is shown in Fig.8 presenting the effect of 670 keV proton irradiation on the resistive turn-OFF of the investigated PiN diode to the reverse voltage of 1kV. Figure shows that increasing proton fluence substantially reduces the reverse recovery current maximum and the reverse recovery charge Q_{RR}. It also shows the advantage of proton irradiation – with increasing fluence, the recovery is getting softer without significant voltage overshoots. Finally, Fig.9 which is showing the trade-off between the reverse recovery charge Q_{RR} and the forward voltage drop V_F of the PiN diode subjected to 670 keV proton irradiation allows finding an optimal fluence for balancing the ON-state and OFF-state losses.

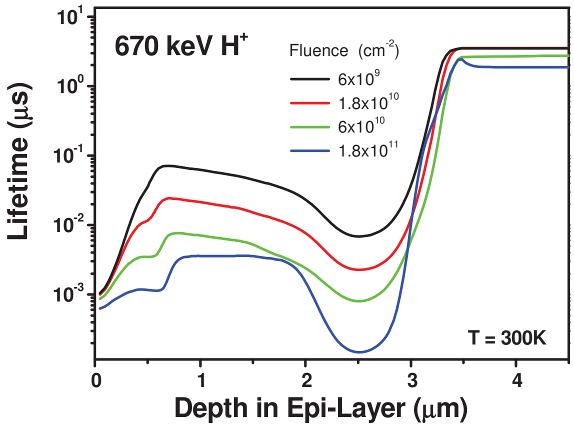

Fig. 6. Simulated variation of carrier lifetime with depth in the epi-layer irradiated with different fluences of 670 keV protons (left side irradiation).

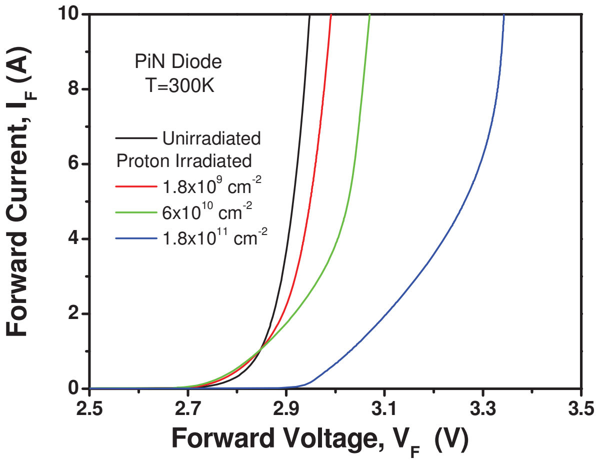

Fig. 7. Simulated room temperature forward characteristics of a PiN diode irradiated with different fluences of 670 keV protons.

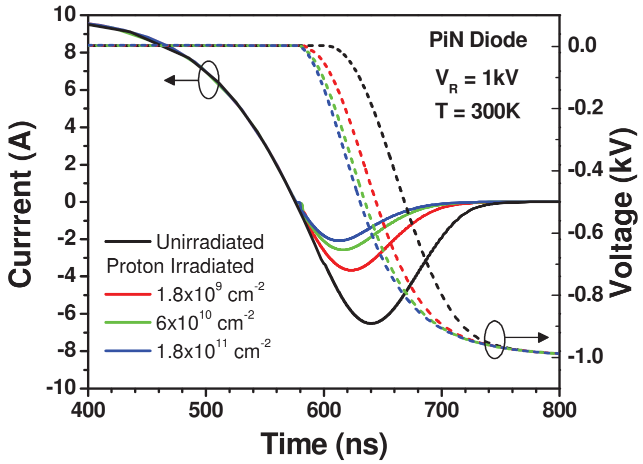

Fig. 8. Reverse recovery of a PiN diode irradiated with different fluences of 670 keV protons – room temperature simulations.

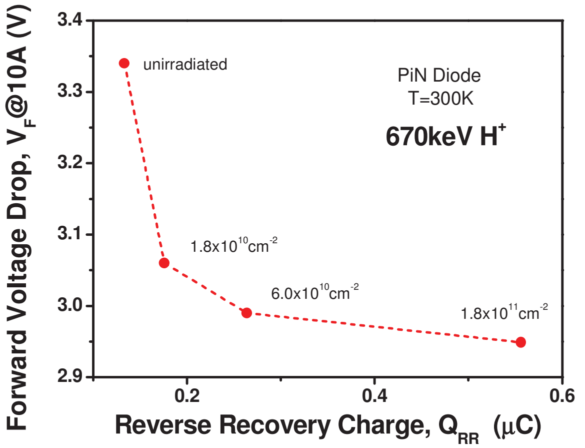

Fig. 9. Trade-off between the Reverse Recovery Charge Q_{RR} and the Forward Voltage Drop V_F@I_F=10A of the PiN diode irradiated with different fluences of 670 keV protons – room temperature simulations.

IV. CONCLUSION

The calibration of simulation models for ions irradiated 4H-SiC JBS diode is presented. The developed models show close proximity with experimental data and is used for the carrier life-time control in PiN diode. For the first time, the free carrier concentration profile obtained through C-V simulation is presented. The detailed information about the physics of damaged region can be understood through this analysis. Furthermore, the developed models are worthwhile for the optimization of SiC bipolar power devices.

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Rupendra Kumar Sharma received Ph.D. degree in electronics from Delhi University, India in 2010. His research interest includes modeling, simulation, and characterization of nanoscale multi-gate MOSFETs and of high voltage power devices. Currently, He is working on silicon carbide based power devices and their applications for power savings at Czech Technical University in Prague. He has authored or coauthored over 26 papers in various international and national journals and conferences.

Pavel Hazdra received the M.Sc. and Ph.D. degrees in Microelectronics from Czech Technical University in Prague, Czech Republic, in 1984 and 1991. Electron Device Group leader (1992), Associate (1996) and Full (2010) Professor in Electronics therein. Research interests include radiation defects and their application, nanostructures, and quantum dots. Author or co-author of hundreds scientific papers. Longtime Chairman and Vice-Chairman of the Joint MTT/AP/ED/EMC Chapter of the Czechoslovakia Section of IEEE.

Stanislav Popelka received the B. S. and M. S. degrees in Electrical Engineering from the Czech Technical University in Prague in 2011 and 2013, respectively. He is currently working toward the Ph.D. degree in electrical engineering at Czech Technical University in Prague. His doctoral research is focused on simulation and testing of radiation hardness of power devices based on silicon carbide.