APPLIED PHYSICS LETTERS **110**, 083503 (2017)

Impact of high energy electron irradiation on high voltage Ni/4H-SiC Schottky diodes

V. V. Kozlovski,[1] A. A. Lebedev,[2,3] M. E. Levinshtein,[2] S. L. Rumyantsev,[2,3] and J. W. Palmour[4]

[1]*Department of Experimental Physics, St. Petersburg State Polytechnic University, Polytekhnicheskaya 29, St. Petersburg 195251, Russia*
[2]*Ioffe Institute, Polytekhnicheskaya 26, St. Petersburg 194021, Russia*
[3]*National Research University of Information Technologies, Mechanics, and Optics, St. Petersburg 197101, Russia*
[4]*Wolfspeed, A Cree Co., 3026 East Cornwallis Rd., Research Triangle Park, North Carolina 27709, USA*

(Received 7 December 2016; accepted 9 February 2017; published online 24 February 2017)

We report the results of the high energy (0.9 MeV) electron irradiation impact on the electrical properties of high voltage Ni/4H-SiC Schottky diodes. Within the range of the irradiation dose from $0.2 \times 10^{16}\,\mathrm{cm}^{-2}$ to $7 \times 10^{16}\,\mathrm{cm}^{-2}$, electron irradiation led to 6 orders of magnitude increase in the base resistance, appearance of slow relaxation processes at pico-ampere current range, and increase in the ideality factor. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4977095]

4H-SiC Schottky diodes are widely used as active elements of detectors, mixers, and frequency multipliers up to the terahertz frequency range. High voltage/high current 4H-SiC Schottky diodes are elements of power electronics including automotive electronics, power converters, solar cell drivers, and numerous other applications. For many of these applications, radiation hardness is one of the main characteristics. Aside from practical importance, study of the radiation hardness is important for the understanding of the physical mechanism of defect formation and annealing.

The effect of electron irradiation with energy within the range $100 \leq E_e \leq 1000$ keV on 4H-SiC has been studied in many publications (see, for example, Refs. 1–9). The energy of $E_e \sim 100$ keV corresponds approximately to the threshold energy of $Z_{1/2}$ and $EH_{6/7}$ trap levels' generation, which play the role of the lifetime "killers" in 4H-SiC. The concentration of induced defects is mainly determined by total dose and only weakly depends on energy for $100 \leq E_e \leq 1000$ keV.[4] Therefore, the results obtained with different electron sources of different energies can be correctly compared and analyzed.

The majority of publications on the impact of electron irradiation on 4H-SiC structures have been devoted to the study of different defects induced by doses ranging from $6 \times 10^{14}\,\mathrm{cm}^{-2}$ (Ref. 9) to $3 \times 10^{18}\,\mathrm{cm}^{-2}$.[7] The effect of the electron irradiation on current voltage characteristics and Schottky barrier properties was studied in Refs. 4 and 9. However, Ref. 4 was mainly devoted to the formation of semi-insulating layers in n-type 4H-SiC by electron irradiation with very high doses up to $1.9 \times 10^{18}\,\mathrm{cm}^{-2}$. In Ref. 9, current voltage characteristics and their temperature dependencies were studied after very small irradiation doses. Therefore, evolution of the current voltage characteristics of SiC Schottky diodes with gradually increasing irradiation dose has still not been studied.

In this paper, we study the forward current voltage characteristics and their temperature dependencies in 4H-SiC Schottky diodes after electron irradiation with energy 0.9 MeV and doses from $0.2 \times 10^{16}\,\mathrm{cm}^{-2}$ to $7 \times 10^{16}\,\mathrm{cm}^{-2}$.

The effect of irradiation has been studied on commercial 4H-SiC Schottky diodes CPW4-1200S002B with a reverse blocking voltage of 1200 V fabricated by CREE Inc. The diodes were irradiated in a pulse regime with the frequency 500 Hz and pulse duration 330 μs. The average beam current density was 12.5 mA/cm^2. The irradiation doses varied from $0.2 \times 10^{16}\,\mathrm{cm}^{-2}$ to $7 \times 10^{16}\,\mathrm{cm}^{-2}$. The diodes were not annealed after the irradiation.

Since the mean free path of 0.9 MeV electrons in SiC is about 1000 μm (Ref. 10) and the base thickness of the studied diodes does not exceed 20 μm, the defects were generated uniformly within the sample volume.

Figure 1 shows the forward current voltage characteristics of the diodes after different doses of irradiation.

As seen, the effect of irradiation is more pronounced at low and high forward biases. The exponential part of the current voltage characteristic is less affected by irradiation even at the highest dose of $\Phi = 7 \times 10^{16}\,\mathrm{cm}^{-2}$. Although current on the exponential part of the current voltage characteristic did not change significantly, the ideality factor

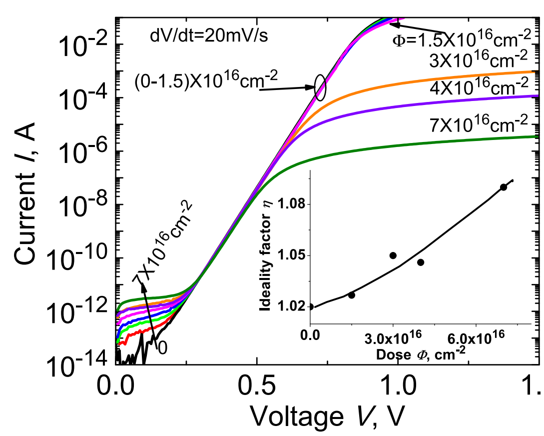

FIG. 1. Forward current-voltage characteristics of Schottky diodes with different doses Φ of electron irradiation. The inset shows the dependence of ideality factor η on dose Φ.

increased from $\eta \sim 1.02$ to $\eta \sim 1.09$ at $\Phi = 7 \times 10^{16}\,\mathrm{cm}^{-2}$, see the inset in Fig. 1. More significant influence of the electron irradiation on the exponential part of the characteristics was observed in publications.[4,9] In Ref. 4, irradiation with the similar dose $\Phi = 6 \times 10^{16}\,\mathrm{cm}^{-2}$ led to the decrease of the current on the exponential part of the current voltage characteristic of about an order of magnitude. In Ref. 9, an extremely small dose of $\Phi = 6 \times 10^{14}\,\mathrm{cm}^{-2}$ resulted in a small but still noticeable increase of the ideality factor at room and lower temperatures. The wide scatter of the SiC radiation hardness in different studies is a known physical problem.[8,11,12] The detailed study of this problem is beyond the framework of this paper.

The current-voltage characteristics shown in Fig. 1 can be considered as steady-state *I-V* dependencies only at relatively large forward biases $V \geq 0.4$ V. At small forward biases, these characteristics depend qualitatively on the ramp of voltage scan dV/dt. Characteristics shown in Fig. 1 were measured at relatively large voltage ramp $dV/dt = 20$ mV/s. The smaller the dV/dt is, the smaller the current is at a given bias V. At $dV/dt < 0.4$ mV/s, the current voltage characteristics are virtually identical for non-irradiated and irradiated diodes. At given constant $V \leq 0.4$ V, current decreases with the time approaching to the value in the non-irradiated structure.

Figure 2 illustrates this process for the sample irradiated with $\Phi = 7 \times 10^{16}\,\mathrm{cm}^{-2}$ in response to $V = 0.1$ V voltage step.

Although it is obvious that this slow relaxation process relates to the deep levels created by electron irradiation, the details of the process are not known. It is noteworthy that this effect is very important for detectors and frequency multipliers operating at small biases.

At high forward voltages, the characteristics are linear and determined by the resistance of the base (Fig. 3). The dependence of the base layer resistivity ρ as a function of the dose is shown in the inset in Fig. 3. Solid line and solid symbols show the results of the present study. As seen, the dependence of the resistivity on irradiation dose is well described by the power law $\rho^{6.8}$. Note that pairs of ρ values correspond to the doses of $4 \times 10^{16}\,\mathrm{cm}^{-2}$ and $7 \times 10^{16}\,\mathrm{cm}^{-2}$ in the inset in Fig. 3. Upper symbols correspond to the ρ values measured just after irradiation. Lower values (lower

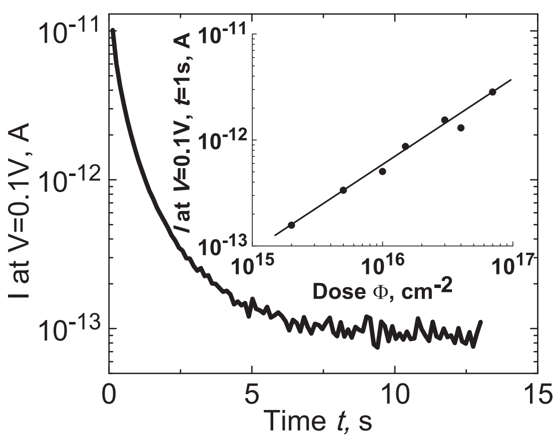

FIG. 2. Transient process of the current drop in response to 0.1 V voltage step. The inset shows the dependence of the forward current I on the dose Φ at $V = 0.1$ V at time $t \sim 1$ s.

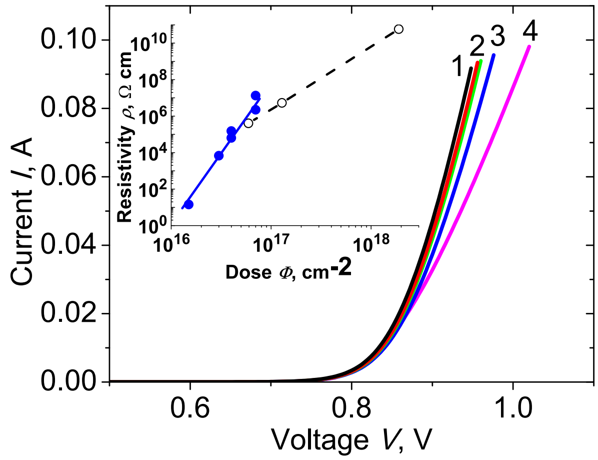

FIG. 3. Forward current-voltage characteristics in linear scale for "low" dose Φ (cm^{-2}): 1–0 (not irradiated), 2–0.2×10^{16} and 0.5×10^{16}, 3–1×10^{16}, and 4–1.5×10^{16}. The inset shows the dependence of the resistivity, ρ, for electron-irradiated n-type 4H-SiC (base layer of Schottky diodes under study) on dose Φ. The solid line represents the data obtained in this study. The dashed line represents the data from Ref. 4.

resistivity) show ρ values after measurements at elevated temperatures ($\sim$470 K, will be discussed later). Open symbols and dashed line are the results from Ref. 4.

Figure 4 shows the dependence of the diode capacitance, C, on Φ at $V = -1$ V and frequency $f = 300$ Hz. The inset in Fig. 4 shows the capacitance frequency dispersion for the diodes with different irradiation doses. Non-irradiated samples demonstrated almost flat dependence at $f > 10^3$ Hz and increase of the capacitance with the frequency decrease below $f < 10^3$ Hz. This capacitance increase is an indication of traps with characteristic emission time $\sim 10^{-3}$ s. In the irradiated samples, these traps are emptied and they do not contribute to the capacitance and its frequency dispersion.

It is noteworthy that the dependences of $1/C^2$ for all diodes, including those with the highest irradiation dose, on the reverse voltage were always linear at least up to $V_r = -40$ V, indicating uniform space charge distribution.

The effect of elevated temperatures on current voltage characteristics was studied in irradiated and non-irradiated samples. The temperature dependence of the base resistance

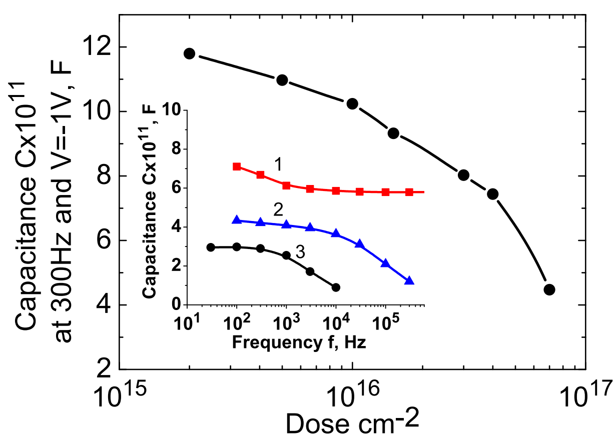

FIG. 4. Dependence of Schottky barrier capacitance, C, at frequency $f = 300$ Hz and $V = -1$ V on dose Φ. The inset represents frequency dependences of C at $V = -10$ V for different doses Φ (cm^{-2}): 1–0; 2–4×10^{16}; and 3–7×10^{16}.

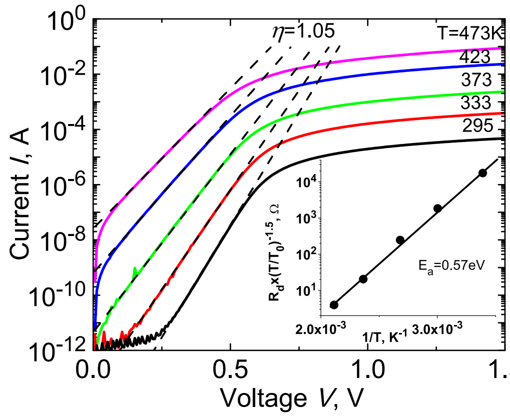

FIG. 5. Current voltage characteristics of the diode with $\Phi = 4 \times 10^{16}\,\mathrm{cm}^{-2}$ irradiation dose. Dashed lines indicate the exponential slope and ideality factor. The inset shows the temperature dependence of the base layer resistance.

in non-irradiated samples was weak and followed well known temperature dependencies of electron concentration and mobility.[13] The evolution of the current voltage characteristics with temperature in the high dose irradiated sample is shown in Fig. 5.

The ideality factor of the exponential part of the characteristics and apparent barrier height calculated based on the thermionic emission (TE) model remained virtually temperature independent even for the highest irradiation dose samples.

The base resistance in irradiated diodes decreased exponentially with temperature growth. The inset in Fig. 5 shows the Arrhenius plot for the base resistance of the sample irradiated with $\Phi = 4 \times 10^{16}\ \mathrm{cm}^{-2}$. The slope of the dependence indicates the activation energy of $E_a = 0.57\,\mathrm{eV}$.

It is well known that the increase of the resistance due to the electron irradiation is caused mainly by the generation of deep $Z_{1/2}$ and $EH_{6/7}$ levels (in equal concentrations).[1,3,4,7] The activation energy of $Z_{1/2}$ determined by other methods is $0.5 < E_a < 0.69\,\mathrm{eV}$.[1,2,7] Therefore, one can conclude that the main contribution to the base resistance temperature dependence comes from the thermal activation of electrons from the $Z_{1/2}$ level.

Heating of the high irradiation dose samples during temperature measurements resulted in partial annealing of the base layer. Figure 6 shows the current voltage characteristics of the highly irradiated sample before and after this kind of "annealing." As seen, the exponential part of the current voltage characteristics remained virtually unchanged, but the base resistance decreased approximately five times. Partial annealing of the sample can also be observed in the decrease of the non-stationary current (see the inset in Fig. 6). It is known that $Z_{1/2}$ defect is stable up to very high temperatures of 1500–1600 °C.[3,7,14] Partial annealing of the defects observed at the low temperature of 473 K indicates that other defects with smaller activation energy are also created by electron irradiation. This kind of low temperature annealing was also observed in earlier publications.[2,3]

In conclusion, the characteristics of class 1.2 kV 4H-SiC Schottky diodes were studied after irradiation by electrons

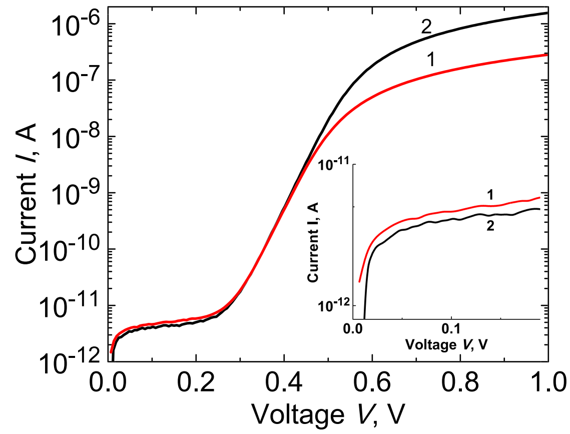

FIG. 6. Current-voltage characteristics of Schottky diodes irradiated with the dose $\Phi = 7 \times 10^{16}\,\mathrm{cm}^{-2}$, just after irradiation (line 1) and after temperature measurement up to 473 K (line 2), $dV/dt = 20\,\mathrm{mV/s}$. The inset shows the same characteristics at low biases.

with an energy of 0.9 MeV. Within the irradiation doses of $1 \times 10^{16} \le \Phi \le 7 \times 10^{16}\,\mathrm{cm}^{-2}$, the base resistivity increases as $\rho \sim \Phi^{6.8}$. The resistivity exponentially depends on temperature with activation energy $E_a = 0.57\,\mathrm{eV}$, which matches the well-known deep level $Z_{1/2}$. Irradiation also led to the non-stationary leakage current at low biases and increase of the ideality factor. Significant increase of the ideality factor and appearance of transient non-stationary current due to irradiation can be attributed to formation of defects close to the semiconductor/metal interface.

At the Ioffe Institute, this work was partly supported by RSF Project No. 16-12-10106.

[1]T. Dalibor, G. Pensl, H. Matsunami, T. Kimoto, W. J. Choyke, A. Schooner, and N. Nordell, Phys. Status Solidi A **162**, 199 (1997).
[2]A. Castaldini, A. Cavallini, L. Rigutti, and F. Nava, Appl. Phys. Lett. **85**, 3780 (2004).
[3]K. Danno and T. Kimoto, J. Appl. Phys. **100**, 113728 (2006).
[4]H. Kaneko and T. Kimoto, Appl. Phys. Lett. **98**, 262106 (2011).
[5]G. Alfieri and T. Kimoto, Mater. Sci. Forum **778–780**, 269–272 (2014).
[6]V. V. Kozlovski, A. A. Lebedev, V. N. Lomasov, E. V. Bogdanova, and N. V. Seredova, Semiconductors **48**, 1006 (2014).
[7]K. Kawahara, X. T. Trinh, N. T. Son, E. Janzén, J. Suda, and T. Kimoto, J. Appl. Phys. **115**, 143705 (2014).
[8]V. V. Kozlovski, A. A. Lebedev, and E. V. Bogdanova, J. Appl. Phys. **117**, 155702 (2015).
[9]E. Omotoso, W. E. Meyer, F. D. Auret, A. T. Paradzah, M. Diale, S. M. M. Coelho, and P. J. Janse van Rensburg, Mater. Sci. Semicond. Process. **39**, 112–118 (2015).
[10]C. Lehmann, *Interaction of Radiation with Solids and Elementary Defect Production*, Defects in Crystalline Solids (North-Holland Publishing Company, 1977).
[11]A. A. Lebedev, A. I. Veinger, V. V. Kozlovski, D. V. Davydov, N. S. Savkina, and A. M. Strelchuk, J. Appl. Phys. **88**, 6265 (2000).
[12]B. G. Svensson, A. Hallén, M. K. Linnarsson, A. Yu. Kuznetsov, M. S. Janson, D. Åberg, J. Österman, P. O. Å. Persson, L. Hultman, L. Storasta, F. H. C. Carlsson, J. P. Bargman, C. Jagadish, and E. Morvan, Mater. Sci. Forum **353–356**, 549 (2001).
[13]Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, and SiGe, edited by M. E. Levinshtein, S. L. Rumyantsev, and M. S. Shur (John Wiley and Sons, New York, 2001), ISBN 0-471-35827-4.
[14]G. Alfieri, E. V. Monakhov, B. G. Svensson, and M. K. Linnarsson, J. Appl. Phys. **98**, 043518 (2005).