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Dependence of the Silicon Carbide Radiation Resistance on the Irradiation Temperature

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Abstract. The effect of high-temperature electron and proton irradiation on SiC-based device characteristics is being investigated. Industrial integrated 4H-SiC Schottky diodes, each with an n-type base and a blocking voltage of either 600 V, 1200 V, or 1700 V, manufactured by Wolfspeed, are being studied. 0.9 MeV electron and 15 MeV proton irradiation were applied. It has been found that the irradiation resistance of silicon carbide Schottky diodes at high temperatures significantly exceeds their resistance at room temperature. This effect is attributed to the annealing of compensating defects induced by high-temperature irradiation. The parameters of radiation-induced defects are determined using the method of deep level transient spectroscopy (DLTS). Under high-temperature ("hot") irradiation, the spectrum of radiation-induced defects introduced into SiC appears to differ significantly from the spectrum of defects introduced at room temperature. It is suggested that approximately half of the compensation is due to radiation-induced defects formed in the bottom part of the bandgap.

Introduction

The first studies of radiation-induced defects (RID) in silicon carbide, carried out in the 1950s–1960s, confirmed the high radiation resistance of this material [1]. It is well known that some crystals studied in those years were heavily doped and had a high density of structural defects. However, as more perfect and purer SiC samples were obtained, their measured radiation resistance gradually decreased. There were studies that indicated that SiC not only does not surpass silicon in terms of radiation resistance but is even inferior to it in some parameters [2-4]. It is also well understood that a decrease in radiation resistance with an improvement in the quality of the material is characteristic of almost every semiconductor material since various structural defects and uncontrolled impurities serve as sinks for RID and thereby reduce the rate of degradation of the material parameters.

However, the comparability of the carrier removal rate in Si and silicon carbide under irradiation looks surprising because the band gap of 4H-SiC (3.2 eV) is almost three times greater than that of silicon. In [5], we suggested that this might be due to different annealing temperatures of primary RIDs in Si and SiC. At 300 K, in silicon, there is noticeable annealing of primary RIDs, while in silicon carbide at this temperature, there is practically no annealing process. To verify this assumption, it seems necessary to study the SiC radiation resistance dependence on the irradiation temperature. The objective of this study was precisely to conduct such investigation.

Experiment

The industrial integrated 4H-SiC Junction Barrier Schottky (JBS) diodes, with an n-type base, and blocking voltages of 600 V, 1200 V, and 1700 V respectively, have been studied. Prior to irradiation, the uncompensated donor impurity concentration (Nd–Na) in the devices mentioned above was approximately 6.5×10^{15}, 4.5×10^{15}, and 3.5×10^{15} cm^{-3}, respectively. Both 0.9 MeV electrons and 15 MeV protons were used for irradiation. The maximum radiation doses were 7×10^{16} cm^{-2} for the electrons and 1×10^{14} cm^{-2} for the protons.

Results and Discussion

Table 1 presents previously obtained data for the carrier removal rate V_d in SiC for irradiation at room temperature. As one can seen, the carrier removal rate in silicon carbide is actually as small as two times lower, than that in silicon. To confirm the hypothesis stated in [5], 4H-SiC JBS structures were irradiated with electrons and protons at temperatures up to 500 ^{0}C. A significant decrease in the carrier removal rate was found with increasing irradiation temperature (see Figure 1).

Table 1. Carrier removal rates in devices based on SiC and Si.

Device type	SiC Schottky diodes 600 V	SiC Schottky diodes 1200 V	SiC JBS 1700 V	Si diodes
N_d-N_a in base region, cm^{-3}	6.5×10^{15}	4.5×10^{15}	3.5×10^{15}	$\sim10^{15}$
V_d (0,9 MeV electrons), cm^{-1}	0.095	0.073	0.06	0.23 [6]
V_d (15 MeV protons), cm^{-1}	63	59	54	110 [7]

When studying the current-voltage characteristics, it was found that with an increase in the irradiation temperature from 23 to 500^{0}C, the base resistance (at an irradiation dose of $1.3\text{x}10^{17}$$cm^{-2}$) decreases by 6 orders of magnitude (see Fig. 2). Similar results were obtained with proton irradiation at elevated temperatures (see Fig. 3 and Fig. 4).

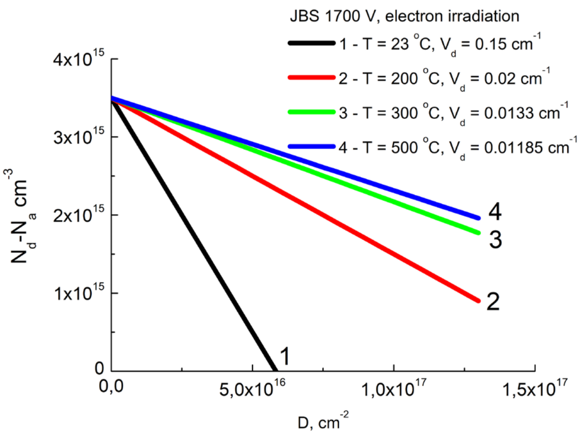

Fig. 1. Concentration *(Nd - Na)* in 1700 V JBS structures dependence on electron irradiation at different temperatures. $Vd_{(23^0C)} = 0.15$ cm^{-1}, $Vd_{(200^0C)} = 0.02$ cm^{-1} , $Vd_{(300^0C)} = 0.0133$ cm^{-1}, $Vd_{(500^0C)} = 0.01185$ cm^{-1} .

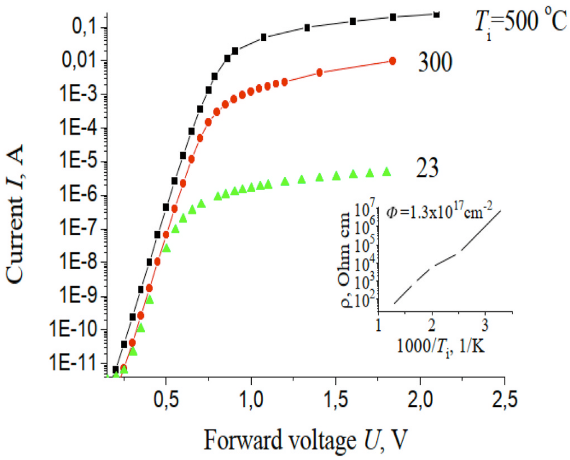

Fig.2. Forward current-voltage characteristics (*CVCs*) of diodes after their irradiation with electrons at three different temperatures *Ti*. The dose is $D = 6\times10^{16}$ cm^{-2}. Insert to Fig. 2: Base resistivity ρ dependence on reciprocal temperature $1/T_i$ after irradiation with a dose of $D = 1.3\times10^{17}$ cm^{-2}

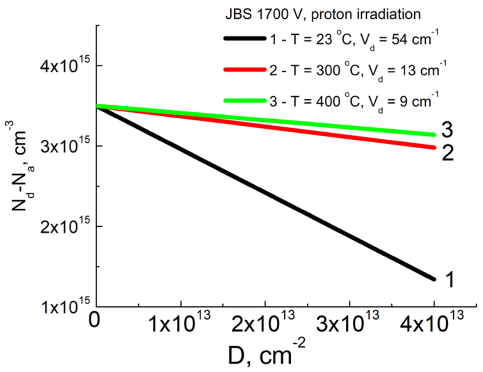

Fig. 3. Uncompensated charge carriers *(Nd - Na)* concentration in 1700 V JBS structure dependences on proton irradiation dose at different temperatures. $Vd_{(23^0C)}$ = 54 cm^{-1}, $Vd_{(300^0C)}$ = 13 cm^{-1}, $Vd_{(400^0C)}$ = 9 cm^{-1}.

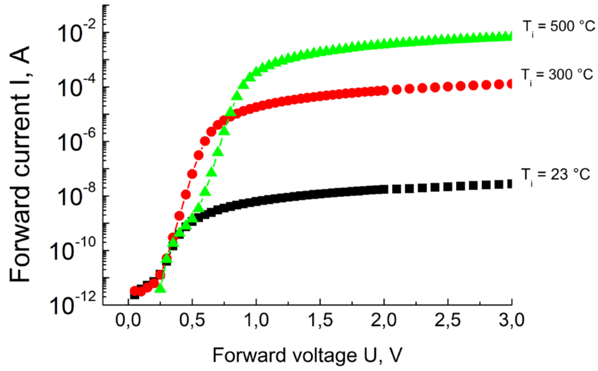

Fig. 4. Forward *CVCs* of diodes irradiated with 15 MeV protons at three different irradiation temperatures T_i. The dose is $D=1\times10^{14}$ cm^{-2}.

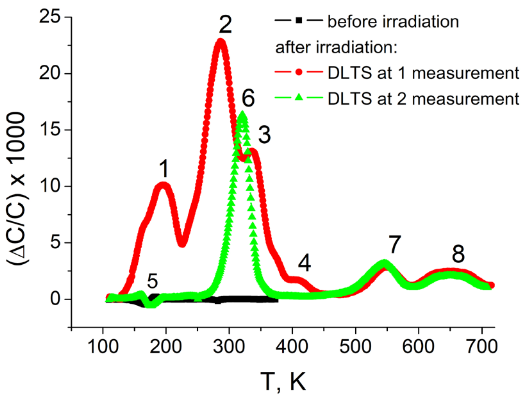

Fig. 5. 0.9 MeV electrons irradiated sample DLT spectra and a dose of 1 x 10^{16} cm^{-2}. 1 – spectrum taken immediately after irradiation; 2 – second-measured spectrum.

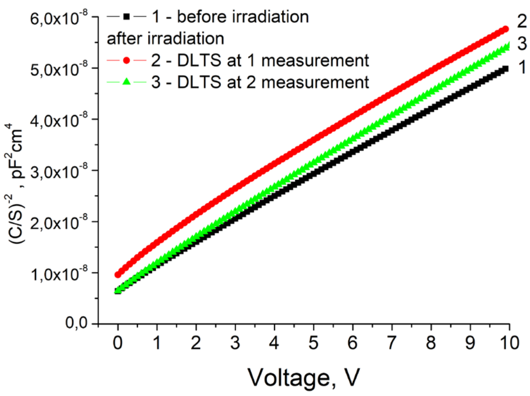

Fig. 6. Voltage-capacitance characteristics *(VCCs)* of the studied samples:
1 – initial (*Nd-Na* = 3.2 x 10^{15} cm^{-3});
2 – prior to irradiation (*Nd-Na*= 3,2 x 10^{15} cm^{-3});
3 – after high-temperature DLTS measurements.

Using the DLTS method, the parameters of deep radiation centers formed after irradiation of SiC were studied.

As had been noted, there might be RID rearrangement partial annealing in 4H-SiC while measuring the DLT spectra [8]. This paper describes DLT spectra we measured at higher temperatures, which noticeably enhanced the annealing effect (Fig. 5). No doubt that annealing is completed already at a temperature of about 400-450 K. As can be seen from Figure 5, at measurement temperatures > 4500K, the DLT spectrum is practically unchanged. Table 2 presents the detected center parameters. Figure 6 shows the sample *VCCs* taken prior and posterior to its irradiation after high-temperature DLT spectra measurements. As one can see from the Figure 6, the irradiation leads to compensating defects formation with a concentration of ~ 2.4 x10^{14} см$^{-3}$. After high-temperature DLTS measurements, approximately half of the compensating defects are annealed and the residual compensation is ~ 1.1 x 10^{14} cm^{-3}.

Table 2. Detected *deep levels* (*deep centers*) parameters

Radiation-induced defects (RID) amount	1	2	3	4	5	6	7	8
Concentration n, cm-3	2.29*1014	5.23*1014	3.17*1014	5.04*1013	1,4 x 1013	3.92x1014	6.9 x 1013	5.9 x 1013
RID ionizing energy Ei, eV	0.575	0.651	0.921	0.73	0,4	0.705	1/14	1.67
Electron capture cross section in RID σn, cm2	3.87*10-10	6.88*10-14	1.12*10-11	1.94*10-16	6.4 x 10-13	2.19*10-14	2,5 x 10-14	4,4 x 10-13
Comparison to the referenced papers [8--12] (ionizing energy, eV)	S1 (0.43)	E2 (0.6)	Most likely this is a distorted peak of the center, Z1/2	E3 (0.72 ÷ 0.74)	Shallow levels of Boron (0. 39)	Z1/2 (0.68)	E5 (1,08)	EH6/EH7 (1,58)
Recharge time of the centers at 300K, τe, sec	1.1 x 10-8	1.1 x 10-3	2 x 10-2	8 x 10-6	0.8 x 10-8	3 x 10-2	4,9 x105	1,5 x 1013

Let's estimate which of the detected *deep levels* can be the main compensating defects in n-4H-SiC. If acceptor level is formed during irradiation in the lower half of the *n*-type zone, then it will be filled with an electron, negatively charged and will contribute to a decrease in the *Nd-Na* value and a decrease in the *n* value.

If the acceptor level is formed in the upper half of the zone, then it will reduce the concentration of free electrons (*n*). But whether it reduces the value of *Nd-Na* or doesn't depend on its depth. If it is a deep level, then it is filled electronically, charged negatively, and reduce *Nd-Na*. If it is shallow (that is less deep) enough, then at *C-V* measurements at room temperature it is emptied, neutral, and doesn't contribute to the value of *Nd-Na.*

When measuring *CVCs,* the *deep center filling degree* is usually differs to that when measuring *VCCs*. As *CVCs* is being measured, this level is in the quasi–neutral region. In this case, this level filling is determined by two processes, namely, thermal emission from the center and reverses capture from the C–zone. I.e., if the level is above the Fermi level, it is emptied, while if it is below it is filled.

When measuring *VCCs*, that level is in the bulk charge layer, there are no carriers in the conduction zone, and everything is determined by thermal emissions from that level. In principle, all levels lying in the upper half of the zone should be emptied after waiting for it sufficiently long. Nevertheless, as *VCCs* is being measured, even during the real time of the experiment, such levels are being emptied, which are deeper as compared to the event at which *CVCs* is being measured.

Annealing performed up to 700 K during DLTS measurements showed that there is a partial restoration of the conductivity of the samples. In this case, all *shallow centers* in the upper half of the zone are annealed, except for Z1/2, EN5 and E6/7 and shallow boron in the lower half of the zone.

The recharge time constant (τ_e) for each of the detected *deep levels* can be estimated by the well-known formula:

$$\tau_e = [\sigma_n V_t N_c \, exp(-E_i/kT)]^{-1}$$

Where V_t is the thermal velocity of charge carriers, N_c is the density of states in the conduction band, k is the Boltzmann constant, and T is the absolute temperature.

Data from Table 2 were used for the calculation. The value of V_t at 300 K was assumed to be 10^7 cm/sec, and $N_c = 8.9 \times 10^{19}$ cm^{-3} [13].

The recharge time constants of all detected *deep levels* in the upper half of the zone (except E5 and E6/7) are small (see Table 2), significantly less than the time of *VCC* measurements. Thus, all these centers do not contribute to the decrease in the value of *Nd-Na*. Only EN5 and E6/7 can give such a

contribution. Moreover, these centers were not annealed during high-temperature DLTS measurements. Their total concentration (~ 1.3 x 10^{14} cm^{-3}) is close to the value of residual compensation of the studied samples (~1.1 x 10^{14} cm^{-3})
In [10], it was concluded that the compensation of conductivity in n-4H SiC under electron irradiation occurs due to the formation of Z1/2 and E6/7 centers. The above analysis shows that the compensation pattern of n-4H SiC is somewhat more complicated. Approximately half of the compensation, when irradiated at room temperature, is due to the formation of *deep levels* in the lower half of the band gap.

Summary

The conducted studies allow us to draw the following conclusions:
1. An increase in the irradiation temperature leads to an increase in the radiation resistance of silicon carbide. This is important for SiC since this material is considered, first of all, as a material for creating high-temperature electronic devices.
2. The decrease in the rate of removal of carriers in SiC at elevated irradiation temperatures is due to the annealing of the resulting RIDs at temperatures of 300–450 K.
3. It is concluded that approximately half of the compensation, when irradiated at room temperature, is due to the *deep levels* formation in the lower half of the band gap.

Acknowledgments

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