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Radiation Damage in 4H-SiC and Its Effect on Power Device Characteristics

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Abstract. The effect of neutron, electron and ion irradiation on electrical characteristics of unipolar 1700V SiC power devices (JBS diodes, JFETs and MESFETs) was investigated. DLTS investigation showed that above mentioned projectiles introduce similar deep acceptor levels (electron traps) in the SiC bandgap which compensate nitrogen shallow donors and cause majority carrier (electron) removal. The key degradation effect occurring in irradiated devices is the increase of the ON-state resistance which is caused by compensation of the low doped *n*-type epilayer and simultaneous lowering of electron mobility. In the case of SiC power switches (JFET, MOSFET), these effects are accompanied by the shift of the threshold voltage. Radiation defects introduced in SiC power devices is unstable and some defects anneal out already at operation temperatures (below 175°C). However, this does not have significant effect on device characteristics.

Introduction

Recent improvements in 4H-SiC polytype allowed for commercialization of different power devices (Schottky diode, Junction Barrier Schottky (JBS) diode, vertical JFET and MOSFET) up to the voltage class of 1700V [1,2]. In this contribution, we investigate the effect of irradiation with different particles (neutrons, electrons, ions) on radiation defects production in *n*-type 4H-SiC epilayer which are forming the active region of the abovementioned devices. The effect of radiation damage on their electrical characteristics is then thoroughly discussed, as well.

Experimental

Devices under test were 10A/1700 V SiC JBS power diodes (C3D10170H diodes and CPW31700S010B chips) and C2M1000170D power MOSFETs produced by Cree™ [1] and vertical 1700 V normally OFF trench SiC power JFETs SJEP170R550 from SemiSouth [2]. All devices were fabricated on 4H-SiC epilayers grown on heavily nitrogen doped SiC substrate. Devices were irradiated with different particles: fast neutrons with fluences up to 4×10^{14} cm^{-2} (1MeV Si equivalent), 4.5 MeV electrons with doses up to 2000 kGy, 670 keV protons and 9.6 MeV carbon ions (fluences ranging from 3×10^{9} to 6×10^{10} cm^{-2}; the damage peak maximum located 2.5 µm below the surface of the SiC epilayer). Radiation defects, their thermal stability and influence on device characteristics were characterized by capacitance deep level transient spectroscopy (DLTS), C-V profiling and I-V measurement.

Results and Discussion

The effect of irradiation with neutrons, electrons, protons and carbon ions on radiation defect production in 4H-SiC *n*-type epilayers is compared in Fig.1 where DLTS spectra recorded on as-irradiated JBS diodes are presented. Presented DLTS spectra show that irradiation with above

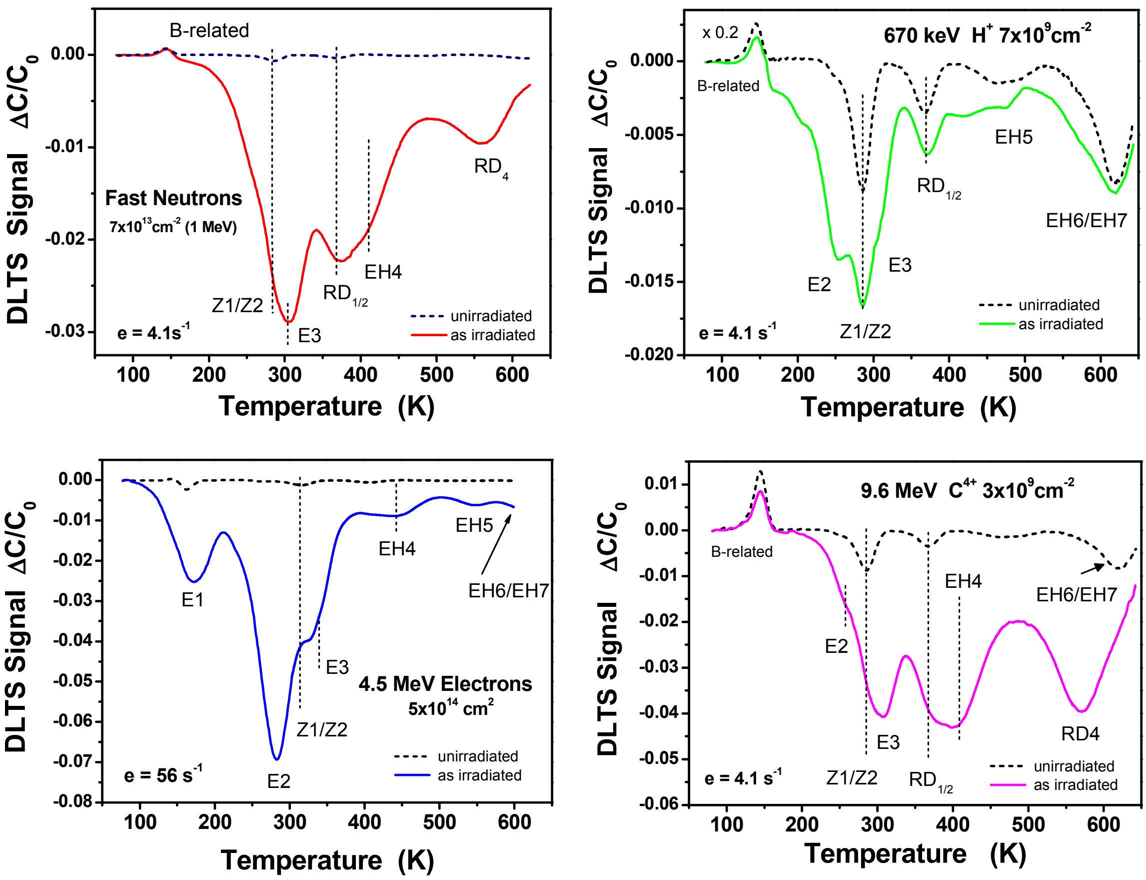


Fig.1 DLTS spectra of 4H-SiC n-type epilayer irradiated with fast neutrons (upper left), 4.5 MeV electrons (lower left), 670 keV protons (upper right), and 9.6 MeV carbon ions (lower right). First temperature scan, rate window 4.1 s^{-1} (neutron, proton and carbon irradiation) and 56 s^{-1} (electrons).

mentioned particles introduce similar series of deep levels (peaks) acting as traps of electrons. Identification parameters of these deep levels including their identity are shown in Table 1. For irradiation with light charged particles (electrons, protons), the most important from the point of device operation are two deep levels labeled E2 and E3 lying 0.60 and 0.72 eV below the edge of the conduction band. Carbon and neutron irradiation give rise to increased production of deep lying and more stable defect centers $RD_{1/2}$ and RD_4 which are typical for irradiation with heavier ions [9].

Table 1: Identification parameters of deep levels registered in n-type 4H-SiC epilayer after irradiation with neutrons (n), electrons (e), H and C ions.

Level	Projectile	Bandgap position [eV]	Capture cross section [cm^2]	Literature
E1	e	$E_C - 0.39$	$6x10^{-15}$	[3,4,5]
E2	e/H/C	$E_C - 0.60$	$4x10^{-14}$	[3,4,5]
Z1/Z2	e/n/H/C	$E_C - 0.68$	$6x10^{-14}$	[4,6,7]
E3	e/n/H/C	$E_C - 0.72$	$7x10^{-14}$	[3,4,5]
$RD_{1/2}$	n/H/C	$E_C - 0.88$	$3x10^{-14}$	[8,9]
EH4	n/C	$E_C - 1.04$	$6x10^{-14}$	[4,6,7]
EH5	e/H	$E_C - 1.10$	$5x10^{-15}$	[4,6,7]
RD_4	n/C	$E_C - 1.45$	$8x10^{-14}$	[8,9]
EH6/7	e/H	$E_C - 1.64$	$3x10^{-13}$	[4,6,7]

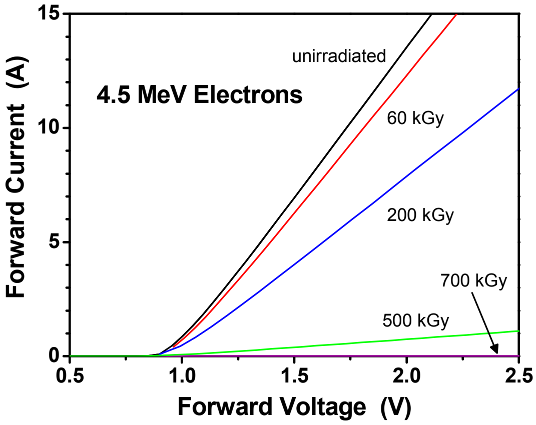


Fig.2 Room temperature forward I-V characteristics of SiC JBS diodes CPW31700S010B irradiated with different fluences of 4.5 MeV electrons.

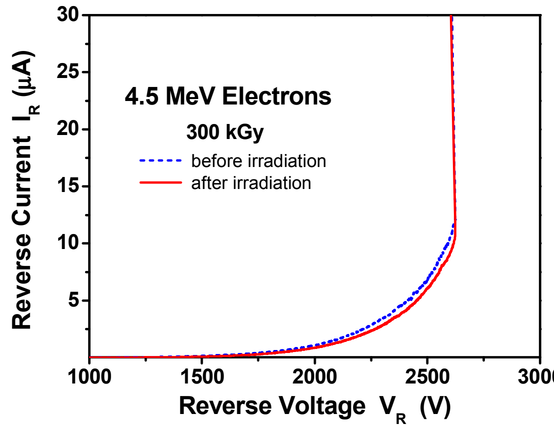


Fig.3 Room temperature reverse I-V characteristics of SiC JBS diode CPW31700S010B measured before and after irradiation with 300 kGy of 4.5 MeV electrons.

Radiation defects produced by electron and neutron irradiation are homogeneously distributed in epilayer [10,11], while irradiation with protons and carbon ions produces strongly localized damage (deep levels) peaking at range ion's projected range. In this case, the profile of deep levels follows well the distribution of primary damage (Bragg curve) [12,13]. Compared to silicon, defect introduction rates are high. Our investigations show [10-13] that up to ten percent of primary generated damage, Frenkel's pairs, transforms to stable defects. Since majority of introduced defects, namely the E1, E2, E3 and Z1/Z2 centers, exhibits acceptor character, the lightly doped *n*-type layers of devices are quickly compensated. In the case of JBS diodes working in the unipolar regime (only the Schottky part of the JBS structure activated), this compensation degrades namely the ON-state characteristics (see Fig.2). With increasing irradiation dose, the ON-state resistance increases and, when the epilayer becomes fully compensated (above the dose of 500 kGy), the diode loses its functionality. Our investigations show that the increase of the ON-state resistance is given by decrease in electron concentration and mobility. For electron and neutron irradiated *n*-type epilayers, the decrease in electron concentration can be described by equation [14]

$$n = n_0 - K_N \cdot \phi \qquad (1)$$

where n_0 and n are the pre- and post-irradiation electron concentrations in the epilayer, Φ is the particle fluence and K_N is the corresponding carrier removal rate (K_N=14 cm^{-1} for 1MeV neutrons equivalent and 1.0 cm^{-1} for 4.5 MeV electrons). Detailed simulation of the ON-state characteristics of the JBS diode and their comparison with experimental ones [11] shows that electron mobility significantly degrades with irradiation dose due to the increased number of radiation defects

$$\mu_n = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + (N_D/C_r)^{\alpha} + (N_T/C_t)^{\beta}} \qquad (2)$$

In this formula, N_D is the total doping concentration, N_T is the total concentration of deep levels, $C_r = 2\cdot10^{17}$ cm^{-3}, $\alpha = 0.76$, $C_t = 2.3\cdot10^{15}$ cm^{-3}, $\beta = 2.9$ are fitting parameters, and mobilities for the plane <1120> are: $\mu_{max<1120>}$ = 920 cm^2/V·s, $\mu_{\min}$ = 10 cm^2/V·s, for the plane <0001>: $\mu_{max<0001>}$ = 830 cm^2/V.s, $\mu_{\min}$ = 10 cm^2/V·s.

On the other hand, radiation damage does not have a significant effect on blocking characteristics of SiC devices. Both the breakdown voltage and leakage stay nearly unchanged (see Fig.3).

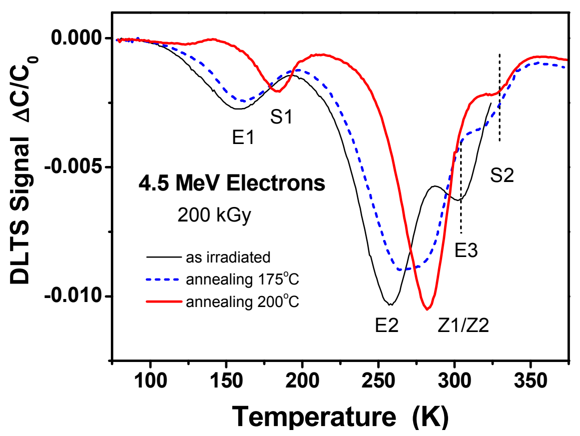


Fig.4 Majority DLTS spectra measured in the 4H-SiC epilayer irradiated with 200 kGy of 4.5MeV electrons during different stages of 30 minutes isochoronal annealing: 25, 175 and 200 ºC, rate window 4.1 s^{-1}.

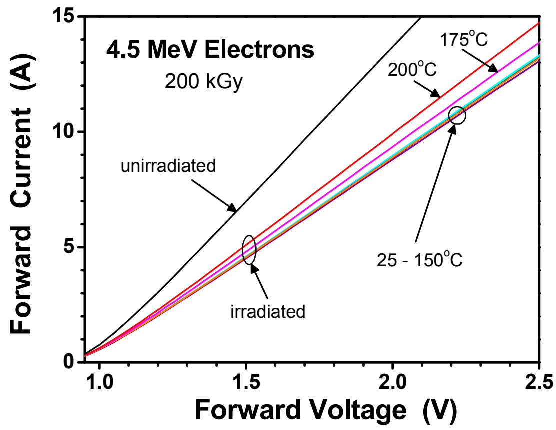
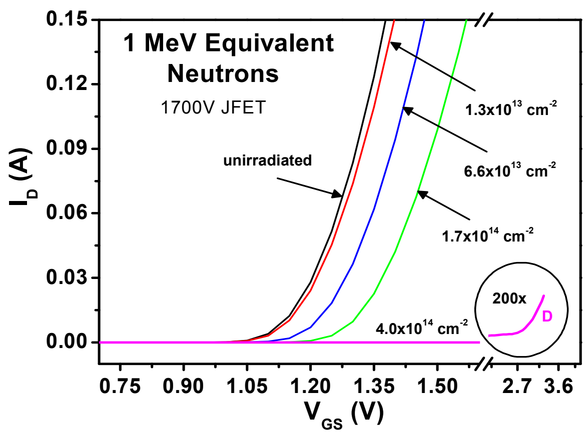


Fig.5 Room temperature forward I-V characteristics of SiC JBS power diode irradiated with 200 kGy of 4.5MeV electrons measured after 30 minutes isochoronal annealing at temperatures ranging from 25 to 200ºC.

Radiation damage produced by neutrons, electrons and swift ions in SiC is unstable. Annealing in the temperature range of device operation (up to 200°C) results in transformation of thermally unstable defects evidenced by the E1, E2, and E3 features to S1, Z1/Z2 and S2 centers (see DLTS spectra shown in Fig.4). The S1 and S2 centers then disappear after annealing at temperature higher than 300 °C. The annealing of E1-E3 defects and their transformation to Z1/Z2 centers does not change significantly the ON-state characteristics of irradiated diodes (see Fig.5). In the temperature range of device operation (below 175°C), the change in the forward voltage drop is negligible. Increasing of device temperature above 175°C then leads to a partial recovery of JBS diode's ON-state characteristics.

We showed above, that the key degradation mechanism in irradiated JBS diodes is the compensation of the low doped *n*-type epilayer and the lowering of electron mobility. In the case of SiC active power switches, the effect of radiation damage is more complicated and additional degradation phenomena have to be considered. The effect of neutron irradiation on electrical characteristics of the 1700V SiC power JFET SJEP170R550 is shown in Fig.6 where the variation



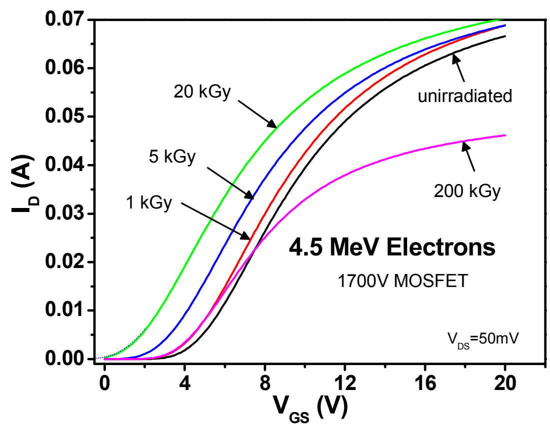


Fig.6 Variation of the transfer characteristics I_D=f(V_{GS})@V_{DS}=5V of the 1700V SiC power JFET SJEP170R550 SiC irradiated with different fluences of neutrons (room temperature measurement).

Fig.7 Variation of the transfer characteristics I_D=f(V_{GS})@V_{DS}=50mV of the 1700V SiC power MOSFET C2M1000170D with applied dose of 4.5 MeV electrons (room temperature measurement).

of transfer characteristics I_D=f(V_{GS})@V_{DS}=5V with increasing fluence of neutrons is presented. First, transfer characteristics show relatively small increase in threshold voltage V_{TH} and decrease in transconductance g_m with increasing fluence of neutrons. At a neutron fluence of $1.7x10^{14}$ cm^{-2}, the ON-state resistance $R_{DS(ON)}$ of the JFET starts to grow sharply (not shown) and, for higher irradiation fluences ($4x10^{14}$ cm^{-2}), JFET loses its functionality. Simulation showed [14] that the shift in threshold voltage is given by following degradation mechanisms: the removal of electrons in the channel, the removal of holes in the P^+ gate region, and the embedding of the surface states at the interface between SiC and SiO_2 passivation. The sharp increase of $R_{DS(ON)}$ (V_{TH}) and a subsequent loss of JFET's functionality is caused by a loss of conductivity of the drift region (epilayer) since this lightly doped region is the most sensitive to the decrease in electron concentration and mobility.

In the case of SiC power MOSFET, the effect of irradiation is similar. Fig.7 shows the variation of the transfer characteristics I_D=f(V_{GS})@V_{DS}=50mV of the 1700V SiC power MOSFET C2M1000170D with applied dose of 4.5 MeV electrons. This experiment was performed on the set of devices with nearly identical electrical parameters so the effect the total irradiation dose on transfer characteristics can be compared directly. As can be readily seen, already very low doses of electron irradiation cause a significant lowering of V_{TH} which decreases rapidly and goes out of the specification (V_{TH} > 2.4V@I_D=0.5mA) already for doses higher than 1 kGy. This effect, which was already registered on gamma ray irradiated 1200V SiC MOSFETs [15], is caused by increasing of interface state density. On the other hand, SiC MOSFETs keep their functionality and remaining key parameters like $R_{DS(ON)}$ are nearly unchanged. When electron dose exceeds 20 kGy, the threshold voltage start to move back to its original value, however, the ON-state resistivity increases and transconductance is lowered. As in the case of JBS diodes of the same voltage class (compare with Fig.2), this effect is connected with introduction of acceptor centers into the low doped *n*-type epilayer (drift region). Again, the sharp decrease of conductivity in the drift region causes a sharp increase of $R_{DS(ON)}$ and subsequent loss of device functionality.

Summary

The effect of irradiation with different particles (neutrons, electrons, ions) on electrical characteristics of 1700V SiC power devices (JBS diodes, JFETs and MESFETs) was investigated. We showed that irradiation with these projectiles introduces deep acceptor levels in the SiC bandgap which compensate nitrogen shallow donors and cause majority carrier (electron) removal. After neutron and electron irradiation, these deep levels are uniformly distributed while protons and carbon ions produce strongly localized damage peaking at ion's projected range. The key degradation mechanism causing malfunction of unipolar SiC power devices is the increase of the ON-state resistance which is caused by the compensation of the low doped n-type epilayer and simultaneous lowering of electron mobility. In the case of SiC power switches (JFETs and MOSFETs), these effects are accompanied by the shift of the threshold voltage. While JFETs are not so sensitive to the shift of the threshold voltage with increasing dose, the MOSFET's threshold voltage decreases rapidly and goes out of the specification already at very low irradiation doses (<5kGy for electrons). Radiation damage introduced in SiC power devices is unstable and some dominant defects anneal out already at operation temperatures (below 175°C). However, this does not have a significant effect on device characteristics.

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