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Electron induced damage effects in 4H-SiC Schottky diodes

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Abstract. Deep level transient spectroscopy (DLTS) and capacitance-voltage (C-V) characteristics were used to investigate the effects induced by electron irradiation on the majority carrier traps in Schottky diodes prepared on 4H silicon carbide (SiC) epilayers grown by chemical vapor deposition (CVD). Electron beam induced current (EBIC) method was applied to measure the change in minority carrier diffusion length L related to the generation of traps by electron irradiation. Several energy levels were detected and their concentration monitored as a function of the irradiation dose. The correlation with the diode charge collection efficiency is also reported.

Introduction

Irradiation is being used as a powerful investigation tool of semiconductor materials properties for both physics and applications, namely high-energy particle experiments. Indeed, the high radiation doses associated with high luminosity beams at the future high-energy particle colliders (such as the Large Hadron Collider at the CERN Laboratory) impose severe demands on the radiation hardness of the semiconductor detectors used in the tracking regions [1]. Because of the high radiation hardness of silicon carbide (SiC), there is a great interest in the applicability of silicon carbide radiation detectors. It has been already demonstrated that SiC is a useful material for the realization of neutron [2] and charge particle [3-5] detectors, of dosimeters [6] and spectrometers [7], keeping good performance and potential operating in radiation rich environments [5-8].

Irradiation induced defects are an issue of major importance for all radiation detectors, because they can drastically degrade the detection properties, like energy resolution (FWHM) and charge collection efficiency (CCE) of the detectors [9-11]. Since both drift and diffusion charge transport mechanisms of the generated charge carriers contribute to the values of FWHM and CCE in epitaxial SiC detectors [4,12], an accurate quantitative analysis of the effect of the damage due to irradiation on the generation of traps, hence on their associated deep levels in the energy gap, is mandatory [13 and 14, and wide literature therein]. Deep level transient spectroscopy (DLTS) has been performed by several authors to monitor the defects due to irradiation by several kinds of particles and, whenever possible, to identify their structure matching DLTS results with results from other measurements. This study has been extensively performed in 6H SiC, but only recently it was applied to 4H SiC.

For this reason we have started a thorough investigation of the effects induced by charged particles on 4H SiC. This paper aims to characterize irradiation induced deep levels associated to defects in Schottky diode detectors realized on epitaxial semiconducting 4H-SiC in view of its new application as minimum ionizing particle (MIP) detectors. To this purpose, DLTS investigations have been performed before and after irradiation with 8.6MeV electrons at different doses. Electron beam induced current (EBIC) analyses have been also carried out to monitor the minority carrier diffusion length.

Experimental

Schottky diodes on epilayers on 4H-SiC substrates of CREE Research Inc. Company were investigated to assess their behavior after exposure to electron irradiation. The wafer diameter was 35mm, 360 μmm thick, nitrogen doped with substrate net doping density of $1x10^{18}$ cm^{-3} and selected micropipe density ($10/cm^2$). The epilayer was n-type, 30 μm thick, with net concentration of $2.5x10^{15}$ cm^{-3}. The Si-face was polished and the C-face ground. For all the diodes the ohmic contact, realized on the whole back-surface of the substrate (C-face), was obtained by deposition of 1000Å thick multilayer of Ti/Pt/Au, followed by annealing at 500°C for 30s in argon ambient. Before the fabrication of the Schottky barriers, after the standard cleaning in organic solvents the native oxide layer on the Si surface of the epilayers was removed by a dry sputter etching with 200eV argon ions. Au contacts on the epilayer were deposited by the RF magnetron sputtering method at room temperature and patterned by photolithography. The diameter of the Schottky contacts was 1.415 mm or 2.000 mm, both kinds 1000Å thick and with two guard rings.

The irradiation was carried out at 26°C at CNR-ISOF (Italy) Laboratory with 8.6 MeV electrons of a LINAC accelerator at the three doses of 2, 10 and 40 Mrad. The charge collection efficiency (CCE) was measured by the standard procedure, which normalizes the pulse height with respect to the response obtained in the same experimental condition of a Si p/n junction detector with the energy needed to produce one electron-hole pair being 3.60 eV and 8.40 eV in Si and SiC, respectively.

Results and Discussion

Current-voltage and capacitance-voltage analyses have been carried out before and after electron irradiation both to assess the electric contact reliability and to measure the free carrier concentration N_{eff} . It results that the free carrier concentration decreases monotonically with increasing electron dose (Fig. 1) from the as-prepared value of $7.71x10^{15}cm^{-3}$ to $1.39x10^{15}cm^{-3}$ in the highest dose (40 Mrad) irradiated samples. This finding strongly suggests that irradiation generates new traps and/or increases the density of the pre-existing traps.

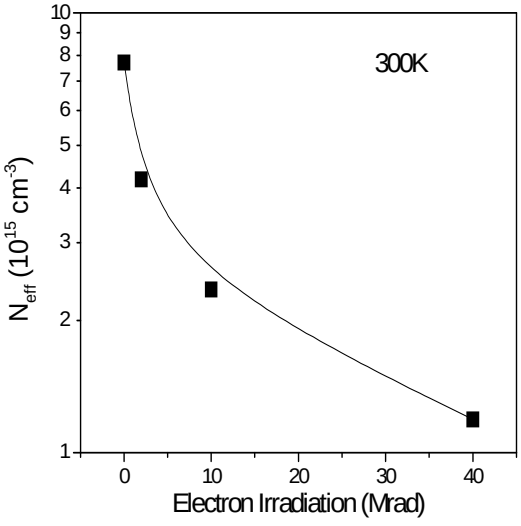

Figure 1 Free carrier concentration dependence on irradiation dose.

This hypothesis was expectedly confirmed by the DLTS analyses performed from liquid nitrogen temperature to 500 K, which detected an increasing number of deep levels by increasing the electron irradiation dose. Namely, in the as-prepared Schottky diodes we found two traps, S0 and S5, at 0.15 and 0.89 eV from the edge of the conduction band E_c, respectively. After exposure to the electron beam we observed further four traps, labeled from S1 to S4, with activation energy (E_c - 0.23 eV), (E_c - 0.39 eV), (E_c - 0.63 eV) and (E_c - 0.75 eV), respectively. Table 1 summarizes the DLTS results concerning the diodes irradiated at 40 Mrad, and it reports activation energy from the conduction band edge, level density N_T and capture cross section σ_{inter} estimated from the intercept of the Arrhenius plot.

It is noteworthy to stress that each trap increases with its own peculiar rate: the density of S0 is nearly independent of the electron exposure while the density of S3 increases from the value of $1.9x10^{13}cm^{-3}$ after 2 Mrad irradiation to $4.2x10^{14}cm^{-3}$ after

Table 1. The energy position, the concentration and the capture cross section for the trap observed in 4H-SiC irradiated with an electron dose of 40 Mrad.

Trap level	E_T (eV)	N_T (cm^{-3})	σ_{inter} (cm^2)
S0	E_c - 0.15	1.4×10^{13}	6.0×10^{-16}
S1	E_c - 0.23	5.5×10^{13}	9.3×10^{-16}
S2	E_c - 0.39	4.0×10^{14}	1.7×10^{-15}
S3	E_c - 0.63	4.2×10^{14}	2.0×10^{-15}
S4	E_c - 0.75	1.3×10^{14}	6.6×10^{-15}
S5	E_c - 0.89	4.6×10^{13}	7.2×10^{-15}

40 Mrad irradiation. Since this finding can be correlated to the defect formation energy, we are on going to study both defect generation rate and filling kinetics in order to identify the defect origin.

Most of the traps observed in this contribution were already reported in the literature for irradiated 4H SiC [see, for example, 15-17] and were attributed to various defects intrinsic in nature (vacancies, Si and C interstitials and/or combinations thereof). The attribution of the traps found in this work to deep levels reported in the literature was assessed by comparing the Arrhenius plots, and we found a good correlation with the available data, thus confirming the results reliability.

However, we also observed that performing DLTS measurements on *fresh* diodes, i.e. not previously tested by DLTS, the spectra and the corresponding activation energy values are slightly different. Figure 2 shows DLTS spectra obtained just on the as-prepared diode (first run) and by a successive DLTS analysis. It is evident that a few traps keep the same features (S0, S4 and S5) while the others evolve to new thermal emission characteristics. By excluding a time-recovery effect on the basis of experimental observations, we can conclude that the highest temperature reached during the DLTS measurements, which means 500 K, produces to a certain extent an *annealing* effect on some of the traps generated by the irradiation. The same effect was previously observed [18] for the level at (Ec–0.70eV) after thermal treatment at 500º C, but the present results indicate that it involves more than a single level and is effective also at lower temperature.

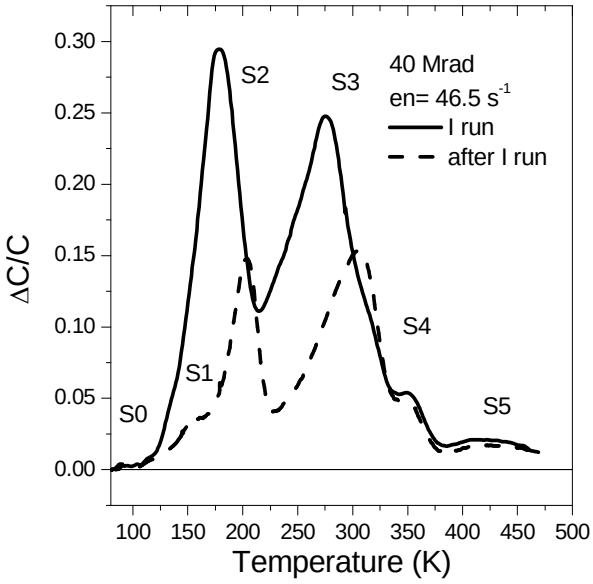

Figure 2 DLTS spectra of 40Mrad irradiated diode. Continuous line refers to the first experiment, dashed line to the successive experiments.

To evidence the electron exposure effects on the minority carrier behavior, we performed electron beam induced current (EBIC) measurements [19,20]. We obtained that the hole diffusion length L ranges from 0.55 to 0.94 μm, apparently without a one-to-one correlation with the irradiation dose. Even if further investigations on statistically more significant sample population need, from the above results we can infer that the

minority carrier diffusion is not controlled by those traps, the density of which dramatically increases with irradiation.

CCE decreases with the dose, exhibiting an initial fast decrease after 2 Mrad irradiation while the data obtained at 10 and 40 Mrad are nearly the same.

Conclusions

We performed irradiation of 4H-SiC using 8.6 MeV electrons. Capacitance-voltage characteristics show that the net free carrier concentration decreases, and DLTS results indicate that this phenomenon is due to the generation of *new* traps by the irradiation. Some of these traps are, however, thermally unstable since we observed that they are reduced and, additionally, change their thermal emission characteristics after thermal treatment at 500°C.
The minority carrier diffusion seems not to be affected by the irradiation induced energy levels, while the CCE keeps constant after the initial decrease at the first irradiation steps.

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