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Point defects in 4H–SiC epilayers introduced by neutron irradiation

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ABSTRACT

Electronic properties of radiation damage produced in 4H–SiC by neutron irradiation and its effect on electrical parameters of Junction Barrier Schottky (JBS) diodes were investigated. 4H–SiC N-epilayers, which formed the low-doped N-base of JBS power diodes, were irradiated with 1 MeV neutrons with fluences ranging from 1.3×10^{13} to $4.0 \times 10^{14}\ \mathrm{cm}^{-2}$. Radiation defects were then characterized by capacitance deep-level transient spectroscopy, *I–V* and *C–V* measurement. Results show that neutron irradiation introduces different point defects giving rise to acceptor levels lying 0.61/0.69, 0.88, 1.03, 1.08 and 1.55 eV below the SiC conduction band edge. Introduction rates of these centers are ranging from 0.64 to 4.0 cm^{-1}. These defects have a negligible effect on blocking and dynamic characteristics of irradiated diodes. However, the acceptor character of introduced deep levels and their fast introduction deteriorate diode's ON-state resistance already at fluences exceeding $1 \times 10^{14}\ \mathrm{cm}^{-2}$.

1. Introduction

Due to its outstanding properties (wide bandgap, high electric and mechanical strength, high thermal conductivity and stability, and high radiation resistance), silicon carbide (SiC) is suitable material for fabrication of high-power and high-frequency devices or electronics operating at high temperatures and radiation levels. SiC devices are advantageous for space applications, energy efficient power control, high-energy particle detection, production of sensors keeping record of nuclear materials and nuclear waste, etc. However, only the recent improvements in 4H–SiC polytype allowed for its industrial application. At present, the high-voltage SiC devices are used for efficient power conversion in the areas where they can outperform current silicon low power devices. The most frequent device is the Schottky barrier diode and its derivatives like Junction Barrier Schottky (JBS) diode [1] which have been commercialized up to 1700 V voltage classes. The JBS diode, where the anode region is formed by P^+-ohmic and N-Schottky contacts short-circuited with the same anode metallization, combines the advantages of both bipolar PiN and Schottky diodes. JBS diode therefore offers Schottky-like ON-state and switching characteristics (low forward voltage drop and no reverse recovery) and PiN-like OFF-state characteristics (low leakage and high blocking voltage).

Taking into account possible applications of SiC devices in radiation environment of nuclear reactors or nuclear waste, deeper understanding of lattice defects which can be introduced by neutron irradiation is necessary. Likewise silicon devices, the SiC devices are exposed to cosmic radiation, which can cause their failure. Detailed knowledge about radiation defects (vacancies, interstitials and their related defects) is of key importance since they are giving rise to deep levels in the SiC bandgap that can, in relatively small amount, significantly influence electrical characteristics of irradiated devices. Over the last years, the research in this field was mainly focused on understanding of the detection performances of 4H–SiC detectors after heavy neutron irradiation [2]. Substantially lower attention was then paid to investigation of degradation of SiC power devices working in the proximity of radiation field of nuclear power reactor [3]. In this contribution, we show the effect of neutron irradiation on radiation defect production in low doped 4H–SiC epilayers which are used as an active layer of JBS power SiC diodes.

2. Experimental

Devices under test were CPW3-1700-S025B chips of 25 A/1700 V JBS power diodes produced by Cree™. Diodes were fabricated on 4H–SiC epilayers grown on heavily nitrogen doped N^+ (0.025–0.028 Ω cm) 360 μm thick SiC substrate. Thickness of the N-epilayer was 20 μm and the level of nitrogen doping about $5 \times 10^{15}\ \mathrm{cm}^{-3}$. Diode has a tungsten Schottky barrier and its active area is 16.8 mm^2.

Diodes were irradiated with four different fluences of neutrons in the LR-0 light-water, zero-power, pool-type nuclear reactor in Research Centre Řež, Czech Republic. The neutron irradiation was accompanied by gamma-rays irradiation (see the neutron and photon spectra in Fig. 1). The equivalent 1 MeV neutron fluences

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calculated according to NIEL (non-ionizing energy loss) scaling in silicon were: 1.3×10^{13}, 6.6×10^{13}, 1.7×10^{14}, and 4×10^{14} cm^{-2}. Radiation defects, their thermal stability and influence on diode characteristics were then characterized by capacitance deep-level transient spectroscopy (DLS-82E and 83D spectrometers from Semilab Ltd.), capacitance to voltage (*C–V*) profiling and current to voltage (*I–V*) measurement.

3. Results and discussion

The effect of neutron irradiation on radiation defect production in 4H–SiC N-type epilayer is shown in Fig. 2. The figure compares majority DLTS spectrum of an unirradiated diode with spectra recorded immediately after 1 MeV neutron irradiation to fluences of 1.3×10^{13} and 6.6×10^{13} cm^{-2} (the first DLTS temperature scan to 350 °C – thick lines) and spectra taken after subsequent 30 min annealing at 350 °C which was necessary for the DLTS analysis in the full temperature scale (thin lines). The DLTS spectra measured after irradiation show that neutron irradiation introduces different defects evidenced by broad features peaking at 304, 370 and 563 K. They are most likely given by superposition of several peaks (defects) with close activation energy. The positive DLTS peak labeled H144, which appears in all measured spectra, is then given by capture of holes on the acceptor level of boron [4]. Comparison of the DLTS spectra measured before and after annealing shows that radiation damage produced by neutron irradiation is unstable, especially the broad peak E304. This peak, usually referred as S3 [5], is a dominant feature of the DLTS spectra measured in 4H–SiC irradiated by electrons, neutrons, protons and alphas [3,5–8]. In electron irradiated samples [5,6], it is usually accompanied by a satellite level S2 at $E_C - 0.39$ eV which is attributed to the carbon interstitial (C_i). The origin of the E304 peak is still under discussion. Increasing the temperature above 50 °C causes fast disappearance of E304, which is probably given by low thermal stability of related radiation defects, and shift of its temperature position. This shift occurring during annealing between 50 and 200 °C is interpreted either as a release of the stress produced by defect clusters introduced by irradiation or by removing of the 3C polytype (with smaller bandgap) which can be created in the damaged region by irradiation induced stacking faults [6]. After annealing at 350 °C, DLTS spectra shows five stable peaks E282, E370, E400, E481, and E563. The identification parameters of deep levels connected with these defects, their introduction rates and tentative identity are shown in Table 1. The spectra are very close to those obtained on identical SiC epilayers irradiated with protons or alphas which were annealed at 325 °C [9]. However, significant difference is the appearance of the level E370 in our spectra of SiC irradiated by neutrons. This level which was attributed to positively charged silicon vacancy V_{Si}^{+} [3] represents one of the dominant defect centers in neutron irradiated 4H–SiC. The distinctive peak E284, which appears already in the DLTS spectrum of the unirradiated sample and arises by transformation of E304 during annealing, was identified as the Z1/Z2 electron trap. This intrinsic acceptor-like defect appears at low concentrations in as-grown material and is enhanced by irradiation. The Z1/Z2 trap is observed as a two electron emission from the defects, and therefore the E284 peak is two times higher than that of a normal trap [8]. This center is very stable. It starts to anneal out at 1300 °C and retains even annealing at 2000 °C [7]. Many interpretations have been proposed for the possible structure of this defect: a divacancy ($V_{Si} + V_C$), silicon vacancy (V_{Si}), antisite pair ($Si_C + C_{Si}$), a pair of an antisite and a vacancy of different atoms, Si antisite, carbon interstitial or anitisite [8]. Recent investigation lead to conclusion that the Z1/Z2-center is the acceptor state of the carbon vacancy (V_C) [10]. The level E400 is identical with the level EH4 reported in [6,7]: the center is related to higher-order defect cluster since it has been detected after 2.5 MeV electron irradiation for fluences higher than 10^{14} cm^{-2} but not after the irradiation with electrons at lower (80–250 keV) energies. The level E481 exhibits similar properties as the center EH5 detected in electron or proton irradiated 4H–SiC after the annealing at 300 °C [6,7]. The broader peak EH565 is given by contributions of two levels known as EH6 and EH7 [6,7]. The level EH6 is related to a higher-order cluster while EH7 involves more elementary defects since only this center is produced in 4H–SiC after irradiation with low energy (210 keV) electrons [6,7]. According to [6], the levels EH4 and EH5 (E400 and E481) anneal out between 400 and 600 °C while the level EH6/7 (E563) is stable up to 800 °C.

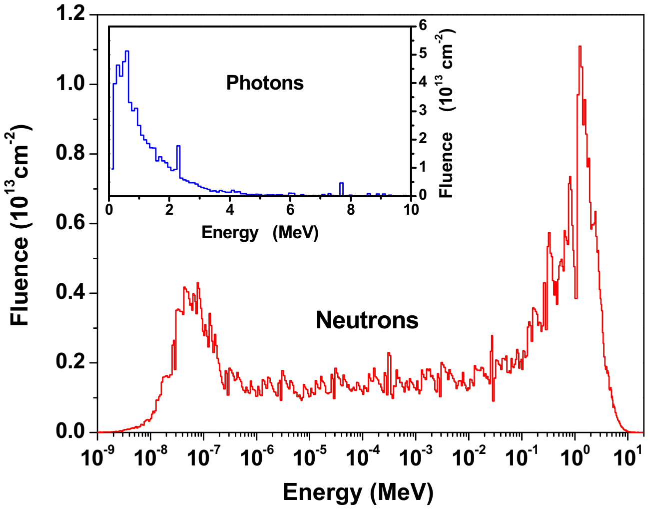

Fig. 1. Neutron energy spectrum (the total group fluence versus neutron energy) for the fluence of 4×10^{14} cm^{-2} (1 MeV NIEL in Si). Corresponding spectrum of the gamma-rays is shown in the inset.

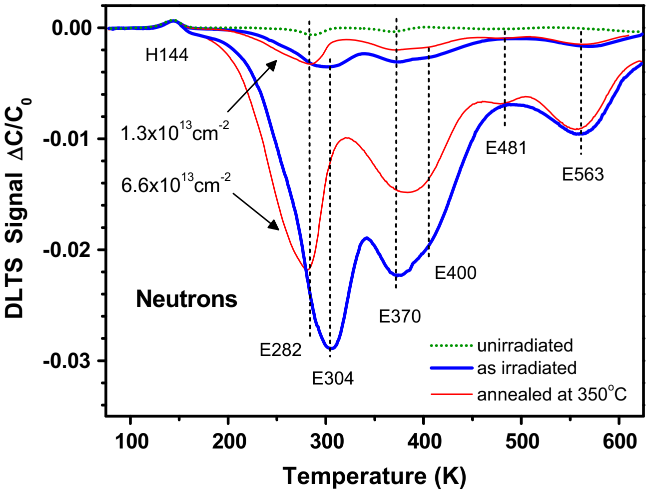

Fig. 2. DLTS spectra measured on 4H–SiC N-epilayer after irradiation with 1 MeV neutrons to fluences of 1.3×10^{13} and 6.6×10^{13} cm^{-2} (solid thick) and after subsequent 30 min annealing at 350 °C (solid thick). The spectrum taken prior to irradiation is shown as reference (dotted), rate window 4.1 s^{-1}.

The defects introduced by neutron irradiation are homogeneously distributed in the epilayer. This is evidenced by Fig. 3 right which shows the profiles of the dominant deep level E304 measured by DLTS in as irradiated samples. Defect introduction rates $dN/d\Phi$ of introduced centers are relatively high, ranging from 0.64 (E481) to 4.0 (E304) cm^{-1}. Temperature dependent *C–V*