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Effect of Trap Levels and Defect Inhomogeneities on Carrier Transport in SiC Crystals and Radiation Detectors

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We present investigation of carrier transport and trapping in 4H-SiC single crystals and high-energy radiation detectors. SiC detectors were produced from bulk vanadium-compensated semi-insulating single crystal 4H-SiC and provided with nickel ohmic and titanium Schottky contacts. The prevailing defect levels were revealed by means of thermally stimulated current and thermally stimulated depolarization methods and their advanced modification — multiple heating technique. From $I-V$ measurements a Schottky barrier height of ≈ 1.9 eV was found. In 4H-SiC:Va the following thermal activation values were deduced: 0.18–0.19 eV, 0.20–0.22 eV, 0.3–0.32 eV, 0.33–0.41 eV, and 0.63 eV. The maximum with activation energy of 0.33–0.41 eV appears below 125 K and most probably is caused by thermal carrier generation from defect levels. In contrast, the first three maxima with lowest activation energies, which appear at higher temperatures, are likely associated with material inhomogeneities causing potential fluctuations of the band gap. The existence of different polarization sources in different temperature ranges is also demonstrated by thermally stimulated depolarization.

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1. Introduction

SiC is an emerging material that is undergoing rapid development for use in high-temperature, high-power applications. SiC electronics can also have unique advantages in nuclear power applications. 6H-SiC and 4H-SiC have a wide band gap (> 3 eV), therefore their equilibrium carrier concentration and leakage current are low, specific resistivity at room temperature can be as high as 10^{11} Ω cm, and a breakdown field is up to 3×10^{6} V/cm. 4H-SiC is more preferable because of

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its higher electron mobility. The SiC devices can operate at temperatures up to 700°C. The response of SiC Schottky high-energy radiation detectors was shown to be linear with thermal neutron fluence rate and gamma dose to better than 5% over nine orders of magnitude.

On the other hand, SiC device yield and efficiency are significantly limited by a relatively high density of defects, acting as carrier traps and thus deteriorating device effectiveness. Usually many levels with different parameters are reported by different investigators even in the samples produced and processed by the similar technological process. Therefore, it is essential to investigate such traps in various detectors and develop methods to examine and determine their parameters.

2. Samples and experiment

We investigated bulk 4H-SiC crystals and radiation detectors on their basis. A vanadium compensation was used to give high material resistivities, $\rho > 10^{11}$ Ω cm. SiC detectors were produced from bulk semi-insulating (SI) single crystals, 550 μm thick. The detectors were made in a parallel plate configuration by depositing a nickel ohmic contact on the bottom surface and a titanium Schottky contact on the top. To minimize surface leakage effects, a titanium guard ring was used to surround the top contact [1], coupled with silicon nitride passivation of remaining free SiC surfaces. In so produced detectors the charge collection efficiency by irradiating the samples with α-particles was found to be only about 60% at the reverse bias voltages up to 600 V [2]. This suggests the presence of defect levels that trap and recombine the charge before it can be collected. A study of the defects in native samples has been therefore carried out.

The prevailing trap levels were identified by means of thermally stimulated current (TSC) method. Samples were excited by white light or by applied voltage. To reveal the influence of the individual levels, we used the thermal emptying of the traps by multiple heating technique [3]. It is a powerful tool for the discrimination of the individual defect levels. It enables the sequential emptying of the initially filled shallower traps thus giving the information about the deeper ones in the repetitive temperature scans. The heating cycles were realized by heating and cooling the samples in 10 K steps. Defect activation energies were evaluated by numerically fitting experimental curves. To reveal the polarization effects we also investigated the short-circuit thermally stimulated depolarization (TSD) currents of the samples polarized by electric field under light excitation.

The TSC caused by thermally generated carriers can be approximated as [3, 4]:

$$I = \frac{1}{2} q L A v S_{\mathrm{n}} N_{\mathrm{c}} n_{\mathrm{t0}} \exp\left[-\frac{E_{\mathrm{t}}}{kT} - \frac{v S_{\mathrm{n}} N_{\mathrm{c}} k T^2}{\beta (E_{\mathrm{t}} + kT)} \exp\left(-\frac{E_{\mathrm{t}}}{kT}\right)\right], \tag{1}$$

here q is electron charge, L is a sample thickness, A is its area. n_{t} is carrier density at traps of energy E_{t}, T is temperature, v is electron thermal velocity,

S_n is a capture cross-section, N_c is the effective density of states, β is a heating rate. This approximation allows one to have an informative analytical solution that does not deviate strongly from the exact numerical calculations.

3. Results and discussion

In Fig. 1 typical $I-V$ curves of the investigated SiC Schottky diodes are presented. In the dark, high sample resistivity causes nearly all applied voltage to drop over the sample volume resulting in nearly linear dependencies. Under illumination diode behaviour becomes different. From these $I-V$ dependences a barrier height of ≈ 1.9 eV was found [2]. Examples of the TSC spectra are presented in Fig. 2. Though qualitatively comparable, the spectra were nevertheless different even in unirradiated detectors. These differences evidence a complex defect structure, which is significantly influenced by the defect charge state. Moreover, TSC curves itself as well as the maxima positions and the effective activation energies

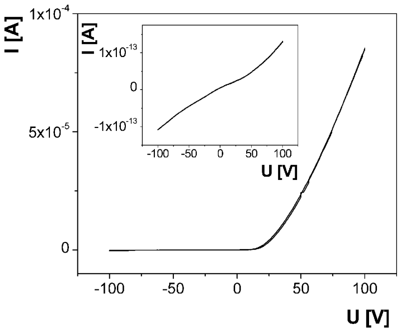

Fig. 1. Typical $I-V$ curves of the investigated SiC radiation detectors in the dark (inset) and under the white-light illumination.

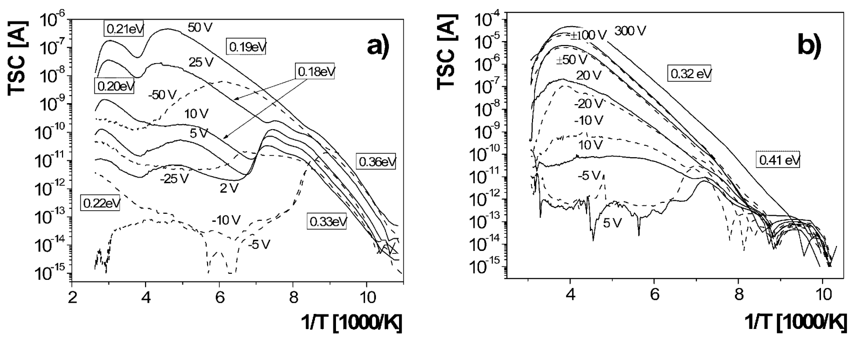

Fig. 2. TSC spectra in two SiC samples at different applied voltages. Solid lines indicate direct voltages, and dashed curves mark voltages applied in reverse direction. Nearby the curves the effective thermal activation energy values are indicated.

were notably dependent on the applied voltage. In Fig. 2a several maxima can be discriminated that behave differently depending on the bias. In the low temperature region of approximately 110–140 K a maximum appears which has effective activation energy of about 0.33–0.36 eV. Similar maximum with activation energy of about 0.41 eV is observed in Fig. 2b at slightly higher temperature on the background of other thermally activated processes. These activation energy values are independent of the voltage. Meanwhile the height of this maximum is directly proportional to the bias. These facts evidence thermal generation from trap levels, according to Eq. (1). Similar values of 0.32 eV for the maximum observed at 118 K and 0.39 eV for the maximum at 135 K were reported in [5]. They were attributed to the localized dislocation. The 0.35 eV value was reported for uncompensated boron dopant activation in SI SiC [6].

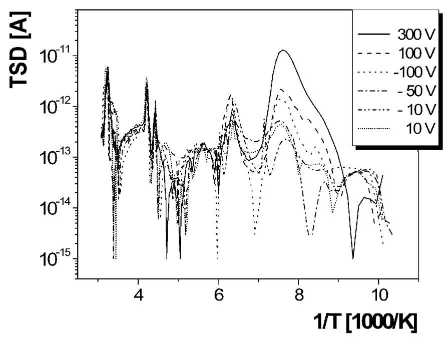

Fig. 3. Thermal depolarization current dependencies on temperature after excitation of the sample by light and applied electric field.

The existence of different polarization sources is being demonstrated by depolarization current data in Fig. 3. Usually appearance of TSD is associated with spatial inhomogeneities of electrical properties, which can either be introduced upon excitation, or to be a characteristic of material itself. The recharge of the described level in the region of 110–140 K is also associated with sample polarization, and the TSD current depends on the polarizing voltage. This supports the idea that the defect is extended in space, as in the case of dislocations.

At the higher temperatures (above 130–140 K) dependence of the TSD on the polarizing voltage disappears. Nevertheless its rich structure can hardly be resolved in detail. The character of the TSC spectra changes as well (Fig. 2), demonstrating a nonlinear dependence on the bias: the height of the maximum at the temperatures of 205–220 K changes by up to 7 orders of magnitude by varying the voltage from 2 V up to 50 V. Meanwhile the effective activation energy increases with voltage up to approximately 50 V, i.e., until the electric field strength becomes about 1 kV/cm. The saturation values of the activation energy in different samples range from 0.19 eV up to 0.32 eV. Besides being notably scattered they remain lower than that of the first maxima, observed at lower temperatures. Such behaviour of the TSC cannot be explained within the model of homogeneous semiconductor. Indeed, though in principle defect level with lower activation energy can be observed at higher temperature due to significant differences in capture cross-sections, but in practice probability of such observation is low, because capture cross-section appears as a pre-exponential multiplier in Eq. (1), meanwhile activation energy stands in an exponent. Therefore effect of material inhomogeneities leading to the potential relief of the band gap has to be taken into account. Different inhomogeneities can appear in SiC because of its complicated structure. It is known that in SiC, besides its complex energy band structure, several polytypes can co-exist, depending on technology [7]. Furthermore, compensation usually introduces additional local deviations from the stoichiometry due to temperature variation during crystal growth. Because of the potential relief, excited carriers can be trapped in potential wells and be excluded from electrical conductivity. The applied electric field can activate conductivity by making carriers capable to overcome potential barriers. Otherwise, potential relief can be screened by injected carriers. Therefore effective thermal generation energy values do not remain constant. They saturate at high electric fields when transport conditions become favourable for the generated carriers. This model explains the decrease in activation energy with increasing temperature. Such situation can be realized because of the different competing generation and transport mechanisms. For example, if inhomogeneities are formed by a large number of atoms, multiple re-trapping can take place causing a shift of the TSC maxima towards higher temperatures [8]. The significant scatter of the thermal activation energy values in different samples — from 0.18 eV up to 0.35 eV — might be due to different average amplitudes of the potential relief.

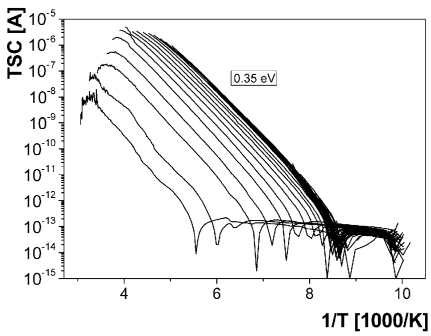

Fig. 4. Results of the TSCs in the repetitive heating regime at 50 V applied voltage.

In order to test the effect of potential inhomogeneities we used the repetitive heating technique (Fig. 4). It can be seen that during successive thermal scans activation energy does not change even when the TSC decreases by several orders of magnitude. This confirms that indeed the effective activation energy values are given not by a number of carriers, but rather by the applied voltage, which modifies transport conditions in a network of potential barriers. Assuming that the applied voltage can modulate the effective barrier height by their thermal activation energy value until saturation is reached, and that all the barriers are connected in series, the mean dimensions of inhomogeneous regions can be evaluated as 1.5–3.8 μm, which is close to the real values [9].

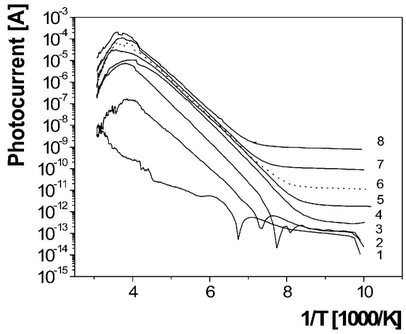

Fig. 5. Dependence of the photocurrent on temperature at different incident white light intensity. The relative intensity increases by a factor of approximately 9 starting from the lowest curve numbers.

Different properties of defects observed at lower and at higher temperatures are evidenced also by photocurrent temperature dependencies (Fig. 5). At low temperatures photocurrent does not change at low excitation intensities. Afterwards it starts growing proportionally to the light intensity. In contrast, at higher temperatures the steep photocurrent increase takes place namely at the lowest light intensities; afterwards it saturates. Such behaviour confirms that carrier generation and transport conditions are different. It can be assumed that at higher temperatures photoconductivity increases because light-generated carriers smooth the potential relief, improving carrier percolation conditions.

Near the room temperature, a growth of the dark current occurs, which has thermal activation energy of about 0.63 eV. A level with similar activation energy was reported in [10]. It was attributed to carbon vacancy [5], carbon interstitial–nitrogen complex, or silicon vacancy [10].

4. Summary and conclusions

Carrier transport and trapping were investigated in semi-insulating vanadium-compensated 4H-SiC single crystals and ionizing radiation detectors on their basis. The detectors were supplied with nickel ohmic contacts on the bottom surface and titanium Schottky contacts on the top. The prevailing defect levels were identified by means of thermally stimulated current and thermally stimulated depolarization methods. Samples were excited by light with different intensities and applied voltages. To analyze the influence of different thermally activated processes, we used the thermal emptying of the traps by fractional heating, which is a powerful tool for the discrimination of the individual defect levels in materials with many levels in the band gap.

From $I-V$ measurements of the diodes a barrier height of $\approx$ 1.9 eV was found. In 4H-SiC:Va the following thermal activation values were deduced: 0.18–0.19 eV, 0.20–0.22 eV, 0.3–0.32 eV, 0.33–0.41 eV, and 0.63 eV. The maximum with activation energy of 0.33–0.41 eV appears below 125 K and most probably is caused by the thermal carrier generation from defect levels. In contrast, the first three maxima with lowest activation energies, which nevertheless appear at higher temperatures, are likely associated with material inhomogeneities causing potential fluctuations of the band gap. This conclusion is based on the fact that the current value as well as the form of the TSC spectrum markedly and non-linearly depend on applied voltage. Furthermore, peculiarities of the TSC were observed that could not be explained by a homogeneous semiconductor model. The existence of different polarization sources in different temperature ranges is also demonstrated by TSD.

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