Effect of High-Energy Electrons on Conductivity Compensation in n-4H-SiC

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Processes of radiation defect formation and conductivity compensation in identical silicon carbide samples irradiated with 0.9 and 3.5 MeV electrons were compared for the first time.

n-SiC (4H) epitaxial layers with thickness of 50 µm were grown in a commercial horizontal hot-wall CVD-system at the Leibniz Institute for Crystal Growth, Berlin, Germany. Commercial SiC (4H) wafers served as substrates. The electron concentration due to uncompensated donors, n = N_D−N_A, did not exceed 2⋅10¹⁵ cm⁻³ in these layers. Schottky diode structures were fabricated on the SiC layers. The sample irradiation and measurement procedures used in the present study were described in detail in [1].

Figure 1 shows experimental values of the carrier removal rate in silicon carbide (ηₑ), obtained in the present study for two electron energies, 0.9 and 3.5 MeV, and in [2, 3] for the energy range (6--8) MeV. It can be seen in Fig. 1 that the values of ηₑ for the case of irradiation with 8 MeV electrons are approximately an order of magnitude larger than those for 0.9 MeV electrons. The same figure shows how the calculated Frenkel pair formation rate η_FP for silicon carbide depends on the energy of bombarding electrons. It can be seen that the calculated rate of Frenkel pair formation under irradiation with 0.9 MeV electrons is only twice that for 0.9 MeV electrons. Thus, it is rather difficult to attribute the experimental data to a simple increase in the generation rate of radiation defects due to the interaction with impinging particles and primary knock-on atoms (PKAs).

It was assumed that the reason for these differences is in the influence exerted by the energy of PKAs. The range of PKAs and the average distance between the genetically related FPs grows with increasing PKA energy. Figure 2 shows how the range of PKA ions in silicon and silicon carbide...
depends on the PKA energy in the range from 50 to 1200 eV, calculated by TRIM software [4]. It is known that the defect formation efficiency mostly depends on how full is the dissociation (separation) of primarily created genetically related Frenkel pairs constituted by a vacancy (V) and an interstitial atom (I). In the course of dissociation, the charge of the pair components may change its sign. This circumstance determines the nature of the interaction between V and I and makes it possible to determine the FP recombination radius \( r_a \) (distance between the FP components, critical for their recombination). In this situation, the following two circumstances are of key importance: (i) distribution of primarily created FPs over the distances between the components and (ii) presence of electrons and holes providing the recharging. It is known that V and I are neutral at the instant of generation, and the recombination radius of \([V^0 I^0]\) is \( \sim 2a \), where \( a \) is the lattice constant [5]. When the vacancy captures an electron, the pair \([V^- I^0]\) recombines at \( r_a > 4a \). In the case of a full recharging of the pair \([V^+ I^-]\), the distance increases and \( r_a > 7a \). Figure 2 shows by the dashed lines the critical recombination radii for the three cases under consideration. It is possible to determine from Fig. 2 the PKA energies to which the ranges \( 2a \), \( 4a \), and \( 7a \) correspond. These energies are 110, 420, and 1150 eV, respectively. As a consequence, the fraction of dissociating FPs, \( f_{FP} \), will grow with increasing energy of recoil atoms: \( f_{FP} = \eta_{e} / \eta_{FP} \). The carrier removal rate in n-SiC in initial stages of irradiation can serve as a measure of formation in silicon carbide of these "remote" pairs, i.e., pairs that have separated into isolated vacancies and interstitial atoms. According to our data, the formation rate of dissociated pairs in moderately doped silicon carbide with \( n \approx 10^{16} \text{ cm}^{-3} \) under irradiation with 0.9 MeV electrons is 0.25 cm\(^{-1}\), which gives the following values: \( f_{FP} \approx 8\% \) of the total FP generation rate of 3 cm\(^{-1}\).

Let us estimate for the case in which silicon carbide is irradiated with 0.9 MeV electrons the characteristic PKA energy (\( E_{\text{char}} \)) at which 8\% of the total number of PKAs falls within the right-hand ("high-energy") part of the spectrum. We take into account that the number of atoms primarily knocked-on by a relativistic electron from their equilibrium positions is distributed by approximately the inverse-square energy law. With this dependence, it is easy to estimate the fraction of PKAs in the right-hand part of the spectrum (fraction of separated FPs):

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f_{FP} = (1/E_{\text{char}} -- 1/E_2)/(1/E_1 -- 1/E_2). \tag{1}
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where \( E_1 = 25 \text{ eV} \) (threshold defect-formation energy), and \( E_2 = 130 \text{ eV} \) is the maximum PKA energy [5]. Under these conditions, the characteristic energy \( E_{\text{char}} \) is 107.5 eV. As already noted, the range equal to two lattice constants corresponds to this energy. This value of the recombination radius may indicate that the genetically related components of Frenkel pairs recombine in the neutral state \([V^0 I^0]\). With increasing energy of bombarding electrons, the fraction of PKAs that received an energy exceeding 107.5 eV becomes larger. For example, this fraction is about 20\% for the energy of 3.5 MeV. With the electron energy increasing to 6 MeV, \( f_{FP} \) in silicon carbide grows to become nearly 30\% [2, 3].

References


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