# Temperature dependence of the carrier removal rate in 4$H$-SiC

© S.Yu. Davydov [1], K.S. Davydovskaya [1], V.V. Kozlovski [2], A.A. Lebedev [1]

[1] Ioffe Institute,
194021 St. Petersburg, Russia
[2] Peter the Great Saint-Petersburg Polytechnic University,
195251 St. Petersburg, Russia
E-mail: shura.lebe@mail.ioffe.ru

Received April 16, 2024
Revised August 1, 2024
Accepted October 30, 2024

The temperature dependence of the rate of carrier removal in 4$H$-SiC upon irradiation with electrons (0.9 meV) and protons (15 meV) is considered. It was found that this dependence is exponential in nature with activation energies of 49−76 meV. It is shown that these values are close to the energies of acoustic phonons in SiC. It has been suggested that acoustic phonons can stimulate the process of annealing of radiation defects.

**Keywords:** irradiation with electrons and protons, annihilation of structural defects, acoustic phonons.

DOI: 10.61011/SC.2024.09.59914.6289A

## 1. Introduction

It is known that devices based on wide-band semiconductors, such as silicon carbide polytypes, have a wide range of operating temperatures [1]. Therefore, the study of the radiation resistance of such devices in the case of operation at elevated temperatures is of great practical interest [2,3]. Papers [4,5] showed that the radiation resistance of 4$H$-SiC significantly increases if irradiation was carried out at temperatures of 500−800,K. The carrier removal rate is most often used as a characteristic of the radiation resistance of a material which was introduced back in the middle of the 70s [6], defined as

$$V_d = (N_0 - N)/D, \qquad (1)$$

where $N_0$ is the concentration of electrons in the conduction band of silicon carbide $n$-type before irradiation (or holes in the valence band of silicon carbide $p$-type), $N < N_0$ is the concentration of carriers after irradiation, $D$ is radiation dose. It was previously established that under cold irradiation 4$H$-SiC the dependence $N(D)$ is linear [7] and the parameter does not depend on the radiation dose.

## 2. Samples and experiment

Industrial 4$H$-SiC Schottky integral diodes (JBS — Junction Barrier Schottky, „Schottky contact−$p$−$n$ junction") of $n$-type of conductivity with a blocking voltage of 1700 V manufactured by the CREE. The concentration of uncompensated donor impurity in the initial devices before irradiation was $\sim 3.5 \cdot 10^{15}\,\text{cm}^{-3}$. The electrons (energy 0.9 MeV, doses up to $1.3 \cdot 10^{17}\,\text{cm}^{-2}$, irradiation temperatures 300−800 K) and protons (energy 15 MeV, doses up to $4 \cdot 10^{13}\,\text{cm}^{-2}$, irradiation temperatures 300−700 K) were used for irradiation. The values were determined by measuring the values and using the volt-farad characteristics method. The accuracy of concentration measurement was ±10%. Based on the experimental data obtained, the values of the carrier removal rate for each of the irradiation temperatures were calculated according to the formula (1). The average value was calculated in the case of irradiation with two different doses at the same temperature. The obtained results are shown in Figures 1 and 2. It follows from the figures that both dependences are of an activation nature: the value of the activation energy $E_{\text{act}}$ when irradiated with electrons is $\sim 49$ MeV, and when irradiated with protons $\sim 76$ MeV. Thus, we have

$$V_d(T) \propto \exp(E_{\text{act}}/k_{\text{B}}T). \qquad (2)$$

## 3. Results and discussion

The main question of the theory is to explain the low values of $E_{\text{act}}$, which are an order of magnitude lower than the barriers for migration of defects to 4$H$-SiC [8]. It should be noted that the found values of $E_{\text{act}}$ practically coincide with the energies of acoustic phonons of polytypes SiC: $\omega_{\text{TA}}(\Gamma) = 32{-}33,\ 47{-}51,\ 46{-}54$ and $\omega_{\text{LA}}(X) = 76,\ 77,\ 77$ MeV, respectively, for polytypes 3$C$, 4$H$, 6$H$ [9].

Further, according to the data from Ref. [10], the nonradiative capture of a conduction electron by a deep trap level in the band gap, which corresponds to energy loss, is accompanied by the release of vibrational energy of the same order near the defect. First, let's show by a simple example that the local fluctuations that occur in this case stimulate the diffusion of defect atoms (which leads to the possibility of its annihilation). Let the probability of a diffusion jump of an atom in the absence of lattice vibrations be $f_0 \sim \exp(-U/k_{\text{B}}T)$, where $U$ is the value of the diffusion barrier [11]. For simplicity, let's assume that during the half-period of compression of the area near the defect, the diffusion barrier increases by $u$,

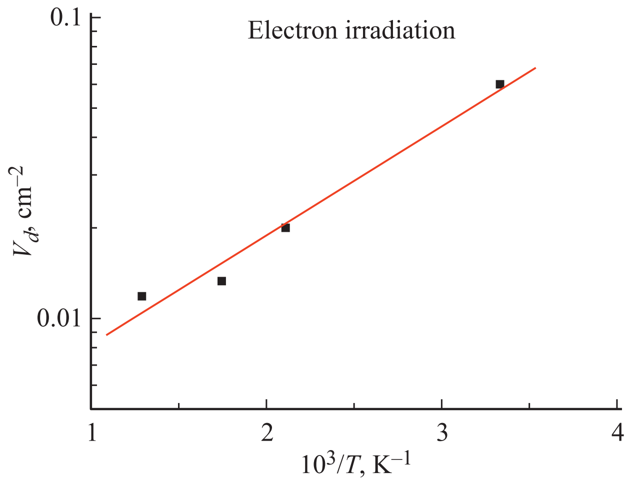


**Figure 1.** The dependence of the carrier removal rate on the temperature of irradiation with electrons with an energy of 0.9 MeV.

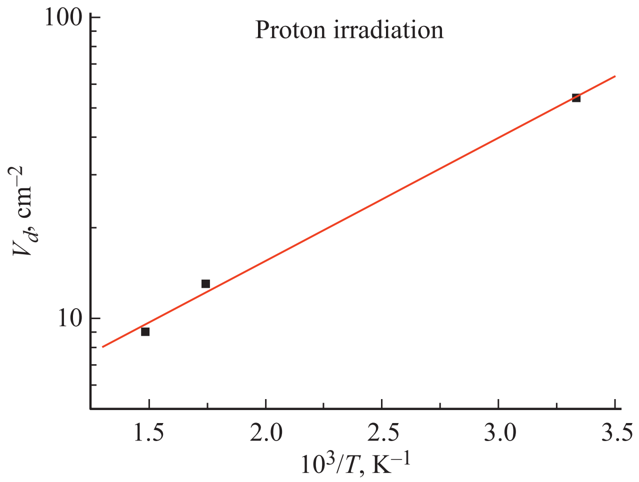


**Figure 2.** The dependence of the carrier removal rate on the irradiation temperature with protons with an energy of 15 MeV.

and decreases by the same amount during the next half-period of stretching. Then, the probability of a diffusion jump is $f/f_0 \sim \cosh(u/k_\mathrm{B}T)$ for the oscillation period. Consequently, the number of defects decreases and $N \rightarrow N_0$ as the temperature increases. Strict consideration gives

$$f/f_0 = I_0(u/k_\mathrm{B}T) > 1,$$

where $I_0(\alpha) = \sum_{k=0}^{\infty} \frac{(\alpha/2)^{2k}}{(k!)^2}$ is a modified Bessel function having the asymptotic $I_0 \sim \exp(\alpha)/\sqrt{2\pi\alpha}$ [12] for $\alpha \gg 1$. It should be noted that, with exponential accuracy, the ratio $f/f_0$ is equal to the ratio of the corresponding diffusion coefficients $D/D_0$ [9].

Let us now estimate the value of u by putting, in accordance with the diffusion model [13], $u \sim |\partial E_b/\partial a|\Delta a$, where $E_b$ and $a$ is the energy and length of the Si bond–C, $\delta a$ is the amplitude of the acoustic phonon. Using the results of paper [14], we get $u \sim |E_b|(\delta a/a)$, where we neglected the weak polarity of the Si–C bond. The latter ratio can be rewritten as $u/U \sim \delta a/a$. Let us use the Lindemann formula to estimate the value of the ratio $\delta a/a$:

$$\delta a/a = \sqrt{9\hbar^2 T/M k_\mathrm{B}\Theta r_s^3},$$

where $M$ is the reduced mass „of the molecule" SiC, $r_s$ — the radius of the unit cell, $\Theta$ is the Debye temperature, which can be rewritten as $\delta a/a = \sqrt{T/T_m}$, where $T_m$ is melting point [15]. Since $(da/a)_{\max} \approx 0.20-0.25$ [15] and $T_m \sim 3100$ K [9], for $T = 500$ K we get $u/U \sim 0.1$. Since $U \sim 1$ eV [8,16,17], we obtain $u \sim 100$ MeV, which corresponds in order of magnitude to the experimental values of the activation energy. An alternative explanation for the observed dependences is associated with an increase of the cross section $\sigma \propto \exp(-w/k_\mathrm{B}T)$ of the multiphonon capture of an electron (hole) at the local level with an increase of temperature [10]: where $w$ is the characteristic energy of the lattice. We obtain the expression (2) assuming $V_d \propto \sigma^{-1}$ and $w = E_\mathrm{act}$. The value $E_\mathrm{act} = 0-0.56$ eV, was obtained for GaAs and GaP in paper [18] within the framework of this mechanism. Thus, both proposed explanations are related to local acoustic phonons that occur in a crystal when it is irradiated at elevated temperatures. To confirm the „phonon version" of the observed effect proposed here, we can cite studies of GaAs, GaP [18] and Si [19], where acoustic phonons were also used to explain low activation energies.

## 4. Conclusion

The paper shows that the rate of carrier removal in case of SiC irradiation at elevated temperatures is of an activation nature. The activation energy is 49 MeV (when irradiated with electrons) and 76 MeV (when irradiated with protons), which is close to the energy of an acoustic phonon in SiC. It is known that the concentration of such phonons in a crystal increases with increasing temperature. It is suggested that local acoustic phonons increase the probability of recombination of primary radiation defects formed after irradiation. This leads to an activation dependency $V_d = F(T)$.

The difference in the values of activation energies during electron and proton irradiation may be related to the different nature of defect formation during these two types of irradiation [2]. In the case of electron irradiation, only uniformly distributed Frenkel pairs are formed (vacancy + internodes), and with proton irradiation, local regions with a high concentration of defects can form. Within the framework of the models proposed in this paper, the difference $E_\mathrm{act}$ can be formally attributed to a 2-fold increase in lattice deformation $\delta a$ under proton irradiation compared with electron irradiation.

### Funding

The study was funded by a grant of the Russian Science Foundation No. 22-12-00003.

### Conflict of interest

The authors declare that they have no conflict of interest.

## References

[1] A.A. Lebedev, P.A. Ivanov, M.E. Levinstein, E.N. Mokhov, S.S. Nagalyuk, A.N. Anisimov, P.G. Baranov. UFN, **189**, 803 (2019). (in Russian).
[2] E.V. Kalinina. FTP **41**, 769 (2007). (in Russian).
[3] A. Lebedev, V.V. Kozlovski, K.S. Davydovskaya, M.E. Levinshtein. Materials, **14**, 4976 (2021).
[4] V.V. Kozlovsky, A.E. Vasiliev, K.S. Davydovskaya, A.A. Lebedev. Poverkhnost, № 2, 1 (2019). (in Russian).
[5] A.A. Lebedev, V.V. Kozlovskiy, M.E. Levinstein, D.A. Malevskiy, G.A. Oganesyan, A.M. Strel'chuk, K.S. Davydovskaya. FTP **56**, 441 (2022). (in Russian).
[6] D.V.Lang. *Review of Radiation — Induced Defects in III–V Compounds*. In: *Radiation Effects in Semiconductors* (London, Institute of Physics, 1977) p. 70.
[7] V.V. Kozlovski, A.A. Lebedev, E.V. Bogdanova. J. Appl. Phys., **117**, 155702 (2015).
[8] J. Coutinho. Crystals, **11**, 167 (2021).
[9] M.E. Levinshtein, S.L. Rumyantsev, M.S. Shur (eds). *Properties of Advanced Semiconductor Materials: GaN, AIN, InN, BN, SiC, SiGe* (John Wiley& Sons, Inc., N.Y., 2001).
[10] V.N. Abakumov, V.I. Perel', I.N. Yassievich. *Bezyzluchatel'naya rekombinatsiya v poluprovodnikakh*. (Publishing house „Petersburg Nuclear Physics Institute named by B.P. Konstantinov of RAS", St. Petersburg, 1997). (in Russian).
[11] M. Lanno, J. Bourgoin. *Tochechnye defekty v poluprovodnikah* (Moscow, Mir, 1984). (in Russian).
[12] I.S. Gradshteyn, I.M. Ryzhik. *Tablitsy integralov, summ, ryadov i proizvedeniy*, (M., Nauka, 1971). (in Russian).
[13] S.Yu. Davydov. Phys. Solid State **41**, 8 (1999).
[14] S.Yu. Davydov, O.V. Posrednik. Phys. Solid State **57**, 837 (2015).
[15] J. Ziman. *Printsipy teorii tverdogo tela* (M., Mir, 1974). (in Russian).
[16] M. Bockstedte, A. Mattausch, O. Pankratov. Phys. Rev. B, **68**, 205201 (2003).
[17] M. Bockstedte, A. Mattausch, O. Pankratov. Phys. Rev. B, **69**, 235202 (2004).
[18] C.N. Henry, D.V. Lang. Phys. Rev. B, **15**, 989 (1977).
[19] J.B. Wallace, L.B.B. Aji, A.A. Martin, S.J. Shin, L. Shao. Sci. Rep., **7**, 39754 (2017).

*Translated by A.Akhtyamov*