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Effect of neutron irradiation on charge collection efficiency in 4H-SiC Schottky diode

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ABSTRACT

The charge collection efficiency (CCE) in 4H-SiC Schottky diode is studied as a function of neutron fluence. The 4H-SiC diode was irradiated with fast neutrons of a critical assembly in Nuclear Physics and Chemistry Institute and CCE for 3.5 MeV alpha particles was then measured as a function of the applied reverse bias. It was found from our experiment that an increase of neutron fluence led to a decrease of CCE. In particular, CCE of the diode was less than 1.3% at zero bias after an irradiation at 8.26×10^{14} n/cm^2. A generalized Hecht's equation was employed to analyze CCE in neutron irradiated 4H-SiC diode. The calculations nicely fit the CCE of 4H-SiC diode irradiated at different neutron fluences. According to the calculated results, the extracted electron $\mu\tau$ product $(\mu\tau)_e$ and hole $\mu\tau$ product $(\mu\tau)_h$ of the irradiated 4H-SiC diode are found to decrease by increasing the neutron fluence.

1. Introduction

4H-silicon carbide (4H-SiC) is one of the most attractive semiconductor materials for solid-state neutron detector thanks to its high displacement threshold energy (22–35 eV) and wide band gap (3.27 eV) [1]. These excellent physical properties make 4H-SiC desirable for neutron detection in harsh environments with intensive radiation and/or elevated temperature [2]. Much research in recent years has focused on the effects of neutron irradiation on the electrical properties of 4H-SiC diode, including *I–V* characteristics [3], resistivity of materials, and free-carrier concentration [4]. However, little attention has been paid to the effect of neutron irradiation on charge collection efficiency (CCE) of 4H-SiC diode, which is crucial to the neutron detector's quality and lifetime. Although a decrease in CCE of 4H-SiC diode with neutron irradiation was reported in Refs. [2,5], the effect of neutron irradiation on CCE is not fully understood.

In this paper, we present the result of a systematic study on the effect of neutron irradiation on CCE in 4H-SiC Schottky diode. First, fabrication and characterizations of 4H-SiC diode are performed. Next, the diode is irradiated with fast neutrons and the CCE is then measured with a ^{241}Am alpha source. Finally, we present the experimental CCE results and carry out the analysis with a generalized Hecht's equation.

2. Experimental setup

Fig. 1(a) is a schematic diagram of the SiC Schottky diode. The 4H-SiC epitaxial layers were grown onto 4H-SiC substrate wafers by vapor-phase epitaxy at Nanjing Electronic Devices Institute, Nanjing (China). A 1 μm n^+ buffer layer ($\sim 10^{18}$ nitrogen atoms per cm^3) was epitaxially grown onto a 360 μm conducting 4H-SiC substrate wafer. On the n^+ buffer layer, a 13 μm lightly doped n^- epilayer was deposited with nitrogen doping concentration of 1.97×10^{15}/cm^3. The ohmic contact was realized by the deposition of a Ni/Au (1 μm/6 μm) multilayer followed by an annealing at 1000 °C for 5 min in N_2. The Schottky contact was formed on the surface of the epitaxial layer by the deposition of a 100 nm nickel film. The 4H-SiC diode was then mounted on a copper base plate (Fig. 1(b)).

Device parameters such as the ideality factor and the Schottky barrier height were obtained through forward *I–V* (I_f–V) measurement, using an Agilent 4155C Semiconductor Parameter Analyzer. In order to acquire the net doping concentration of 4H-SiC epilayer, *C–V* characteristic of the diode was measured using Agilent 4155C and Agilent 4284A. All measurements were performed in darkness at room temperature.

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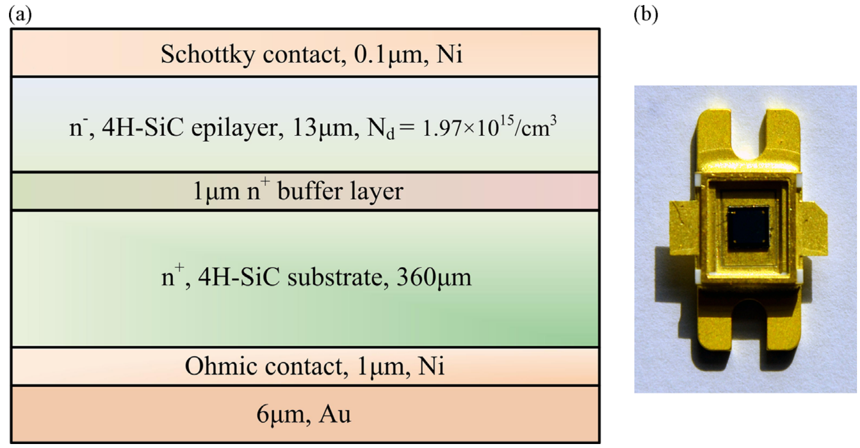

Fig. 1. (a) Schematic drawing of the 4H-SiC Schottky diode (dimensions are not to scale) and (b) photograph of a 4H-SiC diode mounted on a copper base plate. The active area of the diode is $3 \times 3\ \text{mm}^2$.

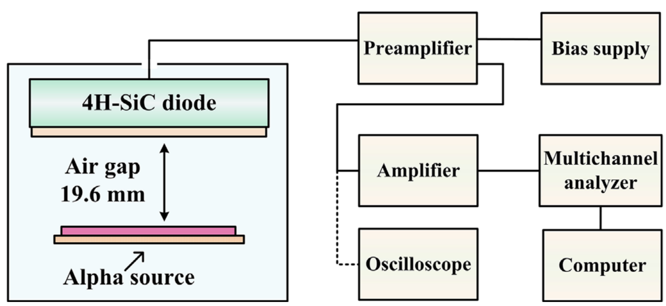

Fig. 2. Experimental setup for CCE measurement. Preamplifier – ORTEC 142A, Amplifier – ORTEC 671, Bias supply – ORTEC 428, Multichannel Analyzer – ORTEC 926, and Computer – PC with MAESTRO-32 software installed.

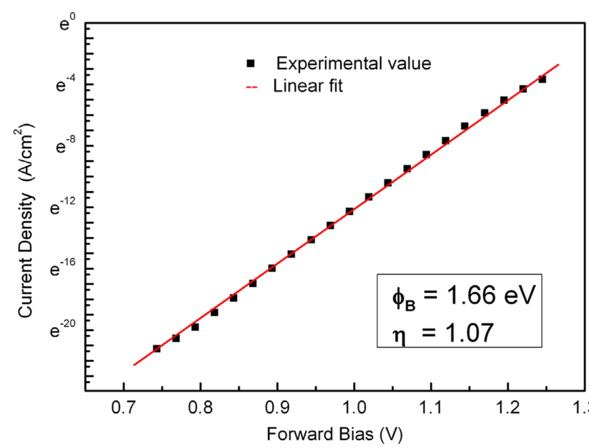

Fig. 3. Forward I–V characteristic of the 4H-SiC Schottky diode.

The CCE is defined as the ratio between the collected charge and the charge produced by the particle in the detector [6]. As shown in Fig. 2, the CCE was measured through a standard procedure which normalizes the pulse height with respect to the response obtained in the same experimental condition of a Si Schottky diode [7]. Standard electronic devices such as preamplifier of 45 mV/MeV gain and amplifier with 0.5 μs shaping time were used to process the signals. A 19.6 ± 0.1 mm air gap was chosen to stop all the alpha particles emitted by ^{241}Am source in 4H-SiC diode's active layer. Through the employment of the SRIM2011 code [8], the remaining kinetic energy of the alpha particle is determined to be (3.5 ± 0.02) MeV after transporting through the air gap. The projected range of 3.5 MeV alpha particles was calculated to be (9.6 ± 0.4) μm by SRIM2011. Since this range is smaller than the 13 μm thickness of 4H-SiC epilayer (i.e. the maximum active layer of the diode), all the energy of alpha particles are deposited in the active layer. When CCE saturation value of the Si Schottky diode approximates to 100%, CCE in 4H-SiC diode can be calculated as follows:

$$CCE_{\mathrm{SiC}} = \frac{(P_{\mathrm{SiC}} + C_s)\varepsilon_{\mathrm{SiC}}}{(P_{\mathrm{Si}} + C_s)\varepsilon_{\mathrm{Si}}} \tag{1}$$

where P_{SiC} and P_{Si} represent peak centroid of spectra measured by 4H-SiC diode and Si diode, respectively; $\varepsilon_{\mathrm{SiC}}$ and $\varepsilon_{\mathrm{Si}}$ are the average energies needed to produce one electron-hole pair and they are 7.78 eV and 3.6 eV in 4H-SiC and Si respectively [1]; C_s represents the shift in peak centroid related to the calibration of the system. In addition, as the electronic system relies on a trigger (46.7 keV) from the signal, the lower limit of our CCE measurement system is found to be 1.3% (46.7 keV/3500 keV = 1.3%).

In order to simulate the working conditions of neutron detector, the 4H-SiC Schottky diode was irradiated in a mixed neutron/γ field of a critical assembly in Nuclear Physics and Chemistry Institute, Mianyang (China). The neutron fluence rate at the diode was $5.2 \times 10^9\ \text{cm}^{-2}\,\text{s}^{-1}$ with an average neutron energy of 1.42 MeV, and the ratio between neutron fluence and γ dose was $1.0 \times 10^{12}\ \text{Gy}^{-1}\,\text{cm}^{-2}$. After irradiation, CCE was measured at different reverse biases.

3. Results and discussion

3.1. IV/CV characterization

The Schottky barrier height (Φ_B) is given by [9]

$$\Phi_B = \frac{\kappa T}{e} \ln\left(\frac{A^{**}T^2}{J_s}\right) \tag{2}$$

where κ is the Boltzman constant, e is the electronic charge, T is the absolute temperature, A^{**} is the Richardson constant given as $72\ \text{A cm}^{-2}\,\text{K}^{-2}$ [10], and J_s is the saturate current density. The room-temperature I_f–V characteristic of the Schottky diode is shown in Fig. 3, from which the barrier height $\Phi_B = 1.66 \pm 0.01$ eV can be obtained in good agreement with literature data [10]. In addition, the ideality factor (η) of a diode, which is a measure of

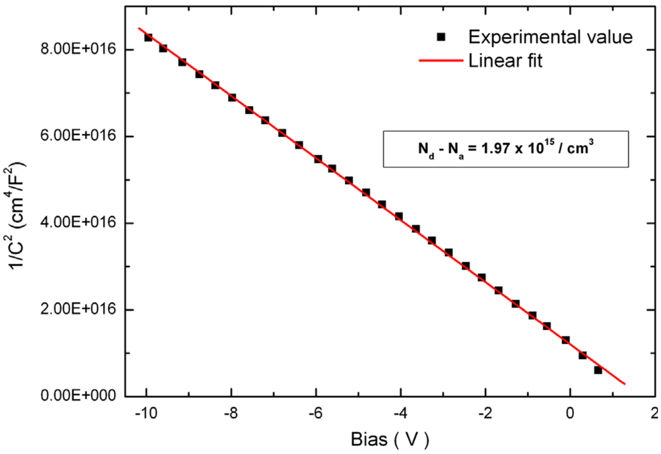

Fig. 4. Reciprocal of the squared capacitance vs. reverse bias.

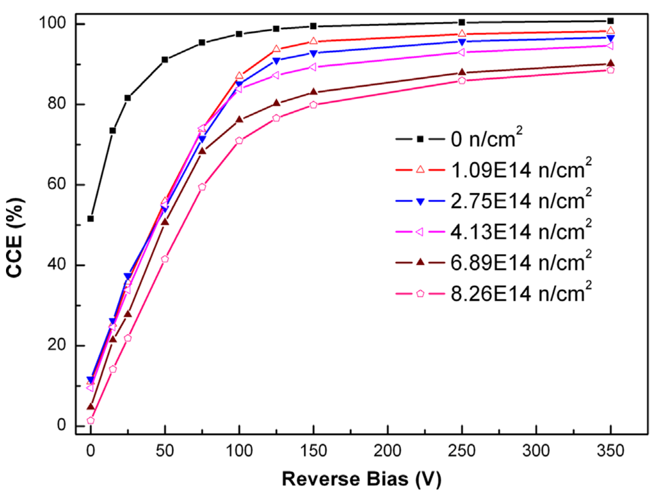

Fig. 5. The CCE dependence on the reverse bias for 4H-SiC diode irradiated by fast neutrons.

the departure from ideal behavior, can be evaluated by [9]

$$\eta = \frac{e}{\kappa T}\frac{dV}{d(\ln J)} \tag{3}$$

The value $\eta = 1.07 \pm 0.01$ obtained from Fig. 3 indicates that the current is dominated by thermionic current [11].

Fig. 4 shows the reciprocal of the squared capacitance ($1/C^2$) as a function of reverse bias. The net doping concentration ($N_\mathrm{d} - N_\mathrm{a}$) of $(1.97 \pm 0.01) \times 10^{15}\ \mathrm{cm}^{-3}$ can be obtained from the linear fit curve.

3.2. Charge collection efficiency results

Fig. 5 shows the dependence of CCE on reverse bias for the 4H-SiC Schottky diode irradiated at the indicated fluences. The experimental CCE of the un-irradiated diode reaches its saturation value at reverse bias above the value that is necessary to generate a depleted region equal to the projected range of 3.5 MeV alpha particle in SiC. The corresponding bias value can be calculated using the Eq. [11]

$$W = \sqrt{\frac{2\varepsilon_\mathrm{s}}{e(N_\mathrm{d} - N_\mathrm{a})}(V + \Phi_\mathrm{B})} \tag{4}$$

where W is the depleted region width, and ε_s is the dielectric constant of 4H-SiC; $\Phi_\mathrm{B} = 1.66$ V and $(N_\mathrm{d} - N_\mathrm{a}) = 1.97 \times 10^{15}\ \mathrm{cm}^{-3}$ are the Schottky barrier height and the net doping concentration obtained in Section 3.1, respectively. Therefore the bias value needed to have a depletion width of 9.6 μm can be determined to be 168 V from Eq. (4).

As one can see in Fig. 5, CCE decreases by increasing the neutron fluence, which is consistent with early research [2,5]. Furthermore, CCE of the 4H-SiC diode was less than 1.3% at zero bias after an irradiation at 8.26×10^{14} n/cm^2, indicating that the SiC self-biased neutron detector proposed by Ref. [12] is likely to have a shorter service life compared with those operated with power supply.

Fig. 6 shows the experimental CCE as a function of neutron fluence at 0 V, 75 V and 350 V. CCE decreases linearly by increasing neutron fluence when the depletion width W is larger than particle range R (Fig. 6(c)), while CCE decreases rapidly at first and then drops slowly (Fig. 6(a) and (b)) when W is less than R. Consequently, the 4H-SiC detector should be operated at a higher reverse bias to avoid sharp decrease in signal pulse when used as a neutron flux monitor.

3.3. Charge collection analysis

3.3.1. CCE of the un-irradiated diode

In general, the active region in 4H-SiC Schottky diode is a function of bias and grows with it (see Eq. (4)). In regions where voltage is low, the projected range of incident particle (R) is greater than depletion width (W) and less than 4H-SiC epilayer thickness (T), namely $W < R < T$; when voltage is high, the active region is greater than the particle range, namely $W > R$. An analytical model [7,13], which involves electron/hole drift process in the active region and hole diffusion process in the neutral area, are employed to analyze CCE in 4H-SiC diode

$$CCE_\mathrm{SiC} = \frac{1}{E_\mathrm{ion}}\int_0^W \left(-\frac{dE}{dx}\right)\xi(x)dx + \frac{1}{E_\mathrm{ion}}\int_W^R \left(-\frac{dE}{dx}\right)\exp\left(-\frac{x-W}{L_\mathrm{p}}\right)dx \quad (W < R < T). \tag{5.1}$$

$$CCE_\mathrm{SiC} = \frac{1}{E_\mathrm{ion}}\int_0^R \left(-\frac{dE}{dx}\right)\xi(x)dx \quad (W > R). \tag{5.2}$$

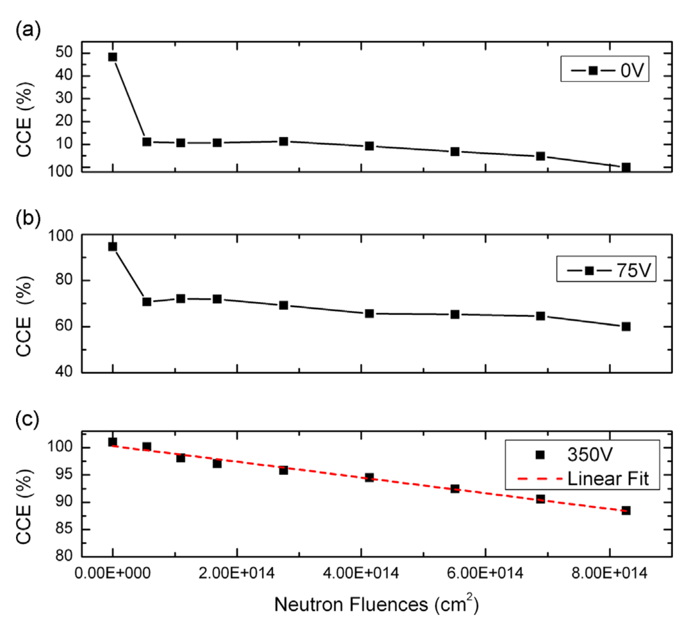

Fig. 6. Experimental CCE value as a function of neutron fluence at 0 V (a), 75 V (b) and 350 V (c).

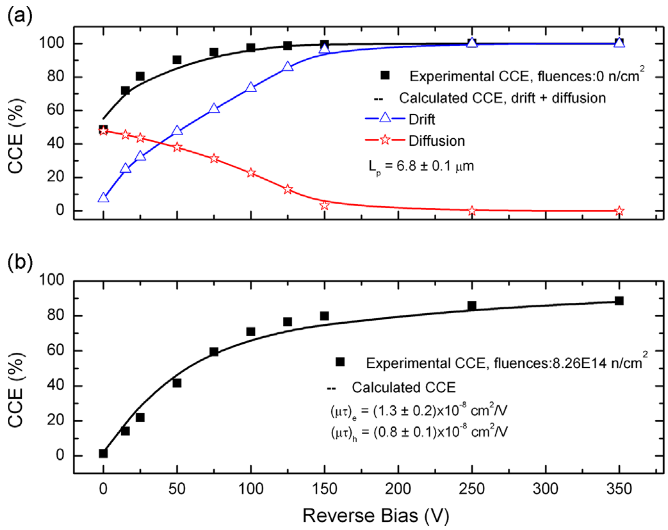

Fig. 7. CCE data at the fluences of 0 n/cm^2 (a) and 8.26E14 n/cm^2 (b) compared with the least-squares fit curves. (a) The least-squares fit curve (—) obtained with the indicated value L_p in Eqs. (5.1) and (5.2); The drift (Δ) and diffusion (☆) contribution curves are also reported. (b) The least-squares fit curve (—) obtained with the indicated values $(\mu\tau)_e$ and $(\mu\tau)_h$ in Eqs. (6) and (7).

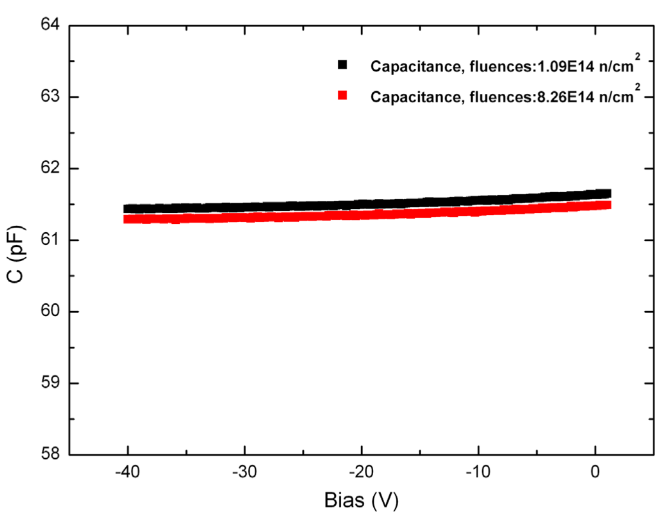

Fig. 8. Capacitance as a function of the reverse bias after neutron irradiation.

where $\xi(x)$ is the probability of the charge generated at a distance x from the front of Schottky diode being collected by the detector; E_{ion} is the ion energy, dE/dx is the electronic stopping power, R is the particle range, and L_p is the hole diffusion length in neutral area of 4H-SiC epilayer. The first term of Eq. (5.1) represents the charge collection in depletion area where charge carriers drift under the influence of electric field; the second term of Eq. (5.1) is the contribution of hole diffusion in neutral area, where holes diffuse and then arrive at the interface at the depth W.

Assuming the drift time is significantly shorter than the carrier lifetime [7,13], charge collection in the depletion area is complete, i.e. $\xi(x)=1$. Then Eq. (5.2) gives a CCE saturation value of 100%, which is consistent with experimental results of un-irradiated 4H-SiC diode (Fig. 5). In Fig. 7(a), a least-squares fit to the experimental CCE of the un-irradiated diode was obtained by taking L_p as free parameters using Eqs. (5.1) and (5.2). As shown in Fig. 7 (a), the experimental CCE is well reproduced by drift-diffusion calculation. In particular, the hole diffusion length L_p, extracted from the fit procedure, is $(6.8\pm0.1)\,\mu\text{m}$, corresponding to $(\mu\tau)_h=(1180\pm50)\times10^{-8}\,\text{cm}^2/\text{V}$.

3.3.2. CCE of the irradiated diode

Fig. 8 shows the C–V curve of the 4H-SiC diode after neutron irradiation. The capacitance of the diode, irradiated at $1.09\times10^{14}\,\text{n/cm}^2$, is constant with reverse bias, which is consistent with Refs. [5,14]. Considering the active area ($3\times3\,\text{mm}^2$), a constant capacitance of $C=61.5$ pF results in thickness of 12.9 um, which is very close to the epitaxial layer thickness. Hence, the material has become intrinsic after the neutron irradiation, which can be ascribed to the compensation of the 4H-SiC epitaxial layer [5,15]. In addition, a similar C–V characteristic was observed after an irradiation up to $8.26\times10^{14}\,\text{n/cm}^2$.

As the diode has become intrinsic after neutron irradiation, a generalized Hecht's equation [16,17], which describes the effect of charge transport in an uniform electric field, is exploited for the analysis of CCE degradation

$$Q(x)=\frac{e}{T}\left\{\lambda_p\left(1-\exp\left(-\frac{x}{\lambda_p}\right)\right)+\lambda_n\left(1-\exp\left(-\frac{T-x}{\lambda_n}\right)\right)\right\} \tag{6}$$

where λ_p and λ_n are the mean free path of holes and electrons ($\lambda_{p,n}=\mu_{p,n}E\tau_{p,n}$), where μ is the carrier mobility, τ is the carrier lifetime and E is the electric field; e is the electronic charge; T and x represent the same meaning as in Eq. (5.1).

CCE can be then evaluated by the following equation:

$$CCE=\frac{1}{E_{ion}}\int_0^R\left(-\frac{dE}{dx}\right)\frac{Q(x)}{e}dx \tag{7}$$

where E_{ion}, dE/dx and R represent the same meaning as in Eq. (5.1).

Fig. 7(b) shows typical least-squares fit to the experimental CCE of the irradiated diode using Eqs. (6) and (7). The mobility-lifetime product (i.e. $\mu\tau$), which fundamentally defines the carrier mean free path, can be extracted from the fit procedure. The experimental CCE of the diode is well reproduced with $\mu\tau$ values on the order of $10^{-8}\,\text{cm}^2/\text{V}$, e.g. $(\mu\tau)_e=(1.3\pm0.2)\times10^{-8}\,\text{cm}^2/\text{V}$ and $(\mu\tau)_h=(0.8\pm0.1)\times10^{-8}\,\text{cm}^2/\text{V}$ for the diode irradiated at $8.26\times10^{14}\,\text{n/cm}^2$, which is consistent with the $\mu\tau$ values of 4H-SiC detectors irradiated with 8 MeV protons at a fluence of 10^{14} p/cm^2 [18]. Fig. 9 shows the $(\mu\tau)_e$ and $(\mu\tau)_h$ of the irradiated 4H-SiC diode. Both $(\mu\tau)_e$ and $(\mu\tau)_h$ decrease by increasing the neutron irradiation fluence, resulting in the degradation of CCE (see Fig. 5). The decrease of $\mu\tau$ values can be ascribed to the creation of defects during neutron irradiation. These defects act as trapping centers for carriers [1], compensating the doping and reducing the probability of their transportation through the crystal.

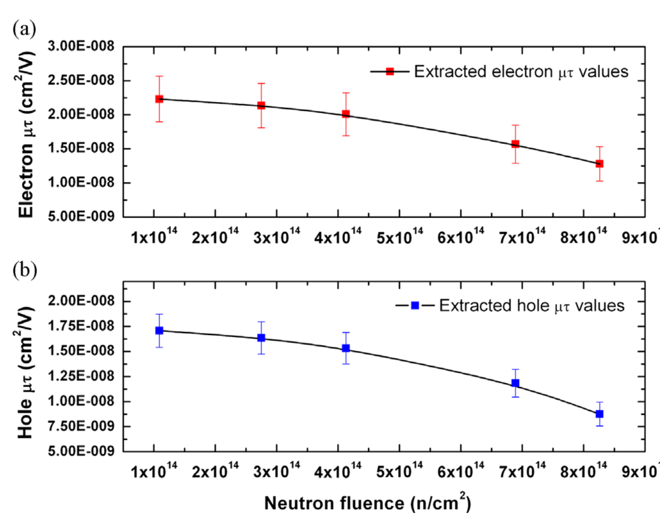

Fig. 9. Extracted electron $\mu\tau$ product (a) and hole $\mu\tau$ product (b) of the irradiated 4H-SiC diode as a function of neutron fluence.

4. Conclusions

In this paper, the CCE in 4H-SiC Schottky diode is investigated as a function of neutron fluence. Experimental CCE of 4H-SiC diode decreases by increasing the neutron fluence, and CCE of the diode was less than 1.3% at zero bias after an irradiation at 8.26×10^{14} n/cm^2. A generalized Hecht's equation (see Eqs. (6) and (7)) is employed to analyze CCE in the neutron-irradiated 4H-SiC diode. The calculations nicely fit the experimental CCE of the 4H-SiC diode. According to the calculated results, the extracted electron $\mu\tau$ product $(\mu\tau)_e$ and hole $\mu\tau$ product $(\mu\tau)_h$ of the irradiated 4H-SiC diode are found to decrease by increasing the neutron fluence, resulting in the degradation of CCE. The degradation of the irradiated 4H-SiC detector was found to be remarkable after the neutron fluence reaches a threshold level ($\sim 10^{15}$ n/cm^2) [1]. Therefore, further work about the effect of intense neutron irradiation on electron/hole transportation in 4H-SiC detector needs to be done in future.

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