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S. K. Chaudhuri

K. J. Zavalla

K. C. Mandal
University of South Carolina - Columbia, mandalk@engr.sc.edu

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Experimental determination of electron-hole pair creation energy in 4H-SiC epitaxial layer: An absolute calibration approach

Sandeep K. Chaudhuri, Kelvin J. Zavalla, and Krishna C. Mandal

Department of Electrical Engineering, University of South Carolina, Columbia, South Carolina 29208, USA

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Electron-hole pair creation energy (ε) has been determined from alpha spectroscopy using 4H-SiC epitaxial layer Schottky detectors and a pulser calibration technique. We report an experimentally obtained ε value of 7.28 eV in 4H-SiC. The obtained ε value and theoretical models were used to calculate a Fano factor of 0.128 for 5.48 MeV alpha particles. The contributions of different factors to the ultimate alpha peak broadening in pulse-height spectra were determined using the calculated ε value and Monte-Carlo simulations. The determined ε value was verified using a drift-Carlo model of variation of charge collection efficiency with applied bias. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4776703]

Silicon carbide (SiC), because of its wide band-gap, radiation hardness, and high breakdown field, stands as a very suitable candidate for radiation detectors even in harsh conditions such as high radiation background and hot and humid environments.1–6 Among other polytypes, 4H-SiC suits best for radiation detectors even in harsh conditions due to its high radiation hardness, and high breakdown field. It is a very suitable candidate for radiation detectors even in harsh conditions such as high radiation background and hot and humid environments.1–6

A similar value of 7.7 eV for alpha particles was reported by Ivanov et al.17 ε = 7.71 eV for alpha particles, and by Bertuccio and Casiraghi,18 ε = 7.8 eV for 59.5 keV gamma rays. A similar value of 7.7 eV for alpha particles was reported by Giudice et al.12 in n-type 4H-SiC. Even ε value as low as 5.05 eV has been reported by Chandrashekar et al.19 in 4H-SiC and determined using scanning electron microscopy. The above-mentioned reports involved experiments with either SiC Schottky detectors with window thickness of the order of 100 nm of high Z (atomic number) metal or standard silicon detectors for calibration purpose. Thick entrance windows of high Z metals can lead to considerable amount of uncertainties in the observed incident radiation energy.4 On the other hand, calibration with other detectors is a relative calibration process and may ignore other losses in the calibration detectors. These two factors may lead to considerable uncertainties in the determination of ε. Reiterating the remark of Day et al.,20 it is very important that the study of the ionization process in semiconductors be continued until the theoretical and experimental discrepancies are resolved.

In this letter, we report a method of iterative determination of ε value which involves an absolute calibration using a precision pulser to match the alpha peak energy (5486 keV) observed using a high resolution 4H-SiC n-type epitaxial Schottky detector. The calculation scheme has been explained in detail in the flowchart in Fig. 1. The absolute calibration was accomplished by injecting pulses of various known amplitudes, Vpulser (mV), from a precision pulser (Ortec 419) through a calibrated feed-through capacitor, C = 2.44 pF, to the preamplifier input and simultaneously noting down the peak-positions of the shaped pulses in a multi-channel analyzer (MCA). The SiC equivalent of the pulse amplitudes, E_pulser in keV was obtained using the following equation:

$$E_{\text{pulser}} = \frac{V_{\text{pulser}} \times \varepsilon \times C}{q}.$$  (1)

q being the electronic charge. The MCA peak positions were then plotted as a function of E_pulser. A linear regression of the data points gave the calibration parameters. The ε value we obtained using the given procedure was 7.28 eV. Figure 2 shows the calibration curve and the related parameters obtained for our detector with the final value of ε obtained from the iteration cycle.

The detectors used for this study were fabricated on 20 μm n-type 4H-SiC epilayer grown on a highly doped...
4H-SiC substrate and $4^\circ$ off-cut towards the [11-20] direction. The crystal dimensions were $8 \times 8$ mm$^2$ which were diced from a 76.2 mm diameter parent wafer. A micropipe density less than $1 \text{ cm}^{-2}$ was evaluated in the epilayer. The Schottky barrier was accomplished by depositing 10 nm thick nickel contacts on the epilayer surface. The effective doping concentration in the epilayer was determined to be $2.4 \times 10^{14} \text{ cm}^{-3}$ from capacitance-voltage measurements. Figure 3 shows the cross-sectional schematic of the detector geometry and a photograph of the detector used in this study mounted on a printed circuit board. Because of the thinner entrance window, the uncertainties (standard deviation) in the 5486 keV incident radiations from a $^{241}$Am source were calculated to be $0.436 \text{ keV}$ using a Monte-Carlo simulation code (SRIM 2012). Another source of uncertainty in the incident energy could be due to the variation of the angle of incidence of the alpha radiations. In our experiment, with a source-detector distance of 12 mm, active source diameter of 7 mm and a detector window diameter of $3.8$ mm, the deviation in the incident energy was found to be negligible based on SRIM 2012 calculations. Yet another source of uncertainty could arise from the self-absorption in the source. The source calibration data revealed a maximum broadening of 20 keV in the 5486 keV alphas. This uncertainty has been taken into consideration during the calculations by including it as a tolerance.

The determined value of $\varepsilon$ can be used to find other parameters of interest in SiC by using existing theoretical models of electron-hole pair creation. Klein’s phenomenological model\textsuperscript{13} suggests that the average energy required to generate one electron-hole pair is given by the sum of the bandgap ($E_G$) plus two loss terms viz. phonon-loss ($E_R$) and thermalization-loss ($E_K$). In his theoretical work, Klein used two dimensionless parameters called the radiation-ionization efficiency $\gamma$ and the relative phonon loss $K$, given by

$$\gamma \equiv \frac{E_R}{\varepsilon}, \quad K \equiv \frac{E_K}{E_G}. \tag{2}$$

Following Shockley’s model of electron-hole pair creation energy,\textsuperscript{22} these two quantities can be related as

$$\gamma = \left(2.80 + K\right)^{-1} \tag{3}$$

and Klein’s formulation in a first approximation leads to the relation between $\gamma$, $K$, and Fano factor $F$ given by

$$F = \left(K^2 + 0.315\gamma\right)^2 \tag{4}$$

Using $\varepsilon = 7.28$ eV, $E_G = 3.26$ eV, and Eqs. (2) to (4), we obtained a value of $F = 0.128$ which is higher than the upper limit, $F = 0.04$, estimated by Philips et al. from $x$-gamma ray line width in an $^{241}$Am pulse-height spectrum.\textsuperscript{23} There is no other value of Fano factor of 4H-SiC detectors reported in the literature. However, Bertuccio and Casiraghi used an $F$ value of 0.12 in one of their works for Fano noise calculations.\textsuperscript{18}

The obtained value of $F$ can be applied to calculate the contribution to the ultimate broadening of peaks in a pulse height spectrum. Figure 4 shows a pulse-height spectrum comprising of 5486 keV alpha-peak and a test pulser peak obtained using our detector. The broadening of a peak ($\text{FWHM}_{\text{calc}}$) in terms of full width at half maximum (FWHM) in SiC is given by the quadrature sum of all the contributing broadening factors as shown in the following equation:\textsuperscript{1,24}
FWHM$^2_{\text{peak}} = FWHM_{\text{elec}}^2 + FWHM_{\text{leakage}}^2 + FWHM_{\text{stat}}^2$

$$+ FWHM_{\text{other}}^2 + FWHM_{\text{SiC}}^2.$$ (5)

The FWHM$^2_{\text{peak}}$ was found to be 19.8 keV for the 5486 keV alpha particles. FWHM$^2_{\text{elec}}$, the broadening due to the noise from the front-end electronics, and FWHM$^2_{\text{leakage}}$, the broadening due to the detector leakage current, can be collectively obtained from the width of a pulser peak recorded simultaneously with the alpha pulse height spectrum acquisition by injecting a pulser signal to the test input of the pre-amplifier. In the case of our detector, the collective broadening was found to be 15.9 keV. FWHM$^2_{\text{stat}}$ is the statistical fluctuation in the number of charge carriers produced by an alpha particle which is given by the Fano factor as shown in the following equation:

$$FWHM_{\text{stat}} = 2.355 \sqrt{\bar{\epsilon} F E_{\alpha}}.$$ (6)

$E_{\alpha}$ being the incident alpha energy. Using the calculated values of $\bar{\epsilon}$ and F, FWHM$^2_{\text{stat}}$ was calculated to be 5.3 keV. FWHM$^2_{\text{other}}$ is the broadening due to variation of energy due to the entrance window, the angle of incidence, self-absorption in the source, etc., and was calculated to be 0.436 using Monte Carlo simulations as mentioned before. FWHM$^2_{\text{SiC}}$ is the broadening due to inherent charge collection property of SiC and using all the above-mentioned FWHM values, FWHM$^2_{\text{SiC}}$ was found to be ~10.5 keV which is lower compared to the value (~20 keV) reported by Ruddy et al. probably due to superior charge collection in our 4H-SiC epilayer.

The determined $\bar{\epsilon}$ value was also put into test by determining the alpha particle induced charge collection efficiency (CCE$^{\text{obs}}$) and comparing those values with a drift-diffusion model of charge collection (CCE$^{\text{theory}}$). Charge collection efficiencies were measured using an alpha source as the ratio of energy deposited in the detector to the actual energy of particles 5486 keV emitted by the source as a function of different bias voltages. According to the drift-diffusion model, CCE$^{\text{theory}}$ can be represented by the following equation:

$$CCE_{\text{theory}} = \frac{1}{E_{\alpha}} \int dE \frac{dE}{dx} dx + \frac{1}{E_p} \int_{d}^{\infty} \frac{dE}{dx} \exp \left( - \frac{(x-d)}{L_d} \right) dx = CCE_{\text{depletion}} + CCE_{\text{diffusion}},$$ (7)

where $d$ is the depletion width at the particular bias, $dE/dx$ is the electronic stopping power of the alpha particles calculated using SRIM 2012, $x_r$ is the projected range of the alpha particles with energy $E_p$, and $L_d$ is the diffusion length of the minority carriers. The first term of Eq. (7), CCE$^{\text{depletion}}$, gives the contribution to the total CCE of charge generated within the depletion region and the second term, CCE$^{\text{diffusion}}$, gives that from the charge carriers created in the region behind the depletion region and diffused to the depletion region. We calculated CCE$^{\text{depletion}}$ as a function of bias voltage. Figure 5 shows the variation of CCE$^{\text{obs}}$ and CCE$^{\text{depletion}}$ as a function of bias voltage. It can be noticed from the figure that CCE$^{\text{depletion}}$ had a larger deviation from CCE$^{\text{obs}}$ for bias voltages below 80 V as the corresponding depletion widths were smaller than or comparable to the alpha penetration depth (~18 µm) and hence the contribution of CCE$^{\text{depletion}}$ to CCE$^{\text{theory}}$ is partial. For bias voltages above 80 V, CCE$^{\text{depletion}}$ values were seen to match CCE$^{\text{obs}}$, and above 80 V and hence the total contribution to the CCE$^{\text{obs}}$ was from CCE$^{\text{depletion}}$. Very close agreement of the experimentally determined values of CCE$^{\text{obs}}$ with the calculated

![FIG. 3. Cross-sectional schematic of the detector structure used in our studies and a top-view photograph of an actual detector mounted on a printed circuit board.](image-url)
FIG. 5. Variation of experimentally obtained (■) charge collection efficiency and theoretically calculated separate contributions to the total CCE from charge drifts in depletion region (●) as a function of bias voltage. The variation of depletion width (▲) as a function of bias voltage is also shown in the figure. The vertical dotted line shows the bias at which the depletion width becomes more than the alpha penetration depth and the horizontal one shows the penetration depth for 5486 keV alpha particles.

CCE_{depletion} values supports the ε value obtained from our experiments. As a further test, the experiment was repeated with another detector of similar kind fabricated from a wafer randomly chosen from the 76 mm parent wafer and the results were found to be perfectly repeatable.

To conclude, we have reported in this letter an experimentally determined electron-hole pair creation energy value of 7.28 eV in order to solve an ambiguity raised during an alpha spectroscopy measurement on using the existing ε values. We have also calculated a Fano factor value of 0.128 estimated upper limit of 0.04 in 4H-SiC. The determined ε value has been used to calculate the CCE which matches very well with the CCE values calculated using a drift-diffusion theoretical model of CCE.

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