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Dose Rate Linearity in 4H-SiC Schottky Diode Based Detectors at Elevated Temperatures

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Abstract

The outstanding material properties make silicon carbide radiation hard and this ability has enabled it to be demonstrated in a range of detector structures for deployment in extreme environments, including those where the ability to tolerate high radiation dose is imperative. This includes applications in space and nuclear environments, where the ability to detect highly energetic radiation is important. In contrast, detectors used in medical treatment, such as imaging and radiotherapy, uses a range of radiation dose rates and energies for both particulate and photonic radiation. Here, we report the response and dose rate linearity of detectors fabricated from silicon carbide to dose rates in the range of $0.185 \text{ mGy.min}^{-1}$, typical of those used for medical imaging. The data show that the radiation detected current originates within the depletion region of the detector and that the response is linearly dependent on the volume of the space charge region. The realization of a vertical detector structure, coupled with the high quality of epitaxial layers, has resulted in a high dose sensitivity of the detector that is highly linear. The temperature dependence of the characteristics indicate that silicon carbide Schottky diode based detectors offer a performance suitable for medical applications at temperatures below 100°C without the need for external cooling.

Index Terms

silicon carbide, Schottky diode, electrical characterization, X-ray detectors, radiation response.

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I. INTRODUCTION

The advancement of technology in the development of radiation detectors has resulted in significant interest in the exploration of new radiation hard detector materials in recent years. The essential material properties in identifying suitable materials for the development of high performance radiation detectors are; i) the capability to withstand high radiation dose and dose rate, ii) a sensitivity that is independent of both dose rate and energy, iii) fast response and high signal stability, iv) high linearity with both dose and dose rate, and v) wide dynamic range [1]. Dose rate linearity and dose sensitivity in radiation detection are defined as the ratio of the current detected in the detector from exposure to increasing dose rate and the collected charge generated by the radiation with increasing absorbed dose, respectively. Increasing the dose sensitivity and response to low-energy X-ray photons enables the use of lower doses in imaging applications. The increases in both characteristics are linked to the generation of electron-hole pairs created in the space charge region that determine the electrical signal generated by the detector.

High radiation hardness and insensitivity to radiation damage, may contribute to high quality device with reduced charge trapping and polarization effects. This is particularly true for beam monitors that are installed in treatment systems, where accurate and precise detection of electrical signal produced is imperative. Conventional radiation detectors are often fabricated from silicon and germanium, which in comparison to silicon carbide (SiC) has a lower radiation tolerance due to their small band gaps and displacement threshold energy, so the detectors are prone to radiation induced damage [1]. Radiation detectors that are prone to radiation damage show evidence of a decrease in dose sensitivity and increase in dark current [1] with continued exposure. Therefore, the development of radiation detectors with performance characteristics that are insensitive to radiation damage and high radiation hardness is required in order to offer long operational lifetimes and high detection efficiency.

Evolution of semiconductor industry began after rapid development of Ge and Si radiation detectors in 1960s [2]. Major improvement in the material growth is the main factor in obtaining great detector performance. In the 1950s, synthesis of large crystals of CdTe has driven to rising advancement of other compound semiconductors [2] including SiC, CZT, GaN, GaAs, and diamond. CdTe and CZT have been dominating in the development of radiation detector for X-ray and gamma ray imaging due to the high density and atomic number (Z) which in turns produce good detection efficiency at high photon energies [3] and high carrier mobilities. However, due to susceptibility to polarization effect in CdTe, its usage has been widely replaced with CZT which has higher band gap, energy of defect formation and removal of polarization effect that reduced the dislocation density and leakage currents [2]. On the other hand,

intermediate Z-material such as GaN and GaAs have photon attenuation coefficients between Si and CdTe/CZT, where GaAs potentially ideal for devices with integrated microelectronics [4]. GaN has been shown to be ideal for high temperature, radiation hard particle and X-ray detection medium due to its wide bandgap, high density, large displacement energy, and thermal stability [2]. Nevertheless, the limited availability of lattice-matched substrates presently limits this to thin layers [2]. Meanwhile, diamond has an advantage of the atomic number close to that of human tissue ($Z = 6$) which make it suitable for clinical dosimetry applications [5], [6]. However, Chemical Vapour Deposited (CVD) process contribute to the presence of bulk defects and high concentrations of deep levels, which may give rise to priming effects and in turns degrade the stability, reproducibility and speed of response of the current and charge signal [5], [6].

Semiconductor detectors based on silicon carbide (SiC) are well suited for use for radiation detection due to the outstanding material properties, including the wide band gap, which results in the high radiation tolerance, low leakage current, and a capability to realize electronic devices that can operate at temperatures significantly beyond room temperature [7]–[9]. Despite the focus on intermediate and high atomic number (Z) materials in the development of radiation detectors, including CdZnTe and CdTe, silicon carbide based diode detectors [10], [11] demonstrate excellent characteristics regarding radiation response, in terms of low leakage current, high long term stability [12] and higher resolution detection of low mass charged particle and low energy photonic radiation [13], at room and elevated temperatures. Silicon carbide also offers a response that is closer to human tissue than the high atomic number materials. However, a significant challenge remains in the development of an ideal radiation detector for operation in low dose rate applications at elevated temperatures that would be responsive to all types of ionizing radiation whilst maintaining a high signal amplitude and charge response.

Previous reports in the literature describe the characterisation of silicon carbide devices for radiation detection and monitoring applications, reporting a response to X-rays, gamma rays, alpha and beta particles, protons and neutrons [14]. However, these previous investigations concentrated on the measurement of noise, full width at half maximum (FWHM), and charge collection efficiency (CCE) based on the spectroscopic measurements [15]–[18]. In addition, the high radiation tolerance of SiC has led to testing in high radiation flux at temperatures significantly beyond room temperature. Ruddy et al. [15] studied the response of SiC Schottky and p-n junction diodes to alpha, neutron and gamma radiation and their findings demonstrate the potential of SiC detectors for use in applications where elevated temperatures and/or high radiation fields are encountered [15]. This finding was supported by Bertuccio et al. [16], who observed that the current density of a SiC pixel X-ray detector increases with temperature, whereas

the resolution of the energy spectrum are slightly deteriorate due to small changes in leakage current for measurement temperature up to 100 °C.

Due to the wide bandgap and high radiation hardness of SiC, several studies have been performed in high radiation fluence to observe the degradation in CCE and full width half maximum of the devices. Bertuccio et al. [17] reported the electrical and dosimetric properties of SiC for exposure to proton beams and compared them with three commercial silicon dosimeters. The data showed that the leakage currents of SiC diodes are practically negligible at temperatures below 100 °C making them ideally suited for dosimetry in radiotherapy applications. Whilst the performance degraded after irradiation, the characteristics were such that the detector was still suitable for spectroscopic measurements at room temperature [17]. In contrast, no significant increase in leakage current was observed after high energy proton irradiation of 10^{11} protons cm^{-2} on semi-transparent SiC Schottky diodes (STSSD) [18]. However, after second irradiation of 10^{13} protons cm^{-2} , the full width at half maximum of the spectral peak broadened significantly, resulting in a degradation of the spectral performance and increased low level noise [18].

The linearity and sensitivity of SiC to X-ray exposure has only been determined in a single study, which observed that the diode characteristics are stable and show no evidence of carrier trapping or detrapping [19], [20]. Moreover, the charge and current responses of the detector were observed to be linear with the dose and dose rate and the sensitivity increased linearly with the applied bias. These results are consistent with those of standard silicon based dosimeters [6], [19]. However, the measurements reported were limited to the low bias regime, with data reported for a single bias voltage or at room temperature.

In this study, we have fabricated 4H-SiC Schottky diodes and characterized them prior to and during low dose rate X-ray irradiation. The performance of the Schottky diode as a radiation detector has been determined based on the dose rate linearity and dose sensitivity as a function of applied bias and temperature using a Phywe Xpert4 tabletop X-ray generator.

II. FABRICATION

A 4H-SiC n-type epitaxial wafer with a thickness of 35.3 μm and a nitrogen concentration of $1.03 \times 10^{15} \text{ cm}^{-3}$ procured from Dow Corning was used to fabricate the diodes used in this study. The wafer was initially cleaned in organic solvents followed by piranha and standard Radio Corporation of America (RCA) cleans to remove surface contaminants. Formation of a low-resistance Ohmic contact was achieved by the deposition of chromium (5 nm) and nickel (80 nm) films, followed by annealing for five minutes at 1040 °C [21] under high vacuum. The Schottky contacts were patterned using a lift-off process, using

AZ-5214E photoresist. As can be observed from the optical micrograph of the fabricated SiC die in Fig. 1(a), the Schottky contact areas range from 3.23×10^{-4} to $3.61 \times 10^{-2} \text{ cm}^2$.

Formation of the nickel silicide (Ni_2Si) Schottky contact is described fully elsewhere [22], [23], but comprises the deposition of Ti/Ni (5/80 nm) using electron beam evaporation and annealing for a period of 25 minutes under high vacuum at 660/700 °C. These process conditions have been demonstrated to result in a highly stable Schottky barrier, with greater thermal stability than pure Ni [24]. Previously published data indicates that the current voltage characteristics for this process show almost ideal forward and low reverse bias electrical characteristics [23]. Subsequently, gold bond pads in annular shape were realized using electron beam deposited chromium/gold (5/200 nm) enforcement layers to allow the diodes to be wire bonded. Fig. 1 shows the (a) top view of a completed detector die and (b) a schematic cross section of the fabricated Schottky diode detectors used in this study.

Fig. 1. (a) Top view of the detector die after fabrication. The overall die dimensions are 10 mm x 10 mm and (b) schematic cross section of fabricated 4H-SiC Schottky detectors.

A Cascade 12000 Summit Series probing station and Keithley 4200 parameter analyser were used to identify several good diodes prior to wire bonding. Diodes were wire bonded using the small binding pad area incorporated within the annular contact for electrical characterization and radiation testing purposes. Afterward, parametric testing using a Keithley 4200 parameter analyser was used to identify suitable diodes for radiation testing. Based on the previous measurement using probing station, their electrical characteristics were unchanged. Two representative detectors designated as detector 1 (D1) and detector 2 (D2) which have Schottky contact areas of $0.81 \times 10^{-2} \text{ cm}^2$ and $3.61 \times 10^{-2} \text{ cm}^2$ respectively, were selected for full testing, based on their characteristics, as described in the next section.

III. CURRENT-VOLTAGE (I-V) CHARACTERIZATION

Prior to low dose rate irradiation, the detectors were characterized under forward bias to determine the barrier height, Φ_b , and ideality factor, n . These parameters were used for screening suitable diodes for the radiation testing study, with the ideality factor used as the critical metric. The ideality factor, n is a parameter used to measure the deviation of ideal diodes from those described by the thermionic emission model [25]. The ideality factor, n of a diode should be in the range between 1 and 2 depending on the dominant current mechanism [26].

The existence of an interfacial layer between the semiconductor and the Schottky contact results in a lowering of the barrier height, Φ_b and increase in the ideality factor, n [27]. In terms of the characteristics for radiation detection, the existence of the interfacial layer results in an increased leakage current at low reverse bias and a soft breakdown, meaning that the detector cannot be operated in the high bias regime, limiting the detector volume that can be depleted. The existence of an interfacial layer is detrimental to the carrier transport across the interface and is therefore expected to degrade the charge collection efficiency of the detector. Both of the detectors reported here have ideality factors below 1.20 and in the case of detector D1, below 1.05. Measurements on electronic properties of the two detectors have been performed using Keithley 4200 parameter analyser at temperatures up to 100 °C. The barrier height, Φ_b , and ideality factor, n were extracted using the method described in [28] to account for the high series resistance of the thick, lightly doped epilayer.

Extracted values of barrier height, Φ_b , and ideality factor, n for D1 and D2 are shown by the data in Fig. 2. The data show that the characteristics of the detectors are stable with temperature in the range of 27 - 100 °C, with only minor variation observed. This is consistent with the data reported in [23], [29] and confirms the hypothesis that both detectors comprise a high quality metal-semiconductor interface. The ideality factor values for D1 has a value of 1.00 ± 0.04 across the temperature range studied, whilst D2 is 1.10 ± 0.04 . Both values are comparable to those reported previously [9], [23]. The barrier height for the two detectors are slightly higher than data published in the literature for Ni_2Si Schottky contacts on 4H-SiC [22], [23]. Some of the discrepancy is thought to arise from the influence of the series resistance on the extracted barrier height and thickness of the interfacial layer [29]. The extracted values of 1.71 ± 0.05 eV for D1 and 1.65 ± 0.04 eV for D2, coupled with the low ideality factors indicate their suitability for radiation detection. It should be noted that the use of the Cheung model in this work results in a barrier height that is higher than that calculated using conventional thermionic emission theory [29] or the Norde Function [23] because the values are not influenced by the high series resistance of the thick, lightly

Fig. 2. Ideality factor and barrier height as a function of temperature for D1 and D2. Electrical characteristics for both detectors exhibited temperature independence at room temperature and up to 100 °C.

doped epitaxial layer.

IV. RESPONSE TO LOW DOSE RATE IRRADIATION

Fig. 3. Calibration curve in terms of dose rate (mGy/min) and current signal density (nA/mm²) plotted against tube current which obtained from RMS 30 and BPW34 Si photodiode, respectively.

Fig. 4. Experimental set up for low dose rate response. Circuit box with a 1.5 cm diameter hole in the middle was positioned in line with the incident X-ray beam.

We have determined the dose rate linearity and dose sensitivity of the silicon carbide detectors to X-ray photons with incident energy of 35 keV. The X-ray beam was generated using a Phywe Xpert4 system with a tungsten anode, operating at tube currents between 0.1 and 1.0 mA. The variation of the dose rate incident on the detectors as a function of tube current was determined using Vishay BPW34 Si photodiode [30] and validated using an RMS 30 from John Caunt Scientific [31], which is specifically calibrated to the energy range of interest (30 keV). The output from both the BPW34 and RMS30 in Fig. 3 indicate that the current signal density and dose rate generated increase linearly with the tube current as has been demonstrated previously by means of direct comparison to air kerma measurements [32]. Dose rate linearity and dose sensitivity tests for both D1 and D2 were performed as a function of reverse bias at room temperature. Following this characterisation, the characteristics of D2 were determined as a function of both bias and temperature up to 100 °C. The experimental set-up used for both tests is illustrated schematically in Fig. 4.

A. Dose Rate Linearity

The current detected by the exposure to the incident radiation with increasing dose rate at room temperature is shown in Fig. 5 for both D1 and D2 as a function of bias voltage. The data in the Fig. 5 show a linear correlation between the current signal density detected in the 4H-SiC Schottky diode and the tube current. This can be directly correlated to the dose rate incident on the detector [32], allowing the observation to be drawn that the current detected in the detector is linearly related to the incident dose rate. Measurements show that the sensitivity of our 4H-SiC Schottky diode in nA.min/Gy is 20% of that measured using the BPW34 Si photodiode detector, making it comparable to conventional silicon based detectors such as SFH206 and BPX90 [32]. The difference in the electron-hole pairs creation energy in

Fig. 5. Current signal density plotted against tube current for D1 (with solid line) and D2 (with dashed line) at room temperature. Linear fitted lines for both detectors at all bias voltages give $R^2=1$.

4H-SiC (7.8 eV) which is almost double than the Si (3.62 eV) [33] might affect the detected current in this measurements. Otherwise, the similarity in the current signal density for D1 and D2 under identical conditions indicates that diode area effects are dominating the response, supporting the hypothesis that the diodes are well suited to operating as radiation detectors. The detected current signal at reversed bias of -100 V determined from the data in Fig. 5, is almost 30 times greater than the value of 150 pA reported in the literature [6]; irradiated with Co^{60} at dose rate of 0.3 Gy/min.

In addition, the data in Fig. 5 show that the increase in current signal density increases with the magnitude of the reverse bias for all dose rates studied here. The observed increase in response can be attributed to the increased volume of the depletion region with increasing reverse bias [6], [34]. However, the majority of the incident photon energy is not lost within the depletion region of the detector. The detection efficiency of a SiC detector with a depletion region thickness of $14.5 \mu\text{m}$ can be estimated to be 0.5% for an incident photon energy of 30 keV [9] and will be lower for the energies and depletion widths used here. This low efficiency is because the majority of the electron-hole pairs are generated in the region beyond the depletion region and do not contribute to the signal. In order to more fully understand the mechanism responsible for the current, the variation in the measured current as a function of depletion region width was determined, as shown by the data in Fig. 6.

The data show the expected linear correlation between the current density and the depletion width (i.e.

Fig. 6. Current signal density versus depletion width for D1 (with solid line) and D2 (with dashed line) at room temperature and tube current ranging from 0.5 mA to 1.0 mA. Linear fitted lines for both detectors at all tube currents give $R^2=1$.

Fig. 7. Current signal density versus leakage current density at temperature up to 100 °C and bias voltage from -40 V till -120 V for D2. Current signal density values plotted were subtracted with the dark current values before measurements were done.

the active volume of the detector) for each dose rate (i.e. tube current) investigated. Linear regression fitting confirms that the generated current falls to zero as the depletion region width is reduced to zero,

which is consistent with the model that the origin of the current is the generation of electron-hole pairs in the depletion region. However, linear fitting for the high tube current are slightly deviate from zero as the depletion region width is reduced to zero. This might due to the current signal that might generated from the scattered radiation and hence, contributed to the additional electron-hole pairs. The data indicates that the depletion width generated by the application of bias voltages below -200 V results in the formation of a wider space charge region than the range of 35 keV X-ray beam inside both detectors. Because the detected current is expected to be linear with tube current and hence dose rate across a wide range, the

Fig. 8. Dose rate linearity versus bias voltage applied at operated temperatures up to 100 °C for D2.

response of our detectors to incident X-ray photons is likely to be greater than those published previously and this enhancement is linked to the improvements in the quality of silicon carbide epitaxy, in particular the decrease in the concentration of carbon vacancies, that has led to the increase in carrier lifetime from μs to ms [35], [36].

The performance of detector D2 has been determined at temperatures up to 100 °C under identical exposure conditions to those used to generate the data in Figs. 5 and 6. Prior to the exposure, the leakage current for D2 has been determined as a function of bias voltage for temperatures up to 100 °C, as shown by the data in Fig. 7. The data in the figure show the variation in the current density generated on exposure to the X-ray beam as a function of the leakage current. The individual data points show different applied bias levels, that increase in the direction indicated by the arrow. The data taken at 27 °C

is dominated by the noise floor of the electrometer and has been omitted. The leakage current through the diodes shows a very low temperature dependence for temperatures of 75 °C and below, whilst the voltage dependence of the 100 °C data indicates a factor of two increase over that observed for the 75 °C values. Whilst the leakage currents are still small, typically in the 20 pA/mm² region at -100 V, the rapid increase between the two temperatures is indicative of an upper operating temperature for high sensitivity measurements [12]. The data in the figure also show that the increase in the leakage current through the detector is correlated to the increase in the detected current (current signal in the figure) and the level of the magnitude of this correlation decreases significantly between 75 and 100 °C, indicating the practical limit on the upper operating temperature of the detector. Similar trend of increasing leakage current at 100 °C operating temperature has been observed previously in 4H-SiC and 6H-SiC [16], [37].

Dose rate linearity values can be extracted from the gradient of a linear fit to the current signal as a function of the incident dose rate. These data are plotted in Fig. 8 as a function of applied bias and temperature. The data show that the dose rate linearity for D2 increases with increasing applied bias up to 120 V and it is relatively constant at temperatures below 100 °C. This temperature stability is due to the extremely low intrinsic carrier concentration in SiC, which arises from the wide bandgap, in comparison to conventional lower bandgap semiconductor materials such as silicon or gallium arsenide [37]. This is the property of SiC that makes it capable of operating in high temperature applications without the requirements of external cooling. Nonetheless, the observed deviation in the linearity at 100 °C can be considered to be the practical temperature limit for the detectors, supporting the observations drawn from the leakage current data.

B. Dose Sensitivity

The low carbon vacancy concentration of the epitaxial layer not only produces detectors with optimum electrical characteristics but is also one of the factors resulting in a highly reproducible and stable signal on exposure to the X-ray flux. Thus, to study the response of our fabricated detectors in terms of dose sensitivity, the X-ray beam has been switched on and off five times over a period of 30 minutes, with a constant applied reverse bias of -80 V, as shown by the data in Fig. 9. The dose rate was maintained at 0.185 mGy/min during the exposure portions of the experiment by ensuring that the tube current was held constant at 1 mA. The high signal-to-noise ratio of the detector can be observed from the difference between the high current portion of the data when the beam is on and the low current portion where the beam is off. The leakage current during the beam off period is reproducible and stable with a typical value of 90 ± 12 pA that is comparable to values reported in the literature from previous studies [6], [34].

Fig. 9. Current response for detector D2 as a function of time for -80 V reverse bias at room temperature. Current signal is stable and reproducible at typically 3.25 nA.

The data in Fig. 10 show the collected charge per unit area as a function of exposure time for a constant dose rate. The collected charge is obtained from the time integral of the data in Fig. 9. The data show that collected charge per unit area increases linearly with exposure time and applied bias for both detectors. The observed increase in the collected charge and hence dose sensitivity of the detector at higher applied bias is due to the increased depletion width [6], [19], similar to the enhancement in the detected current described in a previous section. The data in the figure show that D2 has a higher collected charge per unit area than D1. This increase in the collected charge density for detector D2 is despite the ideality factor being higher and the barrier height lower than D1. This result indicates that the quality of the metal-semiconductor interface, as determined using conventional parametric testing techniques, does not determine the most suitable diode for the detection of low dose rate, low energy X-rays.

The dose sensitivity of D2 has been determined as a function of temperatures up to 100 °C. In order to determine the influence of leakage current on the response of our fabricated detector at high temperature, we show the response as a function of leakage current for different applied biases prior to the dose sensitivity measurement in Fig. 11. The response of the detector when exposed to the X-rays was determined using Eq. 1.

Fig. 10. Collected charge per unit area versus exposure time during irradiation to 1 mA at different bias voltages and room temperature for D1 (with dashed line) and D2 (with solid line).

Fig. 11. Response versus leakage current density at room temperature and elevated temperatures up to 100 °C and bias voltage from -80 V to -150 V for D2.

$$Response = \frac{current\ signal - leakage\ current}{leakage\ current} \quad (1)$$

The data in Fig. 11 shows that in contrast with the current signal density plotted in Fig. 7, the response of detector D2 decreases exponentially with increasing leakage current density for the range of operating temperatures and applied biases considered here. This indicates that the increased leakage current leads to a rapid deterioration in the response of the detector on exposure to X-rays. On the other hand, linear fitted lines to the collected charge as a function of absorbed dose (calculated from the multiplication of the incident dose rate and exposure time) allow the determination of the sensitivity in mC/Gy, as shown by the data in Fig. 12. The observed trend is similar to that observed in the dose rate linearity data reported in section IV A, where the dose sensitivity is higher for high applied bias for all the temperatures investigated.

Fig. 12. Dose sensitivity versus bias voltage applied at room temperature and elevated temperatures up to 100 °C for D2.

V. CONCLUSION

The suitability of 4H-SiC Schottky diodes as radiation detectors for use in low energy, low dose rate applications has been determined for bias voltages up to -180 V and operating temperatures up to 100 °C. Dose rate linearity measurements on two detectors selected for their ideality factor exhibited a highly linear correlation of the current response as a function of dose rate (i.e. tube current) for all applied bias voltages and temperatures investigated. The data show that the detected current originates within the depletion region of the detector and that the response is linearly dependent on the volume of the space charge region, which controlled by the bias voltage applied.

The collected charge within the detector increases linearly with exposure time. The realization of a vertical detector structure, coupled with the reduction in defect concentration in epitaxial layers, has resulted in an enhanced dose rate linearity and dose sensitivity of the detector than those published previously for moderate dose rate testing. Furthermore, we have shown that the dose rate linearity and dose sensitivity are independent of temperature for measurements performed below 75 °C, indicating a highly stable performance.

In conclusion, we have shown that despite the focus on silicon carbide detectors for high dose rate applications, such as those found in the nuclear industry, it is ideally suited to radiation detection in low dose rates and elevated temperatures, such as those found in medical imaging applications, where reliable operation and high dose sensitivity are critical. With the material being inherently solar blind, this offers significant opportunities in comparison to conventional silicon diodes.

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