Development of a Silicon Carbide Radiation Detector

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Abstract

The radiation detection properties of semiconductor detectors made of 4H silicon carbide were evaluated. Both Schottky and p-n junction devices were tested. Exposure to alpha particles from a ^{238}Pu source led to robust signals from the detectors. The resolution of the Schottky SiC detector was 5.8% (FWHM) at an energy of 294 keV, while that of the p-n junction was 6.6% (FWHM) at 260 keV.

No effect of temperature in the range of 22 to 89 °C was observed on the characteristics of the ^{238}Pu alpha-induced signal from the SiC detector. In addition, testing in a gamma field of 10,000 rad-Si h^{-1} showed that the alpha-induced signal was separable from the gamma signal.

I. INTRODUCTION

Semiconductor radiation detectors offer several important advantages over other types of detectors such as gas-filled counters. The faster charge-collection times of these solid-state detectors provide them with the ability to process higher counting rates in the pulse mode of operation, and their compact size allows the measurement of intensity gradient profiles over relatively small distances. However, conventional semiconductor detectors, made of germanium and silicon, are severely limited by the operational temperature constraints and poor resistance to radiation damage of these materials. The limitations of silicon and germanium have prompted studies on the properties of silicon carbide (SiC) as a semiconductor material for radiation detection, since the higher band gap energy and greater radiation resistance of SiC should theoretically lead to a detector capable of operating at elevated temperatures and in high radiation fields. A working SiC radiation detector can be utilized in diverse applications, including ex-core neutron flux monitoring in nuclear reactors (replacing gas-filled counters), measurement of spent nuclear fuel neutron emission to determine burnup, nuclear materials safeguards monitoring and charged-particle detection in harsh radiation environments.

The use of SiC solid-state diodes for the detection of neutrons was investigated by Babcock and co-workers over forty years ago [1-3]. The authors first studied the response of SiC diodes to alpha radiation. They found that these diodes were responsive to alpha radiation, and could produce a signal without an applied bias voltage. Furthermore, the diode response to alpha particles was satisfactory up to a temperature of 700 °C. Although an increase in the pulse height of the alpha-induced signal was observed with increasing temperature, this effect, later attributed to changes in carrier mobility and lifetime at high temperatures, did not interfere with the detection of the alpha radiation at temperatures lower than 700 °C. In a subsequent work, Ferber and Hamilton [4] found good agreement between flux profile measurements made with a SiC p-n junction diode coated with ^{235}U and those made with conventional gold foil activation techniques in a low-power reactor. In addition, the diode response as a function of neutron flux was linear over a reactor power range of 0.1W to 1 kW. These authors also reported that the alpha counting capabilities of a SiC diode remained adequate after exposure to a thermal neutron fluence of 6×10^{15} n cm^{-2}.

Development of SiC diodes for application as neutron detectors was also pursued in the old Soviet Union by Tikhomirova and co-workers [5-7]. An energy resolution of 9% was achieved with a beryllium-doped 6H SiC p-n junction diode at an alpha-particle energy of 4.8 MeV, while the leakage current observed in similar diodes was of the order of a few nanoamperes at applied bias voltages of 1-10 V [5, 6]. After investigating the radiation effects of neutron irradiation on a SiC p-n junction diode using ^{233}U as a neutron-sensitive converter, the authors concluded that the performance of the SiC detector was superior to that of a Si surface-barrier detector subjected to the same irradiation conditions [7]. The counting rate of the SiC detector measured in the current mode did not change significantly up to a thermal neutron fluence of about 5×10^{13} n cm^{-2}, which translated into a fission fragment fluence of 7×10^{8} particles cm^{-2}. However, the counting rate decreased substantially at higher neutron fluences, an effect attributed to the reduction of the lifetime and mobility of charge carriers in the diode. This degradation in performance is believed to result more from damage induced by the fission fragments than from direct neutron-induced damage in SiC.

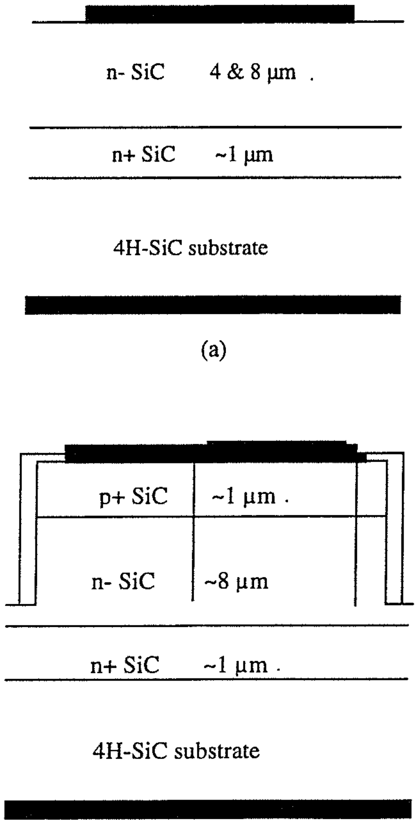
It should be noted that much of the early work on SiC was dominated by issues related to the quality of the material that could be manufactured. Therefore, material properties observed were dominated by the effects of impurities and defects rather than the properties of the SiC itself. Considerable progress has been made in the past few years in both the areas of high-purity SiC crystal growth and SiC epitaxy. Much higher-quality SiC microelectronic devices can now be made, and the SiC nuclear detectors utilized in the present study incorporate these advances in SiC fabrication.

In our work, both Schottky and p-n junction diodes manufactured with high-quality 4H SiC material were evaluated. The nuclear responses of these diodes to alpha, neutron and gamma radiation were investigated. This paper will concentrate on the diode response to alpha radiation. Subsequent papers will report on the use of the diodes as neutron detectors (through the juxtaposition of a ^{6}LiF layer next to the diode surface) and on the effects of neutron and charged-particle radiation damage on the nuclear response of these detectors.

II. DETECTOR FABRICATION

Both the Schottky diode and p-n junction detector types were fabricated by vapor-phase epitaxy onto high-purity 4H-SiC substrate wafers with a nitrogen dopant concentration of 10^{18} cm^{-3}. The 30-mm diameter SiC wafers contained approximately 33 cells with dimensions of 2.6 mm x 3.0 mm. Each cell contained 8 diodes with 400-μm diameters and 14 diodes with 200-μm diameters. The 400- and 200-μm diodes have active areas of 0.217 and 0.066 mm^2, respectively.

A schematic drawing of the two types of diodes is shown in Figure 1. Following epitaxial deposition of a 1 μm n$^+$ layer (10^{18} nitrogen atoms per cm^3) onto the substrate, n$^-$ layers were deposited. The nitrogen dopant in the n- layer was 10^{15} cm^{-3}. In the case of the Schottky diodes, a nickel contact was used over nominal n$^-$ thicknesses of either 4 or 8 μm. Nickel was also used as the back ohmic contact on the Schottky diode. The n$^-$ dopant concentration chosen represents the state-of-the-art in SiC epitaxial growth and corresponds to bias voltages of -20 V and -60 V to fully deplete the 4 and 8 μm structures, respectively.



(a)

(b)

Figure 1. Schematic diagram of (a) Schottky and (b) p-n junction diodes.

In the case of the p-n junctions, the n$^-$ layer was covered by a p$^+$ layer (10^{19} Al atoms per cm^3) with a thickness of 1 μm. A reactive ion etch was used to provide mesa isolation between the individual p-n devices on the wafer. Ti/Al was used to contact the p$^+$ layer, and nickel was used as the back ohmic contact. The wafers were oxidized prior to metallization in both the Schottky and p-n cases. However, this oxide was subsequently stripped on the 4-μm Schottky diode.

III. EXPERIMENTAL DESCRIPTION

The experimental apparatus used to test the SiC detectors is illustrated in Figure 2. A SiC device, which consists of up to 22 SiC diodes, is inserted in a board that is mounted on a positioning stage. The latter can be moved in the x, y and z planes by turning positioning knobs located on the bottom plate of the stage (not shown in the figure). The SiC device is aligned with the center of a ^{238}Pu alpha disc source by positioning the stage to predetermined x-y-z coordinates. In some of the tests, a 100-μm pinhole is inserted between the diode and the source in order to produce a well-collimated beam of alpha particles incident on the diode surface. This geometry was used primarily to study the resolution of individual SiC diodes. All testing was carried out in air at ambient pressure.

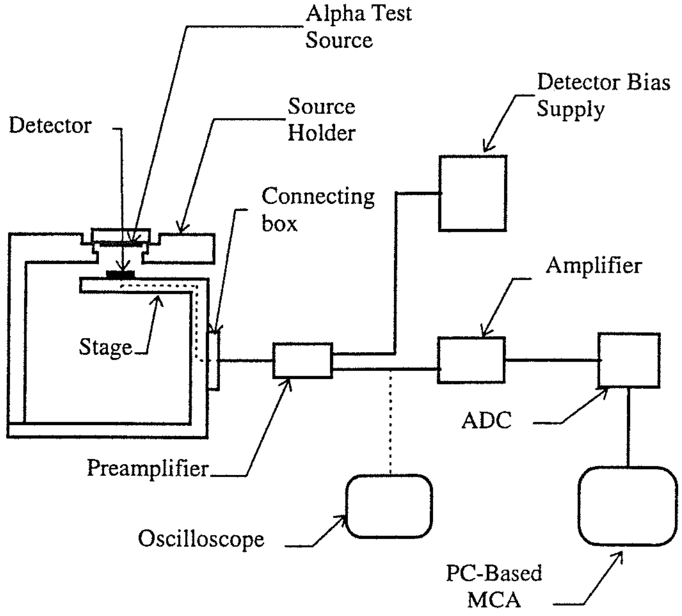


Figure 2. Experimental setup used for SiC detector testing.

The SiC device is connected to a pulse-processing system consisting of a preamplifier, an amplifier, an analog-to-digital converter (ADC), and a multichannel analyzer based on a personal computer. An oscilloscope is occasionally added to the system to study the shape of the alpha-induced pulse originating from the diode. Bias voltage to the detector is supplied by a voltage supply via the preamplifier. The amplifier, voltage supply and ADC are mounted on a NIM bin. An aluminum enclosure surrounds the stage/source holder and the preamplifier to reduce noise pick-up in the circuit.

To investigate the effects of temperature on the performance of the SiC radiation detector, one of the Schottky devices was tested at temperatures ranging from 22 °C (ambient) to 89 °C. The diode response was monitored as the temperature was increased by increasing the current flow through a resistive heater placed in close proximity to the device. A thermocouple probe connected to a digital readout measured the temperature at the diode.

IV. RESULTS AND DISCUSSION

A. Alpha Response

Initial testing of the SiC diodes was performed with a 100-μm diameter pinhole inserted in the test apparatus between the source and diode so that most of the alpha particles enter the diode with trajectories normal to the diode surface. Figure 3 displays a typical spectrum obtained with a SiC Schottky diode in this geometrical configuration. No external bias was applied to the diode. Based on the dopant concentration of the n-layer and on the dielectric constant of the material, the diode's active layer width in the absence of an external bias is 1.1 μm. The well-defined peak observed in the spectrum is attributed to the ^{238}Pu alpha particles entering the diode with normal incidence. The full width at half-maximum (FWHM) of this peak is eleven channels, which translates into a detector resolution of 5.8%. The distribution of energy deposited by the alpha particles in the 1.1-μm active layer of the diode was calculated using TRIM, the Monte Carlo code for the transport of ions in matter [8]. This calculation utilized the ^{238}Pu alpha energies of 5499 keV (branching ratio = 71.11%) and 5456 keV (branching ratio = 28.71%) as the initial particle energies. Due to energy losses in the 13.85-mm thick air gap between the source and the diode surface and in the 1-μm thick protective gold layer of the diode (energy loss in the 250-Angstrom nickel Schottky contact layer is negligible), the mean of the deposited alpha energy distribution in the active layer is 294 keV, with a standard deviation of 3.9%. Consequently, the resolution of 5.8% observed with the SiC Schottky diode is assumed to be at an energy of 294 keV.

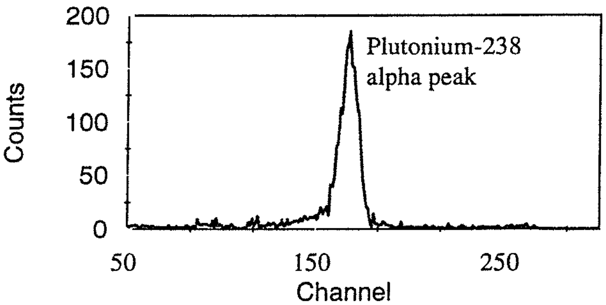


Figure 3. Response of a SiC Schottky detector to ^{238}Pu alpha particles in the "pinhole" configuration. A 0.1-mm pinhole collimator is in place between the detector and the source. The detector-to-source distance is 13.85 mm, and no external bias is applied to the detector.

Some counts are recorded in channels located beyond the peak in the spectrum of Figure 3. These are attributed to the relatively few alpha particles that enter the diode with angles of incidence less than 90°. Since the TRIM calculations show that the ^{238}Pu alpha particles are transmitted through the 1.1-μm active layer of the SiC diode, particles entering the diode at incident angles other than 90° deposit on the average a greater amount of energy in the active layer by virtue of their longer path lengths in this region. This leads to the generation of signals with greater pulse heights, and thus to the observation of counts in channels that are higher than those of the peak, which consist mainly of counts due to alpha particles with normal incidence. A few events are also present in channels that are lower than those of the peak. These events are attributed to alpha particles that have been inelastically scattered by surrounding materials into the diode.

The spectrum obtained with an unbiased p-n junction diode using the pinhole collimator has features that are similar to that obtained with a Schottky diode. The resolution of the p-n junction diode is 6.6% (FWHM) for a calculated energy deposition of 260 keV.

Both types of SiC diodes provide robust responses to alpha radiation without an external bias voltage applied. This feature of SiC presents an important advantage over other types of detectors that require application of large external bias voltages to detect alpha radiation.

The consistency of the SiC detector performance was investigated by testing the alpha radiation response of several detectors of a given type in an identical configuration. In order to obtain a reasonably high counting rate, the pinhole collimator was not inserted in the experimental setup during these tests. The results are given in Table 1 for Schottky detectors with a n^--layer thickness of 3.4 μm. The data show that little variation exists between the response of these detectors, thus indicating that detector performance is very reproducible from diode to diode. Similar results were obtained with p-n junction detectors.

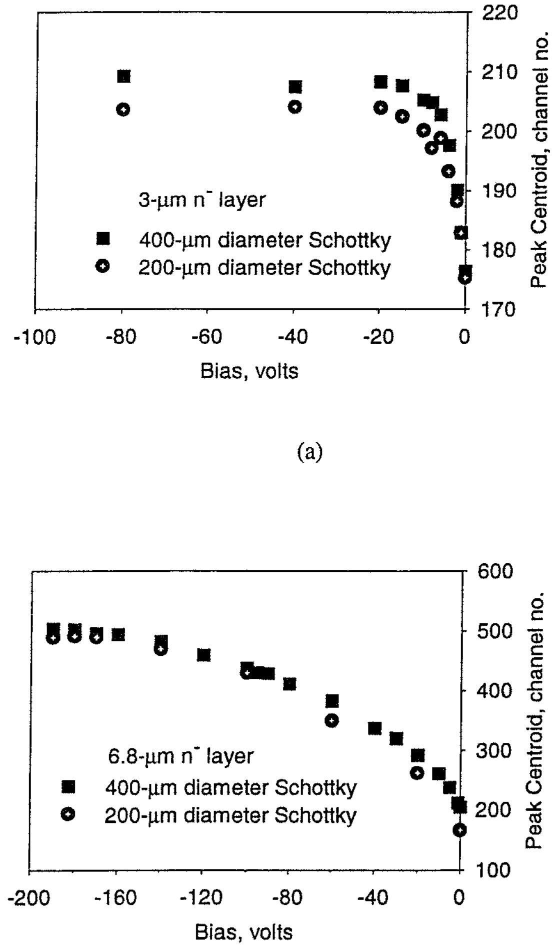
B. Effect of Bias Voltage

The active layer thickness of a diode can be related to the applied (reverse) voltage bias by the following approximation [9]:

$$d \approx \left[\frac{2\varepsilon V}{e N}\right]^{\frac{1}{2}} \qquad (1)$$

where d is the active layer thickness, ε is the dielectric constant of the material, V is the bias voltage, e is the electron charge and N is the dopant concentration of the diode's n^- layer. As an external reverse bias voltage is applied to the diode, the active region grows until the maximum active layer thickness, which corresponds to the thickness of the n- layer, is reached. At this point, the diode is said to be fully depleted, and the applied bias voltage is referred to as the depletion voltage. Further increase in the applied bias can not result in any more growth of the active layer.

Figure 4 shows plots of alpha peak centroid versus applied bias voltage for two Schottky diodes of different n^- layer thicknesses. The centroid position initially shifts to higher channels as the voltage increases. This shift is attributed to the widening of the diode's active layer with increasing voltage (Equation 1). As a result, the alpha particles deposit more energy in the active layer, leading to detector signals with greater pulse heights. When the maximum active layer thickness is reached, further increases in the bias voltage do not change the peak centroid, as indicated by the plateaus observed in both curves of Figure 4.



(a)

(b)

Figure 4. Shift of ^{238}Pu alpha peak as a function of applied bias for SiC Schottky detectors with n$^-$ layer thicknesses of (a) 3 µm and (b) 6.8 µm.

Figure 5 compares the peak obtained with a 0-V bias and with a -180-V depletion-voltage bias applied to the 6.8-µm Schottky detector. It is evident that the peak at -180 V is broader and has a smaller height. This peak broadening at -180 V is attributed to the greater divergence of the alpha-particle path lengths from a normal, straight-line trajectory in the thicker active layer of the diode. The peak areas at 0 V and -180 V are comparable, which is expected since the number of alpha particles traversing the active layer is independent of the layer's thickness in our test configuration.

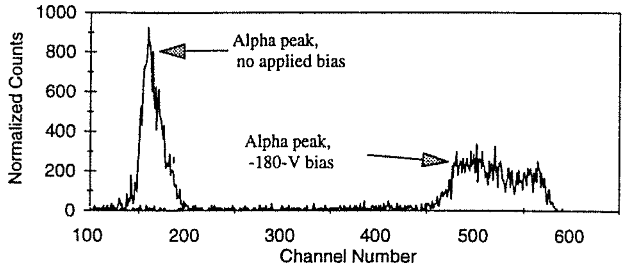


Figure 5. Response of a SiC Schottky detector to ^{238}Pu alpha particles at applied bias voltages of 0 and -180 volts. The thickness of the detector's n$^-$ layer is 6.8 µm.

A plot of peak centroid versus applied bias voltage for a p-n junction diode is given in Figure 6. The active layer thickness of this diode is 3.4 µm. The shape of the p-n junction curve is similar to that of the Schottky diode.

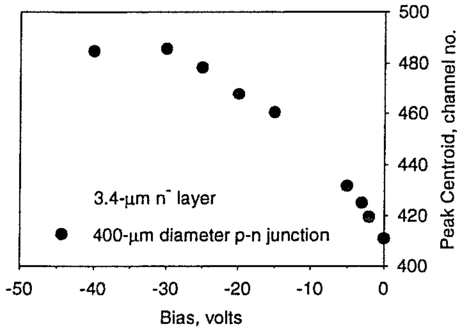


Figure 6. Shift of ^{238}Pu alpha peak as a function of applied bias for a SiC p-n junction detector with an n$^-$ layer thickness of 3.4 µm.

C. Effect of Temperature

Measurements of the peak centroid and FWHM of the alpha signal from a Schottky detector were made at several temperatures (at equilibrium) in the range of 22 to 89 °C, with the ^{238}Pu alpha source located at a distance of 7.5 mm from the surface of the detector. Results are shown in Figures 7 (bias = 0 V) and 8 (bias = -20 V). The peak centroid remains stable over the temperature range studied, with an average value of 161.0 ± 1.3 at 0-V bias, and 204.8 ± 0.9 at -20-V bias. The uncertainty reported is the standard deviation of the peak centroid values. It should be noted that the magnitude of this uncertainty is comparable to that observed when replicate measurements of the peak centroid are made at room temperature. Similarly, the FWHM does not show any temperature dependency in the range studied.

An additional experiment was performed to study the detector response with changing temperature. The Schottky diode was allowed to acquire an alpha radiation-induced peak while the temperature was cooling from 89 °C to 35 °C. This measurement was made with an applied bias of -20 V. No significant change in the centroid or FWHM of the peak acquired during this period was observed relative to the corresponding characteristics of a peak acquired at constant ambient temperature.

These results demonstrate that the response of a SiC detector to alpha radiation is unperturbed by temperature in the range studied. Based on the wide bandgap energy of SiC, the lack of sensitivity to temperature of the SiC detector is expected to persist up to much higher temperatures.

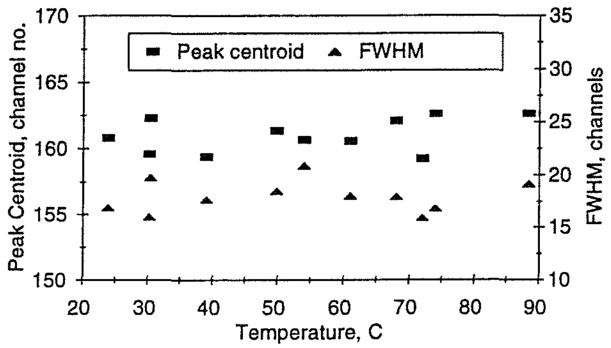


Figure 7. Effect of temperature on the response of a SiC Schottky detector to ^{238}Pu alpha particles with no applied bias.

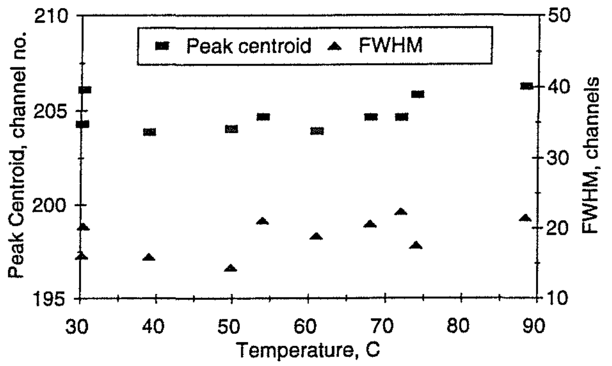


Figure 8. Effect of temperature on the response of a SiC Schottky detector to ^{238}Pu alpha particles with an applied bias of -20 V.

D. Effect of Gamma Radiation

Figure 9 shows the response of a SiC Schottky detector when the latter is placed in a cobalt-60 gamma-radiation field of 10,000 rad-Si h^{-1}, with the alpha source located at a distance of 7.5 mm from the detector surface. Clearly, the observed gamma signal does not interfere with the alpha signal and, as expected, the detector intrinsic efficiency for gamma rays is quite small. Elimination of the gamma-signal can readily be accomplished through pulse height discrimination techniques. Furthermore, based on the pulse shapes of the alpha- and gamma-induced pulses observed with an oscilloscope (Figure 10), the rise time of the alpha pulse out of the detector is much faster than that of a typical gamma pulse. This difference provides a basis for the elimination of gamma signals from the detector response, if desired, through rise time discrimination methods.

An interesting observation made during the gamma radiation testing was that the detector response to gamma rays was linear in the range of dose rates studied. A plot of gamma-induced counting rate versus gamma dose rate is shown in Figure 11 for a Schottky detector. Although this study was primarily concerned with the response of the SiC detectors to charged particles, the linearity of the detector response to gamma radiation at such high dose rates, while still in pulse-mode operation, could make SiC detectors strong candidates for applications where gross gamma counting in extremely high-radiation fields is required.

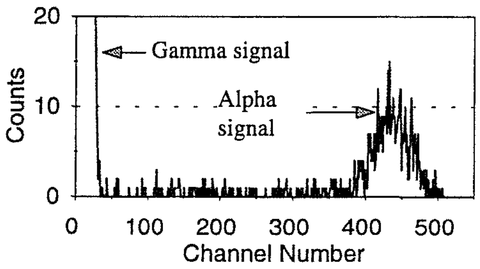


Figure 9. Response of a SiC detector to ^{238}Pu alpha particles in a 10,000 rad-Si h^{-1} gamma-radiation field. The distance between the detector and the alpha source is 7.5 mm. An external bias of -60 V is applied to the detector.

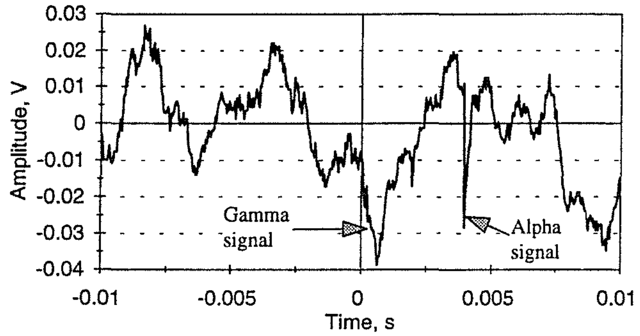


Figure 10. Oscilloscope trace obtained with a SiC detector exposed simultaneously to a ^{238}Pu alpha source and a ^{60}Co gamma-ray source. Rise time of alpha signal is faster than that of gamma signal.

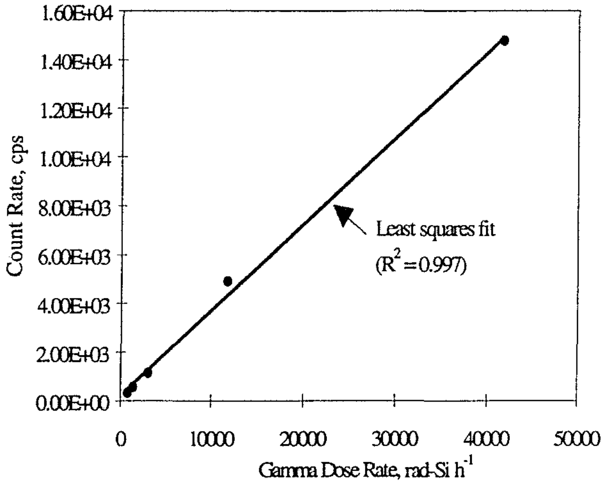


Figure 11. Response of a SiC Schottky detector to gamma-ray intensity. Detector counting rate is proportional to gamma dose rate over the range studied.

Table 1.

Comparison of the alpha-induced peak characteristics observed with Schottky detectors exposed to a ^{238}Pu alpha source.

Detector No.	Bias = 0 V			Bias = -20 V		
	Peak Centroid	**FWHM**	**Area, cpm**	**Centroid**	**FWHM**	**Area, cpm**
1	164.8	13.4	339.8	199.3	15.4	357.8
2	158.7	14.7	372.8	199.5	15.8	367.2
3	165.6	17.2	353.0	192.5	15.4	356.8
4	162.3	19.8	349.6	206.1	20.3	383.0
5	165.0	18.4	361.4	200.5	21.4	371.6
6	162.4	13.6	349.6	200.8	14.9	357.6
7	163.1	18.1	332.6	199.9	17.6	352.2
Mean ± σ^a	*163.1 ± 1.4%*	*16.5 ± 15.5%*	*351.3 ± 3.8%*	*199.8 ± 2.0%*	*17.3 ± 15.2%*	*363.7 ± 3.0%*

[a] σ : one standard deviation

V. CONCLUSIONS

The charged-particle detection properties of Schottky and p-n junction diodes made of 4H-SiC were evaluated. A robust signal was observed when the detectors were exposed to alpha radiation from a ^{238}Pu source. The resolution was measured to be 5.8% (FHWM) at a calculated alpha-particle energy of 294 keV for the Schottky detector, and 6.6% (FWHM) at 260 keV for the p-n junction detector. Both detectors provide robust alpha signals without an external bias voltage, and the response of a given type of detector is very reproducible from diode to diode.

We found no evidence of temperature effects on the performance of the SiC Schottky detector in the range of 22 to 89 °C. The alpha signal was also found to be easily separable from the gamma-induced signal in a 10,000-rad-Si h^{-1} gamma field. Furthermore, the detector's gamma-induced count rate was linear in the range of gamma dose rates (700 to 40,000 rad-Si h^{-1}) studied. These results demonstrate the potential of SiC detectors for use in applications where elevated temperatures and/or high radiation fields are encountered.

VI. REFERENCES

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