Development of Radiation Detectors Based on Semi-Insulating Silicon Carbide

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***Abstract*–Fast-neutron detectors based on high-purity semi-insulating 4H silicon carbide (SiC) semiconductor have been fabricated and tested. The response characteristics of these detectors have been compared with those of epitaxial 4H-SiC Schottky diode detectors. The charge collection efficiency has been tested using alpha particles and the fast-neutron response has been tested with 14-MeV and 2.5-MeV neutrons. Over the applied voltage range tested, the charge collection efficiency for alpha particles is generally lower for the semi-insulating SiC detectors, and the fast-neutron detection efficiencies are also gererally lower. Both the lower charge collection efficiency and the lower fast-neutron detection efficiencies are primarily a result of charge recombination resulting from lower electric fields across the thicker semi-insulating SiC detectors and the inability of the detector packaging to adequately withstand high voltages. Semi-insulating SiC detectors provide a viable alternative to epitaxial SiC diode detectors and methods to improve the performance of semi-insulating SiC detectors are proposed.**

I. INTRODUCTION

SILICON Carbide SiC semiconductor radiation detectors have been demonstrated for charged particle, gamma-ray and X-ray, and neutron detection in a variety of applications. In most cases, the 4H polytype of SiC has been used, and the detectors are diode structures based on lightly doped epitaxial SiC layers. An extensive review on SiC radiation detectors can be found in reference [1].

Although many different SiC diode radiation detector radiation detectors have been demonstrated, the most prevalent design is the Schottky diode. [1] For example, high-resolution SiC alpha particle detectors were demonstrated using a 100-µm thick lightly doped epitaxial SiC layer on a conducting SiC substrate [2]. When a negative bias is applied to the top Schottky contact, the epitaxial layer is depleted of charge carriers, and when ionization is produced in the depleted layer, it is collected under the influence of the applied bias. When used as gamma-ray [3] or fast-neutron [4] detectors, the efficiency will be proportional to the detector active volume, which will be proportional the depletion thickness of the epitaxial layer.

The epitaxial layers used in reference [2] were doped with nitrogen concentrations ranging from (1.2-1.5) x 10^{14} cm^{-3}, requiring a bias of more than 1100 V to fully deplete the epitaxial layer. Because the depletion depth is proportional to the square route of the applied bias divided by the doping concentration, higher doping concentrations require higher voltages to reach full depletion. Therefore, the fast-neutron efficiency will be limited by two factors, the thickness of the epitaxial layer and the intentional doping concentration. At present, although epitaxial layers up to 200 µm can be manufactured, only thicknesses up to about 120 µm are readily available. Furthermore, depletion of epitaxial layers greater than 100 µm at modest voltages requires doping concentrations much less than 10^{14} cm^{-3} and potentially as low as 10^{13} cm^{-3}. [5] Such low concentrations are difficult to achieve. Therefore, epitaxial SiC detectors are presently limited to thicknesses of about 120 µm.

An alternative to using epitaxial SiC devices is semi-insulating SiC. Semi-insulating SiC with a thickness of 360-µm is readily available. In fact, semi-insulating SiC has been tested for detection of minimum ionizing particles [6] and alpha particles [7]. Planar semi-insulating 4H-SiC detectors with thickness of 360 µm were shown to detect beta particles by Rogalla, *et al.* [6], but only 23% charge collection efficiency was obtained. Cunningham, *et al.* [7] demonstrated 110 µm thick planar semi-insulating 4H-SiC detectors, and observed 60% charge collection efficiency for ^{241}Am alpha particles. The low charge collection efficiency was attributed to the intrinsic deep-level traps resulting from intentional doping with vanadium in the semi-insulating material used.

Recently, high-purity semi-insulating 4H-SiC wafers have become available from Cree, Inc. This material is not doped with vanadium and has low residual impurities corresponding to background net doping concentrations less than 10^5 cm^{-3}. Planar detectors have been fabricated using this material and have been tested for alpha-particle and fast-neutron detection.

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II. DETECTOR FABRICATION

Two 7.62-cm diameter x 360-µm thick semi-insulating 4H-SiC wafers were obtained from Cree, Inc. (Durham, NC, USA). Although semi-insulating wafers offer a unique and emerging SiC material product that may offer higher neutron sensitivity and lower costs, the impurities and defects in these bulk materials may lead to higher leakage currents. The concentration of "killer" defects such as microchannel pipes is higher (<15 cm^{-2}) in semi-insulating materials compared to epitaxial materials (~3 cm^{-2}). Therefore, several different device sizes and designs were manufactured to investigate device yields as a function of size. Devices with 0.79-mm^2, 7.1-mm^2, and 28.3-mm^2 areas, corresponding to diameter equivalents of 1, 3, and 6 mm were fabricated using the mask design shown in Fig. 1. This cell design was repeated and is shown superimposed over the entire 7.62-cm wafer in Fig. 2

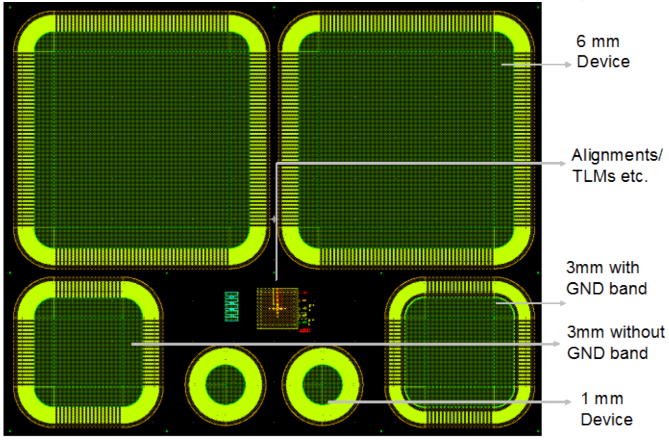

Fig. 1. Mask design showing two 6-mm diameter equivalent devices, two 3-mm diameter equivalent devices, and two 1-mm diameter equivalent devices per reticule.

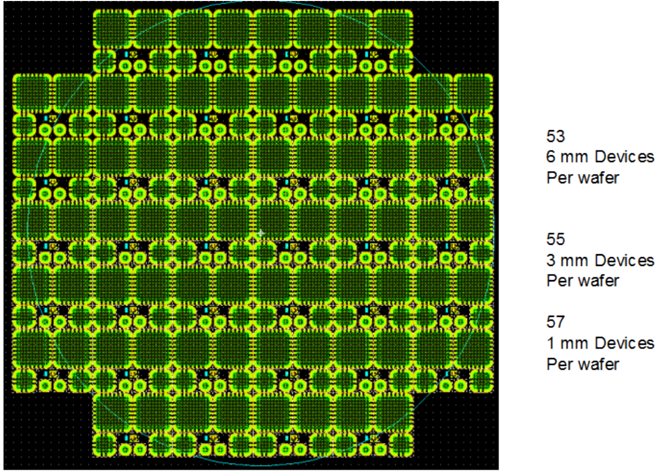

Fig. 2. Mask design repeated over the 7.62-cm SiC wafer.

A combination of photo-lithography and vacuum-deposition techniques were used to manufacture the devices. As shown in Fig. 3. The vertical structure of the detectors is shown schematically in Fig. 4. The top contact consists of a 400 Å titanium layer covered by 600 Å of platinum and 20,000 Å of gold. Initially, 360-µm thick detectors were manufactured, and after testing thiner 150-µm and 160-µm detectors were manufactured. For the thinner detectors the top contact was 400 Å of nickel covered by 15,000 Å of gold. The back Ohmic contacts were 400 Å of nickel covered by 15,000 Å of gold in all cases.

Individual detectors were diced from the wafer and mounted in packages and wire bonded as shown in Fig. 5, which shows a set of six 6-mm diameter equivalent (28.3-mm^2) detectors. Response measurements were carried out on these detectors using alpha particles and fast-neutrons

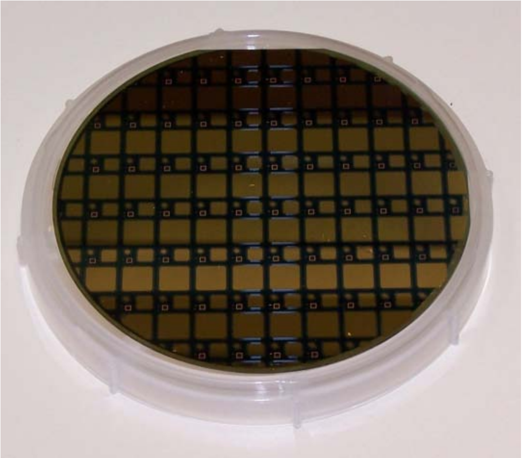

Fig. 3. Completed wafer and detectors.

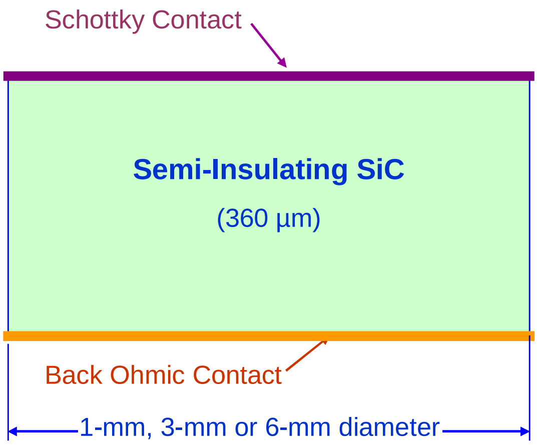

Fig. 4. Schematic representation of a neutron detector based on semi-insulating SiC.

III. DETECTOR TESTING

The detectors were tested with alpha particles from a ^{238}Pu source, 14-MeV fast neutrons from an electronic Deuterium-Tritium (D-T) source, and 2.5-MeV neutrons from a D-D source.

A. *Alpha-Response Measurements*

Charge-collection efficiency measurements were carried out for a semi-insulating SiC detector using a ^{238}Pu source, which emits 5499.2-keV (70.9%) and 5456.5-keV(28.9%) alpha particles. The response spectrum in-vacuum for a 0.79-mm^2 x 120-µm Schottky diode is shown as a function of appplied bias in Fig.6. Only a single peak is observed at each voltage due to the energy straggling in the thick Schottky contact (400 Å

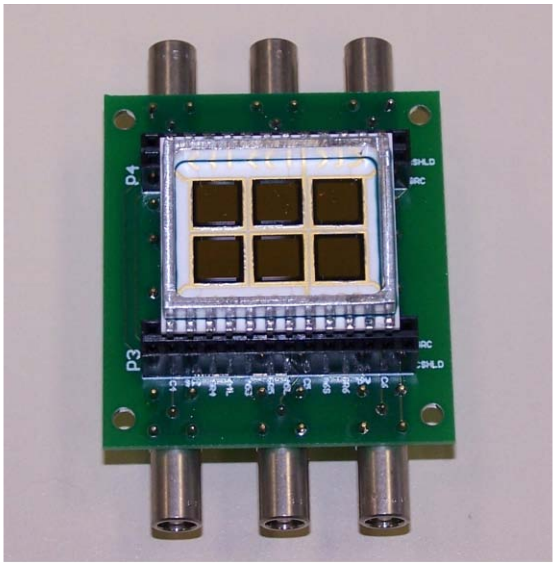

Fig. 5. A 6 x 6 array of 28.3-mm^2 SiC detectors packaged and mounted on a PCB board.

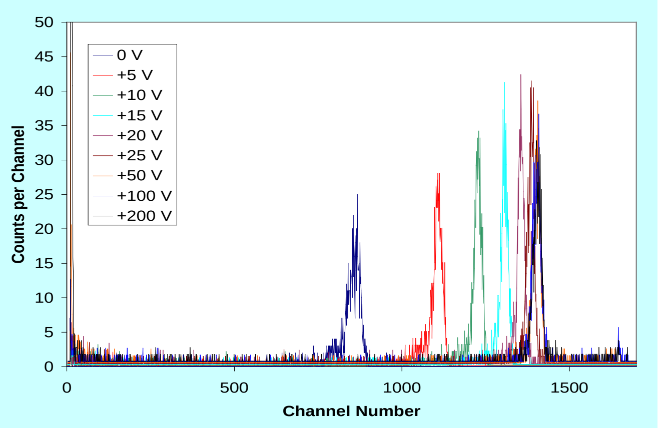

Fig. 6. Peak positions as a function of applied voltage for ^{238}Pu alpha particles in a 0.79-mm^2 x 120-µm Schottky diode. Pulse height is proportional to energy deposited in the detector active layer.

titanium layer covered by 600 Å of platinum and 20,000 Å of gold), preventing resolution of the two ^{238}Pu alpha peaks which are separated by only 42.7 keV. [2] The increase in peak amplitude with voltage corresponds to the increasing depletion depth. The depletion depth becomes greater than the residual ranges of the alpha particles in SiC at voltages greater than 50 V and collection of the charge deposited in the detector active volume is 100% leading to no further increase in the peak amplitude with voltage. A plot of the peak centroid positions as a function of voltage is shown in Fig. 7.

Corresponding measurements were carried out with a 28.3-mm^2 x 360-µm semi-insulating detector as shown in Fig. 8.

The peak centroid positions are plotted as a function of voltage in Figure 9. At the highest voltage (400 V) only about 27 % of the charge deposited by the alpha particles is being collected. Unfortunately measurements could be carried out only up to 400 volts, because the packaging for this detector could not withstand higher voltages.

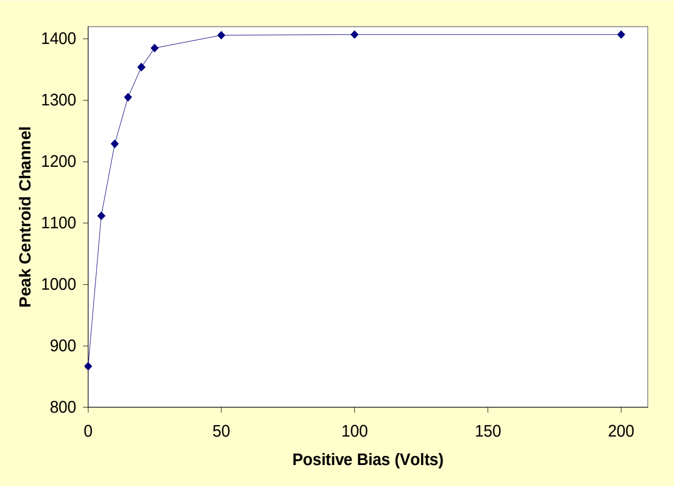

Fig. 7. Peak positions as a function of applied voltage for ^{238}Pu alpha particles in a 0.79-mm^2 x 120-µm Schottky diode.

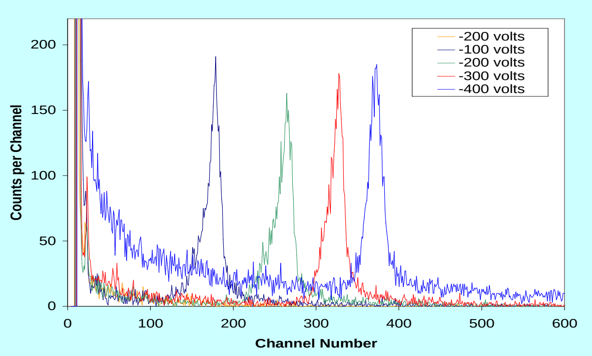

Fig. 8. Peak positions as a function of applied voltage for ^{238}Pu alpha particles in a 28.3-mm^2 x 360-µm semi-insulating SiC detector.

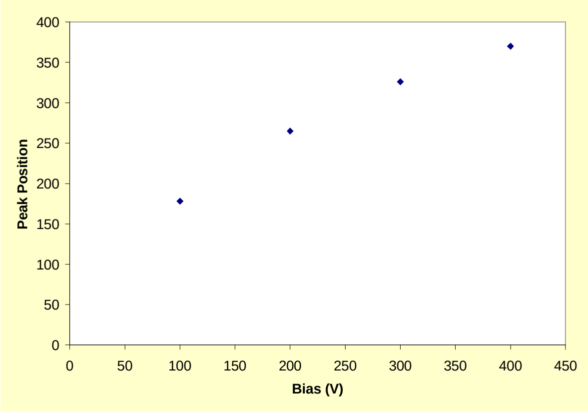

Fig. 9. Peak centroid positions as a function of applied voltage for ^{238}Pu alpha particles in a 28.3-mm^2 x 360-µm semi-insulating SiC detector

Similar ^{238}Pu response measurements were carried out in air with a 28.3-mm^2 x 150-µm semi-insulating SiC detector. Although measurements were carried out at biases up to 800 V with this detector as shown in Fig. 10, only 22% charge collection efficiency was observed at the highest voltage. In both semi-insulating detector cases, the measured charge collection efficiency was increasing as a function of voltage at the highest voltage tested indicating that higher charge

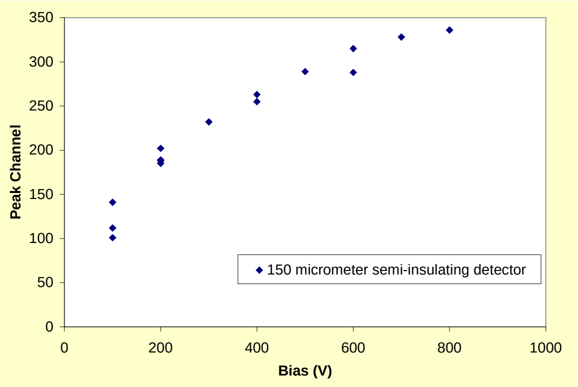

Fig. 10. Peak centroid positions as a function of applied voltage for ^{238}Pu alpha particles in a 28.3-mm^2 x 360-µm semi-insulating SiC detector

collection efficiencies would be obtained if higher voltages could be applied.

B. *Neutron-Response Measurements*

Neutron-response measurements were carried out using a fast amplifier and a time-to-amplitude converter (TAC) triggered by the trigger signal of either a D-T or D-D pulsed neutron generatorusing the electronics configuration shown schematically in Fig.11.

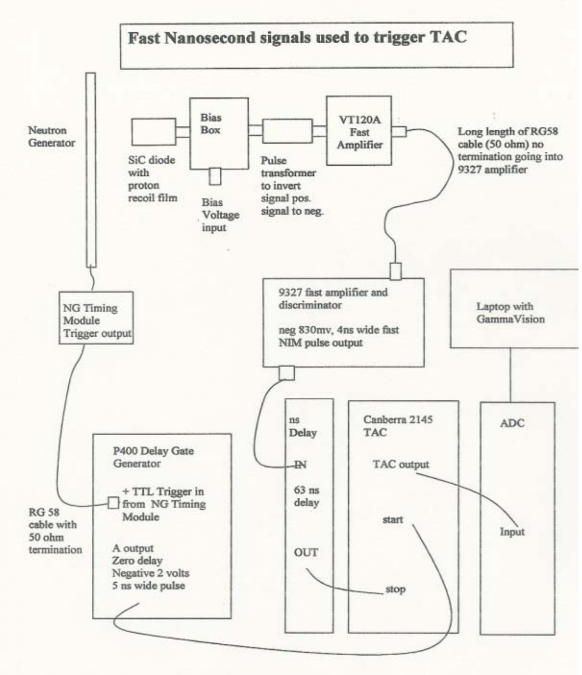

Fig. 11. Schematic of fast-amplifier and time-to-amplitude electronics used in neutron generator measurements.

Initially measurements were carried out using a D-T neutron generator producing 14-MeV neutron bursts of duration 100 µs at a frequency of 1000 Hz.

TAC measurements using a 28.3-mm^2 x 100-µm Schottky diode with a 100-µm thick proton-recoil converter foil [8] are shown in Fig. 12. Most of the neutron counts are observed in a 100-µs interval corresponding to the neutron burst. Only 0.1% of the neutron counts are observed between bursts and

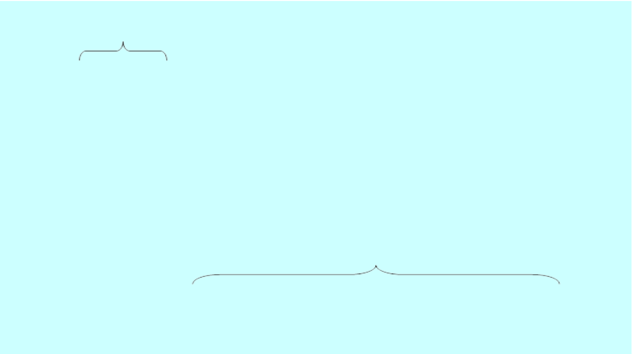

Fig. 12. Neutron counts measured with a 28.3-mm^2 x 100-µm Schottky diode as a function of time following the trigger signal for a 14-MeV neutron generator.

Identical measurements were carried out with a 28.3-mm^2 x 360-µm semi-insulating SiC detector, and the results are shown in Fig.13. Again, the neutron counts are confined

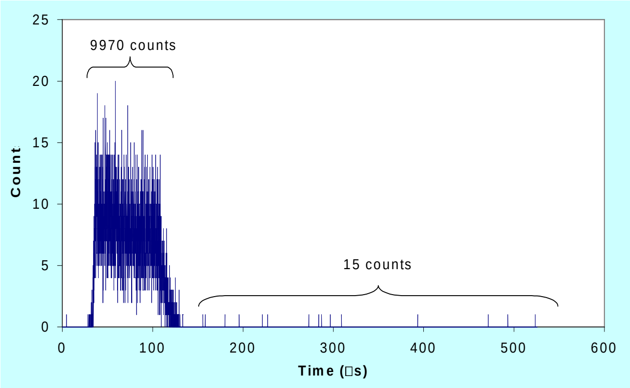

Fig. 13. Neutron counts measured with a 28.3-mm2 x 360-µm semi-insulating SiC detector as a function of time following the trigger signal for a 14-MeV neutron generator.

these are produced by a combination of the non-zero neutron generator dark current and by fission neutrons from enriched ^{235}U, which was present during the measurements.mainly to the 100-µs neutron generator burst, and the 0.1% of the counts observed between pulses is within statistics of the number of counts observed with the Schottky diode.

The counts observed during the generator bursts were summed in 1-µs intervals for both detectors, and the results are shown in Fig. 14.

Fig. 14. Comparison of counts per µs as a function of time for the Schottky-diode and semi-insulating detectors.

The same time profile is observed for the neutron burst with both detectors indicating that the same rapid pulse-response characteristics that have been observed with epitaxial diode detectors are also observed with semi-insulating detectors.

However, the neutron efficiency for the semi-insulating SiC detector is lower than for the Schottky diode as evidenced by the data shown in Fig. 15. The number of observed counts increases as a function of applied voltage indicating that the efficiency is also increasing. A probable cause for the increase is increasing charge collection efficiency as a function of voltage. The count rate was increasing with voltage up to 1500 V, at which point the detector shorted out and was only functional thereafter at much lower voltages.

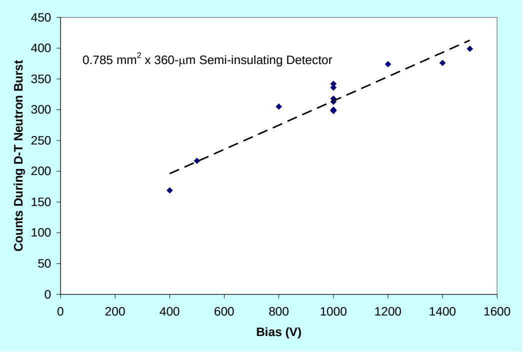

Fig. 15. Number of counts as a function of voltage for a 28.3-mm^2 x 360-µm semi-insulating detector exposed to 14-MeV neutrons.

Similar measurements were carried out with a D-D neutron generator. The 2.5-MeV neutron energy was used as a surrogate for fission neutrons, which have a broad energy distribution and an average energy of about 2 MeV for an unperturbed spectrum. Response measurements are shown for a 28.3-mm^2 x 100-µm Schottky diode in Fig. 16 and for a 28.3-mm^2 x 360-µm semi-insulating SiC detector in Fig. 17.

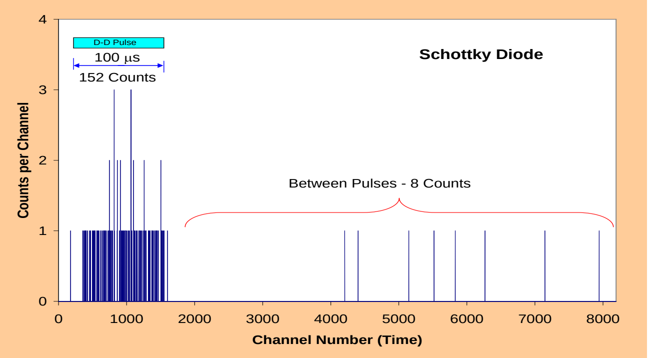

Fig. 16. Neutron counts measured with a 28.3-mm^2 x 100-µm Schottky diode as a function of time following the trigger signal for a 2.5-MeV neutron generator.

The neutron output of the D-D neutron generator is much less than that of the D-T generator, resulting in fewer counts observed for both detectors. However, in both detector cases, most of the observed neutron counts are confined to the time corresponding to the 100-µs neutron generator burst, and 4.9% and 2.2% of the neutron counts were observed between pulses for the Schottky diode and the semi-insulating SiC detector, respectively. The number of counts observed between bursts are within statistics for the two detectors and correspond entirely to the D-D neutron generator dark currrent.

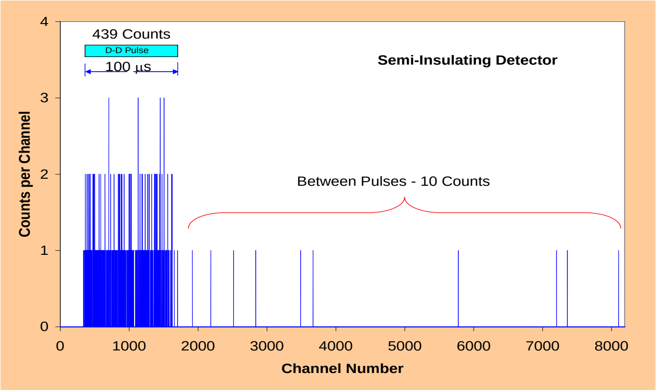

Fig. 17. Neutron counts measured with a 28.3-mm2 x 360-µm semi-insulating SiC detector as a function of time following the trigger signal for a 2.5-MeV neutron generator.

The similarity of the 2.5-MeV neutron response measurements demonstrates that the same rapid pulse response results that have been obtained for fission neutron with Schottky diodes [9] can also be obtained with semi-insulating detectors.

Relative efficiency measurements were carried out for 2.5-MeV neutrons with both the Schottky diode and the semi-insulating SiC detector. In the Schottky diode case, measurements were carried out as a function of applied bias voltage, and the relative detector response is ploted as a function of calculated depletion depth in Fig.18. Response measurements were carried out both with and without the proton recoil converter. The detector response due to proton-recoils is independent of depletion thickness. [8] The detector fast-neutron response from neutron reactions with carbon and silicon nuclei in the detector should be proportional to detecter volume [14], which is in turn proportional to depletion depth as is demonstrated by the data in Fig. 17, which show that the detector response is directly proportional to depletion depth.

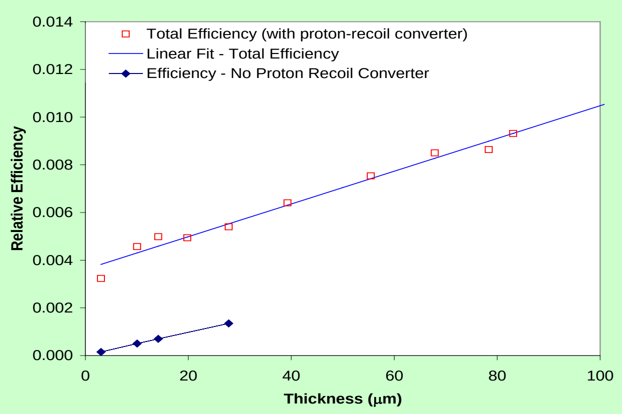

Fig. 18 Relative efficiency for 2.5-MeV neutrons as a function of calculated depletion depth for a 28.3-mm^2 x 100-µm Schottky diode.

A similar proportionality would be expected also for semi-insulating SiC detectors. Only a limited number of response measurements were carried out with semi-insulating detectors due to high leakage currents and detector shorting problems. The results for a 28.3-mm^2 x 150-µm semi-insulating SiC detector are shown in Fig. 19 where counts are plotted as a function of applied bias. Although the measurements are somewhat scattered, there is a general trend towards increasing counts with increasing voltage as was shown by the 14-MeV data in Fig.14.

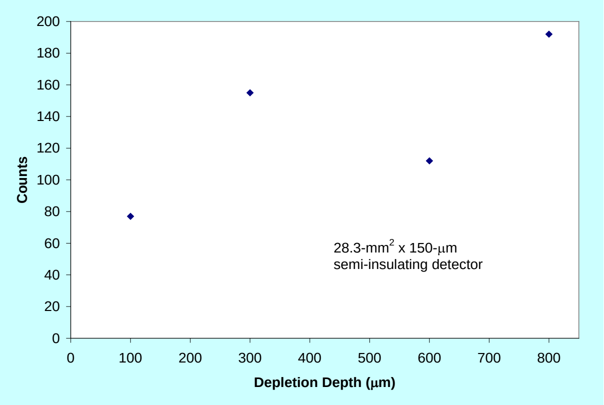

Fig. 19 Semi-insulating detector response as a function of voltage.

Preliminary results for the relative 2.5-MeV semi-insulating SiC detector efficiencies are plotted as a function of thickness and compared with the linearly extrapolated Schottky diode results in Fig. 20. It can be seen that the measured efficiencies for the semi-insulating detector are much less than those predicted by a linear extrapolation of the Schottky diode efficiency curve to the corresponding thicknesses. The observed efficiency is only 44.7% of the expected efficiency for a 150-µm thick semi-insulating SiC detector at 800 V and only 43.8% for a 360-µm semi-insulating SiC detector at 600 V. The primary reason for the low efficiency is probably low charge collection efficiency for the semi-insulating SiC detectors resulting in loss of low-amplitude pulses from neutron interactions which produce low-energy proton, carbon, or silicon recoils in the detector active volume.

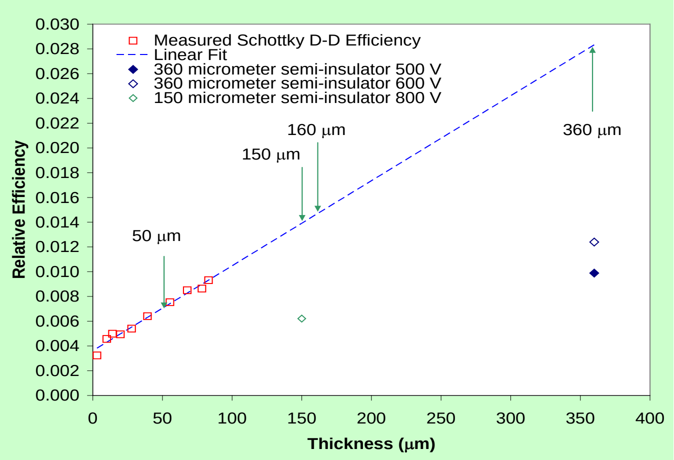

Fig. 20 Comparison of the measured semi-insulating SiC detector efficiencies for 2.5 MeV neutrons with those measured with a Schottky diode neutron detector.

IV. DISCUSSION

The low charge collection efficiency observed for semi-insulating SiC detectors may result from a several causes:

- Charge trapping due to impurities or defects in the material.
- Charge re-combination resulting from the so-called “plasma effect”. [10]
- Charge re-combination due to impurities or defects that act as re-combination sites in the material

Although charge trapping is undoubtedly present to some degree, it is probably not the pre-dominant cause for low charge collection efficiency in the semi-insulating SiC detectors. Charge trapping can be expected to produce tailing on the leading edge of peaks in pulse-height response spectra. The data in Fig. 8 possibly show some evidence of tailing at lower voltages, but the higher voltage peaks are nearly Gaussian indicating that there is not a large amount of charge trapping.

Charge re-combination due to either of the two causeses listed may be present. Because the semi-insulating detectors are thicker than their Schottky diode counterparts, the electric fields that result across the active volume are lower at the same applied bias. Because the carbon and silicon neutron reaction product ions are mostly highly charged ions, the ionization produced in the detector active volume is a very dense plasma and a significan amount of electron-hole re-combination can be expected to occur. This effect is exacerbated by the inability to apply high voltages to the detectors with the current packaging.

Because the nature of the residual impurities in the semi-insulating SiC is generally unknown, the presense of impurity atoms that act as re-combination centers cannot be excluded. At present, the relative contributions of recombination due to the plasma effect and recombination due to impurities of defects in the semi-insulating SiC cannot be determined.

However, based on the observed increases in semi-insulating SiC detector fast-neutron efficiency with increasing voltage, it can be assumed that improved high-voltage packaging of the detectors will lead to higher detection efficiencies. Alternative packaging configurations that minimize surface leakage current and prevent possible shorting of the detector should be tested.

Also, alternative SiC detector electrode configurations should be explored such as the use of 3D electrode configurations. [11,12] Such detectors use penetrating anode and cathode configurations in order to minimize charge collection paths. Such detector configurations are beign developed mainly for silicon detectors in high-energy physics applications where the production of charge traps through radiation damage is an issue and 3D electrode configurations can be expected to prolong detector service lifetimes.

The use of 3D electrode configurations is already being investigated for SiC detectors. [13]

V. CONCLUSIONS AND RECOMMENDATIONS

Semi-insulating SiC detectors offer a promising, less expensive alternative to diode detectors based on epitaxial SiC. Epitaxial layer growth limitations prevent the growth of layers greater than 200 μm thick., Furthermore, dopant concentrations cannot at present be lowered below the 10^{13}-10^{14} range, which leads to the requirement for very high voltages to achieve reasonable depletion depths in epitaxial layers.

On the other hand, 360-μm thick semi-insulating SiC wafers are readily available, and the extremely low residual impurities corresponding to background net doping concentrations less than 10^5 cm^{-3} allow the entire wafer to be depleted at a modest voltage (20-30 V). Semi-insulating SiC wafers up to 6-mm thick are available offering the prospect for bulk SiC detectors.

However, semi-insulating detectors tested to date exhibit poor charge collection properties and low sensitivities for detection of fast neutrons. At present, the lower sensitivity of semi-insulating SiC detectors compared to epitaxial SiC diode detectors almost offsets the lower costs for manufacturing semi-insulating SiC detectors.

The limitations in charge collection efficiency and fast-neutron sensitivity are caused in large part by deficiencies in the packaging of these detectors, and indeed increases in the detection efficiencies with voltage up to the highest voltages tested indicate that higher efficiencies can be obtained with improved packaging. Although potentially difficult to implement in SiC, which is an extremely hard and chemically resistant material, 3D electrode configurations [13] offer the potential for improvement. Such 3D electrode configurations result in shorter maximum drift and charge collection distances and should result in less loss of charge carriers through re-combination.

Further investigation is needed to improve the charge collection and efficiency characteristics of SiC detectors in order to achieve higher efficiency SiC detectors at lower costs.

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