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Boron-Rich Semiconducting Boron Carbide Neutron Detector

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Abstract

Data on the neutron detection capabilities of a variety of boron carbide/Si heterojunction diodes is presented. The pulse height spectra are compared with previously measured conversion layer devices and the variations in shape and position of the peaks are discussed.

Keywords: semiconducting boron carbide, neutron detection, boron-rich semiconductor

Gas-filled and scintillator-based detectors are widely used in detecting neutrons of thermal and higher energies but each of these detectors has at least one significant drawback that limits its applications. Solid-state detectors have the potential to overcome all such limitations simultaneously even in the most challenging applications, such as: in the reflectometers and small angle scattering instruments at future spallation neutron sources; in monitoring water, gas and oil; in space exploration; and in environmental monitoring.

Boron is unique amongst elements for detecting neutrons in that it has a large cross-section for capture of thermal neutrons and that the capture reaction products are primarily highly energetic ions viz.

$$^{10}B + n \rightarrow {}^{7}Li\ (0.84\ MeV) + {}^{4}He\ (1.47\ MeV) + \gamma(0.48MeV) \quad (1)$$

and

$$^{10}B + n \rightarrow {}^{7}Li\ (1.02\ MeV) + {}^{4}He\ (1.78\ MeV) \quad (2)$$

that occur with 94 and 6% probability respectively yielding the large kinetic energies listed in parentheses.[1]

Of neutron-capturing elements, boron is also unique in forming the major component of a refractory ceramic that can also be made as a semiconductor. Detectors based on boron-rich semiconductors have the potential to be nearly ideal neutron detectors if atoms of 10B are present in sufficient numbers in regions of semiconductor from which all the neutron capture product ions can be detected effectively.

The problem of creating boron-rich semiconducting boron carbide was solved in the early 1990s,[2] and was followed by the creation of a wide range of hetero- and homo-junction diodes and transistors, including a heterojunction diode that operates to at least 350°C.[3] We have also reported the first real-time detection of neutrons with a semiconducting boron carbide device.[4] Here we present pulse height spectra from three boron carbide semiconductor/n-Si heterojunction diode neutron detectors and compare the spectra with those from literature reports of real-time solid-state neutron detectors that use boron-rich neutron capture coatings.

Boron carbide films with composition near B_5C were deposited on n-type Si(111) (resistivity ~30 Ωcm) in a custom designed parallel plate 13.56 MHz radio-frequency plasma enhanced CVD reactor.[4] The source gas closo-1,2- dicarbadodecaborane (ortho-carborane, $C_2B_{10}H_{12}$)-provided a suitable ratio of B and C from a single molecular source and was not enriched in ^{10}B above natural isotopic abundance (19.4%). Thin Cr/Au metal contacts were sputter deposited onto the semiconductor surfaces to define a heterojunction diode detection area.

For consistency checks of the heterojunction diode neutron capture product spectra, three differing conditions of neutron flux and direction were used, as summarized in Table I: (1) in the neutron activation location of the moderator of a 20kW TRIGA-type reactor (Veterans Administration Medical Center, Omaha, Nebraska), (2) at a collimated beam port tangential to the neutron reflector of a 250kW version of the same reactor (Kansas State University, Manhattan, Kansas) and (3) adjacent to the 19 cm radius paraffin moderator surrounding a 5 Ci Pu–Be source at our university. The diodes, electrostatically shielded, were connected to a charge-to-voltage preamplifier (Amptek, model A250) and pulse counting electronics (Canberra, Digital Signal Processor model 9600). The electronic noise performance was less optimal in the case of the 20kW TRIGA reactor because the detector was connected by a 6m long triaxial cable to the preamplifier in order to avoid neutron irradiation of the input stage of the preamplifier. In all cases, the preamplifier output was processed by a digital filter, with rise- and fall-times of 0.4 ms and a 0.1 ms flat top.

Table I. Parameters for diode the neutron detection experiments.

Neutron source	Thermal neutron flux at detector	Symbol in figure ($n{\cdot}cm^{-2}s^{-1}$)	Boron carbide thickness (nm)	Detector area (mm^2)	Bias voltage	Leakage current
20kW TRIGA	1.5×10^{11}	O	276	1	–18V	0.19 mA
250kW TRIGA	1.9×10^{6}	K	276	1	–18V	0.4 mA
5 Ci Pu–Be	1.3×10^{4}	E	232	~20	0V	none

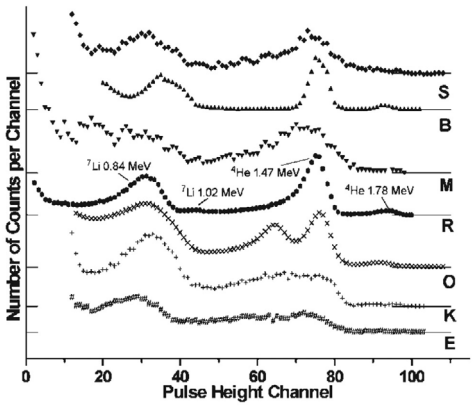

Fig. 1. Neutron capture pulse height spectra K, O, and E are plots of numbers of pulses detected per pulse height channel as a function of rebinned pulse height channel for our Kansas, Omaha, and University of Nebraska data respectively to match the 1.47 MeV ^{4}He feature in the data of Rose[7] in the plot labeled R. Spectra S, M, and B are rebinned data from Sato et al.,[5] McGregor et al.,[6] and Baker et al.[8] respectively. For clarity, all spectra are scaled and offset, as marked by zero-count lines.

The characteristics of the three diodes used for these experiments are given in Table I. Note that the data labeled E corresponds to 0V biasing, which is expected to result in reduced charge collection and reduced electronic noise.

The spectra labeled O, K and E in Fig. 1 are plots, as a function of pulse height, of the relative numbers of pulses detected in our neutron detection experiments in Omaha,[4] Kansas and with the 5 Ci Pu–Be source respectively. Both the flux and the total neutron fluence on the detector for the Omaha case were many orders of magnitude (~10^6) greater than for the K and E data. For comparison, Fig. 1 also contains data reported by Sato et al.,[5] McGregor et al.,[6] Rose,[7] and Baker et al.[8] for boron conversion layer devices in various configurations, labeled S, M, R and B respectively. The data in the figure result from re-binning to match the small number of data channels per unit pulse height in the spectrum of Rose and to provide approximate alignment of all peaks identified with the 1.47MeV α-particle with the corresponding peak of Rose et al. in channel 75. The rebinning has of course reduced the counting-statistics component of the channel-to-channel variations from those visible in the originally reported data.

Labeled in accord with the cited papers are the peaks of features associated with the 1.47MeV ^{4}He ion and the 0.84MeV ^{7}Li ion, as well as a much weaker peak associated with the 1.78MeV ^{4}He ion and, in some cases distinguishable, a peak due to the 1.02 MeV ^{7}Li ion. The three sets of data from our boron carbide/Si heterojunction diodes contain clear 1.78, 1.47, and 0.84 MeV features. The 1.02 MeV feature, which is expected to correspond closely in shape to the 0.84 MeV feature in shape but to have an intensity about 15 times less, is not readily discernable. At channel 64, there is an additional peak visible only in the Omaha data. In data obtained with a 500 nm thick ^{10}B layer on an unbiased GaAs Schottky diode, McGregor *et al.* (Fig. 8 in ref. 6) reported and attributed a somewhat similar feature to incomplete charge collection.

Careful examination of the various spectra reveals that the locations and shapes of the features associated with the Li ions lie at differing pulse height channels relative to the 1.47MeV 4He ion channel. These variations can be attributed, at least in part, to the following factors:

a. Ions will lose energy before they reach the charge collection region if they must first pass through an electrical contact or other material, as is the case for all conversion layer devices.
b. Ions may leave the charge collection region without depositing all their kinetic energy.
c. The electrons and holes that the ions generate in the charge collection region may not all be swept out of this region before significant charge recombination occurs.
d. If the effective charge acceptance time of the pulse processing electronics is shorter than the time for collection of all electron–hole pairs, the charge that is digitized will be reduced.

It is important to note that the spectra in Fig. 1 do not contain peaks associated with simultaneous detection of both capture product ions. Because of momentum conservation, both ions could not be detected simultaneously with the planar single-sided conversion layer detector geometries reported by Sato et al.[5] and McGregor et al.,[6] with a ^{10}B layer deposited on the surface of diodes, and by Rose,[7] with a ^{10}B layer directly deposited on the surface of a Si substrate. While full-energy peaks could be expected from our diodes if the semiconducting boron carbide layers were thick enough, for these initial experiments the layers of semiconducting boron carbide were so thin that the geometrical probability of both ions depositing significant energy to charge generation in the diode was exceedingly small. In addition, the sub-microsecond pulse processing time employed during the collection of our data in Fig. 1 implies that statistically significant evidence of detecting both ions could not be expected, and is not present, in these spectra, which therefore share the characteristics of conversion layer detectors.

Pulse height spectra from the first neutron detectors based on semiconducting boron carbide/n-Si heterojunction diodes confirm the detection of thermal neutrons. Given that these spectra were obtained with such a thin, unenriched semiconducting boron carbide layer and with pulse-processing that was optimized for charge collection from silicon, not semiconducting boron carbide, the spectra share many characteristics, as expected, with those of boron-coated diode detectors previously reported in the literature.

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References

1) G. F. Knoll. *Radiation Detection and Measurement* (John Wiley & Sons, New York, 1979).
2) S. Lee, J. Mazurowski, G. Ramseyer and P. A. Dowben. *J. Appl. Phys.* 72 (1992) 4925.
3) S. Adenwalla, P. Welsch, A. Harken, J. I. Brand, A. Sezer and B. W. Robertson. *Appl. Phys. Lett.* 79 (2001) 4357.
4) B. W. Robertson, S. Adenwalla, A. Harken, P. Welsch, J. I. Brand, P. A. Dowben and J. P. Claassen. *Appl. Phys. Lett.* 80 (2002) 3644.
5) N. Sato, O. Ishiwata, Y. Seki and A. Ueda. *Jpn. J. Appl. Phys.* 29 (1990) 2526.
6) D. S. McGregor, S. M. Vernon, H. K. Gersch, S. M. Markham, S. J. Wojtczuk and D. K. Wehe. *IEEE Trans. Nucl. Sci.* 47 (2000) 1364.
7) A. Rose. *Nucl. Instrum. Methods* 52 (1967) 166.
8) C. A. Baker, K. Green, M. G. D. van der Grinten, P. S. Iaydjiev, S. N. Ivanov, J. M. Pendlebury, D. B. Shiers, M. A. H. Tucker and H. Yoshiki. *Nucl. Instrum. Methods Phys. Res. A* 487 (2002) 511.