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Comments and Replies

Response to the "Comment" by S. Hallbeck et al.

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The first half of the Comment by Hallbeck et al. about our recent paper [1] describes an all BC device, described in Ref. [2], that is unlike the BC–silicon detector we mentioned in our paper. Although their observations about their all BC device are interesting, they are nevertheless inconsequential to our assertions about a BC–Si detector [1]. The use of solid boron compounds for thermal neutron detection has been of considerable interest for many decades [3–10]. We encourage Hallbeck et al. to perform fundamental evaluations of the electrical properties of their BC materials, which are typically performed for all experimental semiconductor radiation detector materials, beginning with measurements of the charge carrier mobilities and mean-free-drift times. Moreover, the claim that neutrons were detected in a pure boron carbide device [2] is hard to assess, especially considering the absence of a clear description of the neutron source, detector dimensions and irradiation configuration. The authors of the Comment report the observation of an extremely small current (fA) [2], which they claim is a clear indication of neutron detection in their boron-carbide material. However, their results should be scrutinized very closely. Leakage currents are well-known to increase in semiconducting materials with increasing radiation intensity [11], or the observed minute currents may be nothing more than the current produced by the ionization of the surrounding air by reaction ions. With a pulse height analysis, as suggested in our paper [1], the authors would have been better able to understand the origins of the tiny currents observed.

We now turn our attention to the BC–Si device mentioned in our paper [1] that Robertson et al. claim to be a BC neutron detector [12,13], the Si substrate being an inert platform upon which they deposited the BC film. Although Refs. [12,13] vaguely describe the crystalline structure of the boron-carbide material in question, it appears to be a disordered solid. Hence, charge carrier collection can be expected to be poor, as observed in other disordered materials, and which is typically too poor to produce spectral energy peaks [14,15]. This material property should have alerted the authors to a possible misinterpretation of measurements.

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In their Comment, Hallbeck et al. now propose, for the first time, that *both* the BC film and Si substrate may have collected charge. We have calculated the spectral response for the case in which the boron-carbide film (upon the substrate) and the Si substrate both act as detectors, although these simulated spectra were not included in our paper [1]. We note that characteristic spectral features identified for a pure BC detector, namely the sum peaks, are still present, in addition to distorted peaks characteristic of BC or B-coated Si detectors. Hallbeck et al. suggest that for a BC film of only 0.27 μm, no sum peaks should be observed because of the limited solid angles required to produce these sum peaks. In Fig. 8 of our paper [1], these sum peaks are clearly present even for a 0.27-μm BC layer. We assert that analysis of spectral features of energy deposition is a definitive mechanism of identifying how thermal neutron detectors function.

Hallbeck et al. state that they have also performed simulations of expected energy-deposition spectra. Unfortunately none has been published to support their claims. They have to date published only three measured spectra for their 0.27-μm BC film on a Si device [12,13]. To allow the readers of NIM to decide how this device functions, we have plotted, in Fig. 1, one of the three measured spectra [12] and our simulated results for a 0.27-μm BC film (Figs. 5 and 8 of our paper [1]), adjusted, approximately, to convert our energy scale to their channel number. Six features can be discerned in the measured spectrum. Features 1, 2, 4 and 5 correspond to the expected spectral features of a boron-covered thin-film-coated diode (in which only the silicon substrate collects charge). We have learned from private discussions [16] that feature 3, located near channel number 2800 in Fig. 1, and feature 6 appeared only when that device was irradiated very close to the core of a nuclear reactor, where copious fast-neutron and energetic prompt-fission gamma-ray interactions would also have been produced in the device. When the same device was irradiated in a thermal neutron beam port, feature 3 no longer appeared, leaving only the distinctive four-peak signature of a thin-film-coated Si diode [16]. From the spectra shown in Fig. 1, and the above discussion about feature 3, it is clear that their BC film on a Si device appears to operate as a boron-coated Si semiconductor detector, previously well developed [17–28]. Finally, feature 6 in Fig. 1 is most likely a result of combined gamma-ray and (n,p) reactions in the Si diode, similar to that shown in Fig. 4.5.12 of Ref. [21].

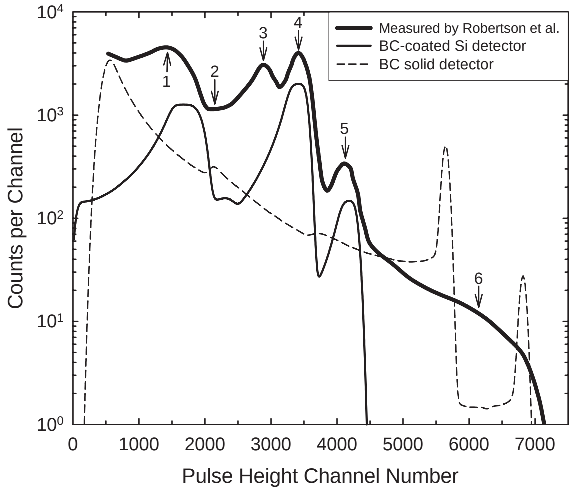

Fig. 1. Shown is a comparison of data from the literature [12] and simulations [1]. Six features are apparent in the spectrum of Robertson et al. [12], and can be identified as follows: feature 1—840 keV ^{7}Li ion, feature 2—1.02 MeV ^{7}Li ion, feature 4—1.47 MeV α-particle, feature 5—1.78 MeV α-particle, feature 6: possible combined effects from gamma rays and fast neutron interactions [21]. Features 1, 2, 4 and 5 are indicative of a common ^{10}B-coated diode [1,19,27]. Feature 3 is unidentified here, as well as the literature [12,13,16]. For further discussion of feature 3, please see the text.

How could this misinterpretation of what was intended to be a bulk-BC neutron detector happen? Chemical vapor deposition of boron materials can cause p-type doping of the n-type Si substrate [29]. The operating voltage reported (18 V) [12], when applied to a reverse biased Si diode composed of 30 Ω cm n-type material [12], as calculated from a simplistic abrupt junction model [30], will form a 10-μm-wide depletion region in the Si, slightly beyond the range of the 1.78 MeV alpha particle of the ^{10}B(n,α)^{7}Li reaction [31]. Hence, the reaction product energies would be fully absorbed in the Si diode active volume, which further supports our assertions.

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