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Effective neutron absorption and conversion with thin $^{10}B_4C$ layers

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Summary:
Isotopically enriched boron carbide $^{10}B_4C$ thin layers were deposited on Si substrates using pulsed DC sputtering technique. The surface density of ^{10}B atoms vs. layer thickness was determined from SEM/EDS and proton backscattering spectrometry experiments. Good agreement was found between measured and calculated neutron absorption efficiencies when considering beam hardening of the poly-energetic cold neutron beam. The optimal layer thickness for maximum neutron absorption and ionoluminescence yield induced by the $^{10}B(n,\alpha)^7Li$ reaction products in a scintillator was ascertained.

Keywords: boron carbide, sputtering, thin layer, neutron absorption, charged particle detection

Background

Scintillation based neutron detector systems consist of a converter material, which interacts with neutrons and produces charged particles, and a scintillator material, which converts ionizing radiation into photons to be detected. Ongoing efforts for improved neutron detection capabilities aim to develop and deploy new converter/scintillator materials and optimized detector design.

Boron-based neutron absorbers offer a promising alternative to commercialized competitors, e.g. ^6Li-based ones. First, there is ca. four times higher capture cross-section of ^{10}B for thermal (cold) neutrons as compared to that of ^6Li. Secondly, lower kinetic energy (2.31 or 2.79 MeV) in the $^{10}B(n,\alpha)^7Li$ reaction is distributed on the daughter products as compared to the $^6Li(n,\alpha)^3H$ reaction with a higher energy release of 4.78 MeV (Therefore, there are shorter stopping ranges of the reaction products in the absorber and in a coupled scintillator layer for ^{10}B as compared to ^6Li), enabling significantly reduced neutron absorber thickness and also, more confined light production volume for scintillation-type ^{10}B-based neutron detector structures. In addition, similar size reduction on the lateral scale may result in enhanced lateral resolution for the neutron detection process.

A promising B-containing neutron absorber material is boron carbide, B_4C [1] with unique combination of properties beneficial for a wide range of applications in nuclear science and beyond. The high melting point (~2450 °C) and thermal stability enable its use in refractory applications. Due to its extreme abrasion resistance, it is applied as abrasive powders and coatings; it also excels in ballistic performance due to its low density and high hardness. Moreover, crystalline B_4C is a high-temperature semiconductor that can potentially be used for novel electronic applications.

A simple construction for neutron detection is a thin B_4C neutron absorber layer atop an efficient scintillator substrate. In this case, 1.47-MeV α and 0.84-MeV Li^+ particles, emitted in the $^{10}B(n,\alpha)^7Li$ reaction induce light emission, i.e., ionoluminescence (IL) in the scintillator. A promising scintillator material is e.g. Al_2O_3, with high radiation resistance and intense IL light emission [2]. Geometrical optimization based on well described energy conversion processes in the $^{10}B_4C/Al_2O_3$ system results in effective neutron capture and detection.

Methods

Isotopically enriched $^{10}B_4C$ layers were deposited on Si substrates by pulsed DC-sputtering. The thickness and atomic composition of the layers were measured by SEM/EDS and 1.6 MeV H^+-RBS. Neutron absorption experiments were performed with a poly-energetic cold neutron beam at the NORMA station of the Budapest Neutron Centre (BNC) [3, 4] equipped with

a ^{6}LiF:ZnS(Cu) scintillation screen and an Andor iKon-M 934 type CCD camera.

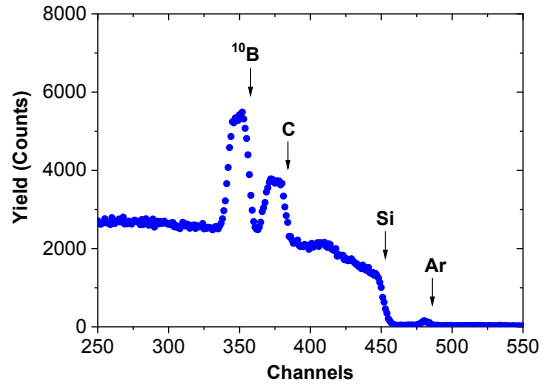

Fig. 1. 1.6 MeV proton-RBS spectrum of a $^{10}B_4C$ layer deposited on Si substrate. Arrows represent spectral edges for the different components in the sample.

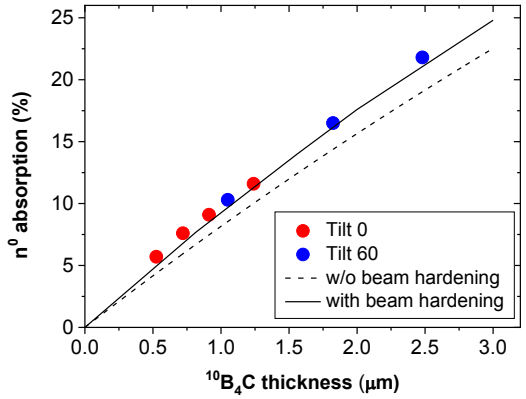

Fig. 2. Neutron absorption as a function of deposited $^{10}B_4C$ layer thickness. Dots represent experimental data recorded at 0° and 60° sample tilt angle, while the solid (dotted) line shows calculated values with (without) taking into account the $^{10}B_4C$ layer induced beam hardening for neutrons reaching the ^{6}LiF:ZnS(Cu) scintillation screen.

Results

Fig 1 shows a typical proton-RBS spectrum of a $^{10}B_4C$/Si sample. Enhanced elastic scattering cross section of protons for ^{10}B and C enables compositional and thickness analysis for the $^{10}B_4C$ layer with good accuracy and therefore the total number of ^{10}B isotopes/cm^2 can be evaluated. Some Ar content remaining in the layer after the sputter deposition process can be recognized. Fig. 2 shows neutron absorption as a function of deposited $^{10}B_4C$ layer thickness. NORMA measurements were performed on the absorber layers at two different sample tilt angles of 0° and 60° with respect to the neutron beam. As the solid line show, good agreement between measured and calculated absorption values can be obtained when the $^{10}B_4C$ layer induced beam hardening for the polyenergetic neutron beam, reaching the ^{6}LiF:ZnS(Cu) scintillation screen after crossing the sample, is taken into account.

When the Si substrate is replaced by a scintillator material, e.g. Al_2O_3, neutron induced energetic α and Li^+ particles, emitted by the $^{10}B_4C$ layer generate light during their electronic stopping in Al_2O_3. The optimal $^{10}B_4C$ layer thickness for maximum IL intensity can be determined considering well described ion-solid interactions, energy conversion processes, and system geometry. More details on such calculations and the related results will be presented.

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