CONF-891119--119

BORON PHOSPHIDE ON SILICON FOR RADIATION DETECTORS

J.C. LUND*, F. OLSCHNER*, F. AHMED**, AND K.S. SHAH*
*Radiation Monitoring Devices, Inc. Watertown, MA 02172
**Devcom Inc., Framingham, MA 01701

CONF-891119--119

DE90 009562

ABSTRACT

We report on radiation detectors fabricated from boron phosphide (BP) layers. These devices were fabricated by growing 1 to 10 μm thick layers of BP by chemical vapor deposition (CVD) on (100) oriented n-type silicon substrates. Ohmic contacts were applied to the Si (Au-Sb). Schottky barrier contacts (also Au-Sb) were applied to the BP layer. The devices were tested as radiation detectors and were found to be capable of detecting individual 5.5 MeV alpha particles. With some improvements we hope to fabricate neutron detectors from these devices, making use of the very high cross-section of boron for thermal neutrons.

INTRODUCTION

Semiconductor detectors are currently the highest performance detectors for most forms of radiation, including optical and high energy photons as well as charged particles. A notable exception to this situation, however, is neutron detection. Currently there exist no semiconductor detectors capable of detecting individual neutrons. Such a detector could be very useful in a number of applications where conventional neutron detectors are deficient. In particular, applications utilizing large arrays of small neutron detectors (*e.g.* neutron diffraction apparatus) would strongly benefit from semiconductor detector technology due to its potential for miniaturization.

In this paper we discuss our attempts at fabricating semiconductor neutron detectors from the compound semiconductor BP. Before we discuss the details of our experimental efforts we will first review the requirements of a semiconductor neutron detector.

REQUIREMENTS OF A SEMICONDUCTOR NEUTRON DETECTOR

Semiconductor materials for use in neutron detectors must possess three properties to be useful as detectors. First, they must stop the incoming neutrons. This capacity is largely determined by the material's neutron cross-section. Second, the interaction of the neutron with the material must produce detectable results. Finally, the semiconductor must have electrical properties appropriate it for use as a semiconductor detector.

There are only two nuclei that simultaneously have a high neutron cross-section and produce easily detectable secondary radiations when interacting with neutrons. These nuclei are ^{6}Li and ^{10}B. Both of these nuclei have a high neutron cross-section and produce easily detectable alpha particles (*i.e.* helium nuclei). The problem of producing a semiconductor neutron detector is thus reduced to finding boron or lithium-containing semiconductors having suitable electrical properties.

To produce a semiconductor detector that operates at room temperature it is necessary that the bandgap of the semiconductor be greater than $\approx$ 1.5 eV. This serves to prevent excess thermal ionization of carriers which would interfere with the detected signal. Additionally, the bandgap of the semiconductor should not exceed $\approx$ 3 eV. Materials with bandgaps greater than this usually have poor mean charge carrier trapping lifetimes (τ) and generally do not lead to good detectors. These considerations lead us to conclude that the ideal semiconductor material for fabricating neutron detectors is a Li or B containing

AC01-89ER80818

semiconductor with a bandgap of between 1.5 and 3 eV. Examination of the literature indicates that there are several compound semiconductors that satisfy these criteria.

$LiInS_2$ [1], $LiInSe_2$ [2], and LiZnP [3] have the correct properties but little success has been obtained with these materials in growing crystals with adequate quality for detector use. More promising are the boron containing III-V semiconductors. BP in particular seems to be an ideal candidate with a bandgap of 2.0 eV [4] and good quality crystals of this material have been epitaxially grown on silicon substrates using chemical vapor deposition techniques [5,6,7,8].

BP PROPERTIES FOR NEUTRON DETECTORS

To operate effectively as a neutron detector material, BP must posses certain specific physical properties. In particular, the BP layers must be thick enough to stop a large fraction of the neutrons passing through it. **Figure 1** illustrates the neutron stopping efficiency of BP crystals as a function of thickness. Depending on the isotopic enrichment, very efficient detectors can be made with films a few hundred μm thick. Even BP layers as thin as 10 μm, however, could be useful in many detector applications. These thicknesses are well within the range of current CVD techniques. BP layers of 300 μm thickness have been reported in the literature [5,6], as well as layers enriched 95% in ^{10}B [7].

There are a few electrical properties that BP films need to facilitate efficient neutron detection. It is desirable that the charge carrier concentration in the films be low enough to allow diodes constructed on it to have sufficiently large charge carrier depletion widths. While calculation of the minimum acceptable depletion width depends on several as-of-yet unknown factors, we estimate that it must be at least ≈ 1 μm in thickness. Ideally, we would like the entire BP layer to be depleted. For a 300 μm thick device operating at 10 V reverse bias, this implies that the carrier concentration should be less than $\approx 10^{12}$ cm^{-3}.

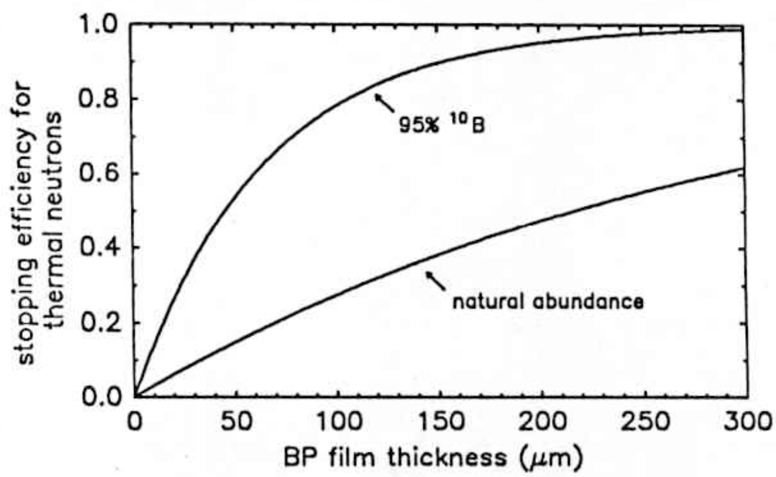

Figure 1. Thermal neutron stopping efficiency as a function of BP thickness. Natural boron contains 19.6% abundance of ^{10}B.

Two properties, related to the transport of carriers, are critical to the successful operation of a BP neutron detector. These are the mobility μ and mean trapping lifetime τ of the charge carriers in the BP. Using some conservative assumptions regarding detector operating conditions, we have computed that the product, $\mu\tau$, of either the electrons or holes in BP should exceed $\approx 10^{-6}$ cm^2 V^{-1} in order to obtain pulses of detectable magnitude from BP neutron detectors.

EXPERIMENTAL RESULTS

To determine the suitability of BP films for neutron detectors we fabricated radiation detectors from BP films in our laboratories. Layers of BP between 1 and 10 μm were grown on single crystal silicon substrates using CVD techniques. Our BP layers were grown by methods similar to those reported by others [5,6]. The BP depositions were carried out inside a cold-walled CVD reactor using diborane, B_2H_6 (1% in hydrogen) and phosphine, PH_3

(5% in hydrogen) as reactants. A silicon substrate temperature of 950°C was found to give the best results. Our substrates were (100) oriented phosphorous doped n-type silicon wafers of 0.1 to 1 Ω cm resistivity.

After we had obtained suitable quality BP films, devices were fabricated from these layers and tested as radiation detectors. The device structure we chose was a Schottky barrier on the BP layer and an Ohmic contact to the silicon. Our BP films were n-type and it was assumed that the BP-Si interface would also be approximately Ohmic. The Ohmic contact to the Si was formed by evaporating an alloy of gold and antimony onto the silicon and heat treating the contact at 650°C for one minute under flowing argon. The Schottky barrier contact to the BP was formed by evaporating an Au-Sb alloy onto the BP layer. Current versus bias voltage studies of these devices indicated good quality diodes were formed by these fabrication techniques.

The BP on silicon devices were tested as radiation detectors by irradiating them with 5.5 MeV alpha particles from an ^{241}Am isotopic source and interrogating the current pulses arising in the detector with conventional nuclear pulse height analysis electronics. **Figure 2** shows pulse height spectra obtained by irradiating a BP-Si device both with and without the alpha particle source present. Detection of the alpha particles is clearly indicated. Unfortunately, subsequent testing with thermal neutrons at the MIT research reactor did not result in neutron detection.

After further analysis of our devices, we have concluded that the reason our devices detected alpha particles from a ^{241}Am source but did not detect neutrons was ultimately due to the high carrier concentration in the BP films. Although our devices had BP layers ≈ 10 μm thick, capacitance studies showed that the charge carrier depletion region thickness in the devices were less than 0.5 μm (carrier concentration $n \approx 1.2 \times 10^{17}$ cm^{3}). Since only the depleted layer has a nonzero electric field, it is the only region of the device capable of detecting the alpha particles produced by the neutron interactions. For this reason, only neutrons stopped inside and in regions closely adjacent to the depletion region should be detectable. In order to increase the sensitivity to neutrons, it will be necessary to produce films with lower carrier concentrations. These films would have the thicker depletion regions necessary for neutron detection purposes.

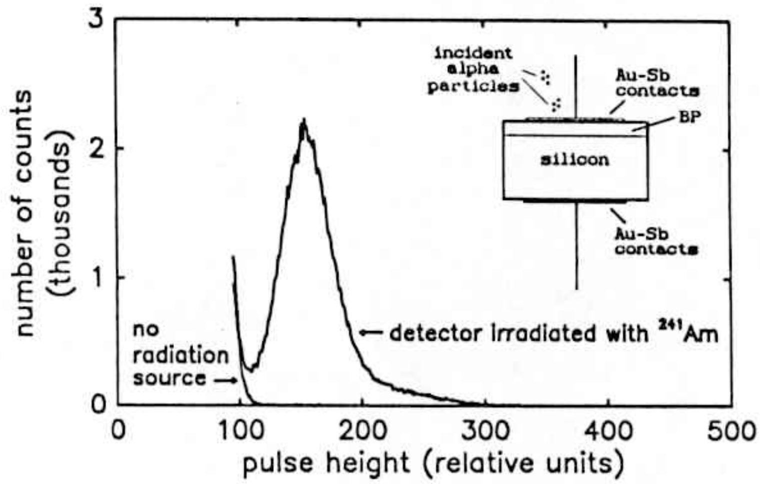

Figure 2. Pulse height spectra obtained with a BP device with and without an ^{241}Am 5.5 MeV alpha particle source present. Inset shows BP-on-silicon device structure used for detection.

One method for reducing the free carrier concentration in BP has been reported in the literature [9] and appears very promising for neutron detector applications. This method involves heat treating the BP films at high temperatures (1000 to 1100°C) for several hours. In this process, excess phosphorous is driven from the BP resulting in huge resistivity gains in the films. Up to 13 orders of magnitude have been reported [9]. In order to prevent the decomposition of the BP at elevated temperatures it is necessary to cap it with a Si_3N_4 layer prior to the heat treatment. We are currently investigating the application of this method in our laboratories.

Another possible technique for reducing the carrier concentration in BP films is by diffusing dopants into the films that act as deep acceptors. It has been reported that diffusion of copper into other III-V semiconductors (*i.e.* InP [10]) results in the production of semi-insulating material from low resistivity n-type starting material. This method may prove to be effective with BP as well. We are investigating the application of this technique to BP neutron detectors in our laboratories.

SUMMARY

We have fabricated radiation detectors from BP films grown by CVD techniques onto silicon substrates. Our studies indicate that BP has nearly the ideal properties for the production of solid state neutron detectors. Currently our detectors are capable of detecting alpha particles from isotopic sources but are incapable of detecting neutrons. We believe that neutron detection should be achievable with CVD BP devices if the carrier concentration can be reduced.

This work was partly supported by an SBIR grant from the DOE (#DE-AC01-89ER80818).

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