Nuclear Inst. and Methods in Physics Research B 432 (2018) 48–54

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Electrical and structural characterization of neutron irradiated amorphous boron carbide/silicon p-n heterojunctions

Michael Nastasi[a,b,c,*], George Peterson[a], Qing Su[b], Yongqiang Wang[d], N.J. Ianno[c,e], Nicole Benker[f], Elena Echeverría[f], Andrew J. Yost[f], J.A. Kelber[g], Bin Dong[g], Peter A. Dowben[c,f]

[a] Department of Mechanical and Materials Engineering, University of Nebraska, Lincoln, NE 68588-0526, United States
[b] Nebraska Center for Energy Sciences Research, University of Nebraska, Lincoln, NE 68583-0857, United States
[c] Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68588-0298, United States
[d] Materials Science and Technology Division, Los Alamos National Laboratory, Los Alamos, NM 87545, United States
[e] Department of Electrical and Computer Engineering, University of Nebraska, Lincoln, NE 68588-0511, United States
[f] Department of Physics and Astronomy, University of Nebraska, Lincoln, NE 68588-0299, United States
[g] Department of Chemistry, 1155 Union Circle #305070, University of North Texas, Denton, TX 76203, United States

ARTICLE INFO

Keywords:
Semiconducting boron carbides
Hydrogenated boron carbides
Radiation hardness
Neutron irradiation
Neutron detectors
Neutron voltaics

ABSTRACT

The electrical and structural properties of amorphous hydrogenated semiconducting boron carbide on silicon p-n heterojunction diodes have been examined following irradiation with thermal neutrons to a maximum dose of 1.08×10^9 neutrons/cm^2. Improvements in the current-voltage response of the heterojunction diode, along with a decrease in the diode ideality factor, are observed with neutron exposure. Capacitance-voltage data were used to extract the hydrogenated boron carbide carrier density and diode built-in potential, both of which decrease with irradiation. Structural and defect characterization, carried out with high resolution TEM and RBS in channeling mode, show that the hydrogenated boron carbide remains amorphous and no discernible damage occurs in the Si component of the diode. These data suggest that the observed changes in electrical properties result from irradiation induced defect passivation in the amorphous boron carbide. For n-type plasma enhanced chemical vapor deposition hydrogenated semiconducting boron carbide on p-type silicon, the improvements in the heterojunction diode are quite dramatic.

1. Introduction

Semiconducting boron carbide/silicon diodes have been investigated for some time for applications as a solid-state neutron detector [1–8] (for a review see [3]) and as a potential energy source as a neutron voltaic [7,8]. Both applications are derived from the interaction of thermal neutrons with ^{10}B, which has a capture cross section of 3840 ± 0.016 barns [3]. ^{10}B neutron capture leads to the loss of boron and creation of daughter fragments with significant kinetic energy [9]. The primary reaction products are the production of 0.84 MeV ^{7}Li and 1.47 MeV ^{4}He ions. Following the capture/fragmentation process, the ^{7}Li and ^{4}He ions deposit energy as they traverse the device in the form of electronic excitation and ionizing (electronic energy deposition) or elastic displacement collisions (nuclear energy deposition) [10]. The deposited ionizing energy creates electron-hole pairs along the ion tracks, and the electric field created across the diode junction separates the charges, generating a current pulse. While this phenomena has been well documented, little previous work has been done to examine the resulting radiation damage effects on the electrical performance of the boron carbide/silicon diode.

Our previous study [11] used 200 keV He ions to simulate alpha particles generated by the neutron capture and fragmentation process in boron carbide/silicon p-n junctions. These studies [11] showed that electrical performance initially improved under irradiation and that higher irradiation doses led to device failure as a result of nuclear damage in the crystalline silicon substrate. It was hypothesized that initial device improvement resulted from electronic energy deposition in the amorphous boron carbide, which resulted in bond breaking and reformation, thereby removing bond defects (defect passivation) that resulted during synthesis. In this work, we use thermal neutrons as the irradiating source, where high energy fragments are produced from neutron capture by a ^{10}B atom in the boron carbide film, to further our understanding of irradiation effects on amorphous boron carbide/Si devices. Our aim is to provide additional insight into the changes of the

* Corresponding author at: Department of Mechanical and Materials Engineering, University of Nebraska, Lincoln, NE 68588-0526, United States.
E-mail address: mnastasi2@unl.edu (M. Nastasi).

https://doi.org/10.1016/j.nimb.2018.07.006
Received 3 May 2018; Received in revised form 2 July 2018; Accepted 2 July 2018

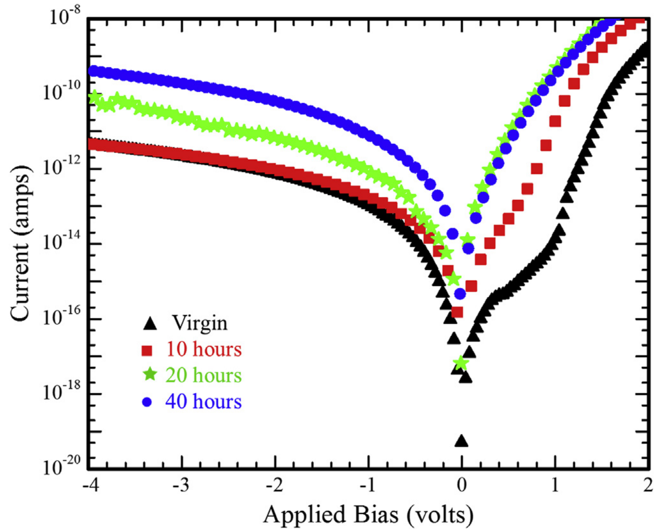

Fig. 1. The current versus voltage curves of a p-n diode following neutron irradiation fluences of zero, 2.7×10^8, 5.4×10^8, and 10.8×10^8 neutrons/cm^2; i.e. 0 (virgin), 10, 20, and 40 h of exposure, respectively.

device as a result of neutron irradiation induced changes in the amorphous partially dehydrogenated semiconducting boron carbide.

2. Experimental details

The plasma enhanced chemical vapor deposition (PECVD) hydrogenated semiconducting boron carbide, $B_{10}C_{2+x}H_y$, based p-n heterojunction were synthesized using an n-type silicon (P doped) substrate (0 0 1) of resistivity 65−110Ω × *cm* (University Wafers). The substrates were cleaned in baths of acetone, methanol, and filtered de-ionized water followed by a 5 wt% hydrofluoric acid (HF) bath for oxide removal and hydrogen termination. Prior to a-$B_{10}C_{2+x}H_y$ deposition, the substrate was exposed to a 30 min Ar^+ plasma etch to remove any residual carbon or other surface impurities. Partially dehydrogenated boron carbide thin films were deposited on the Si via plasma enhanced chemical vapor deposition (PECVD) utilizing ortho-carborane (*closo*-1,2 dicarbadodecaborane, $C_2B_{10}H_{12}$) (Sigma Aldrich) as the source compound at 350 °C. Details of the deposition process have been previously reported [1,4,12]. The composition of the deposited a-$B_{10}C_{2+x}H_y$ films was established by elastic recoil detection measurements [11], with x approximately equal to 0 and y approximately equal to 4. The n-type boron carbide heterojunctions were formed by plasma enhanced chemical vapor deposition (PECVD), as described in prior work [2,13], using *closo*-1,7-dicarbadodecaborane (metacarborane, m-$B_{10}C_2H_{12}$) in a 20 mTorr Ar inductively coupled plasma (20 W), and deposited on atomically clean p-type Si(1 0 0).

In this report, diodes consisting of films derived from PECVD of orthocarborane on n-type Si are referred to as p-n devices. Conversely, diodes consisting of PECVD metacarborane films on p-type Si are labelled as n-p devices.

Contact metallization consisting of Cr, with a Au capping layer was deposited on the p-n heterojunction through a d.c. magnetron sputter source (AJA International Inc.) at a base pressure below 1×10^{-7} Torr. Both metals were sputtered in an Ar^+ plasma at a pressure of 5 mTorr to a thickness of approximately 300 nm.

Neutron irradiation of the heterojunction p-n diodes was carried out using a deuterium-tritium (D-T) neutron source (Thermo Scientific MP 320 neutron generator). The output of the D-T source is 14 MeV neutrons, which was combined with a 10 cm beryllium (Be) cube neutron multiplier. The neutrons were moderated by 1 in. of paraffin, providing approximately 7500 neutrons/cm^2/s with a slightly anisotropic 4π neutron environment for the irradiated samples. Further details about the neutron source can be obtained elsewhere [5,6]. Neutron moderation was confirmed by exposing single crystal Si to 10.8×10^8 neutrons/cm^2 followed by ion channeling where no damage build up was observed. Diode samples were exposed to the neutron flux for 10, 20, and 40 h resulting in neutron fluences of 2.7×10^8, 5.4×10^8, and 10.8×10^8 neutrons/cm^2, respectively.

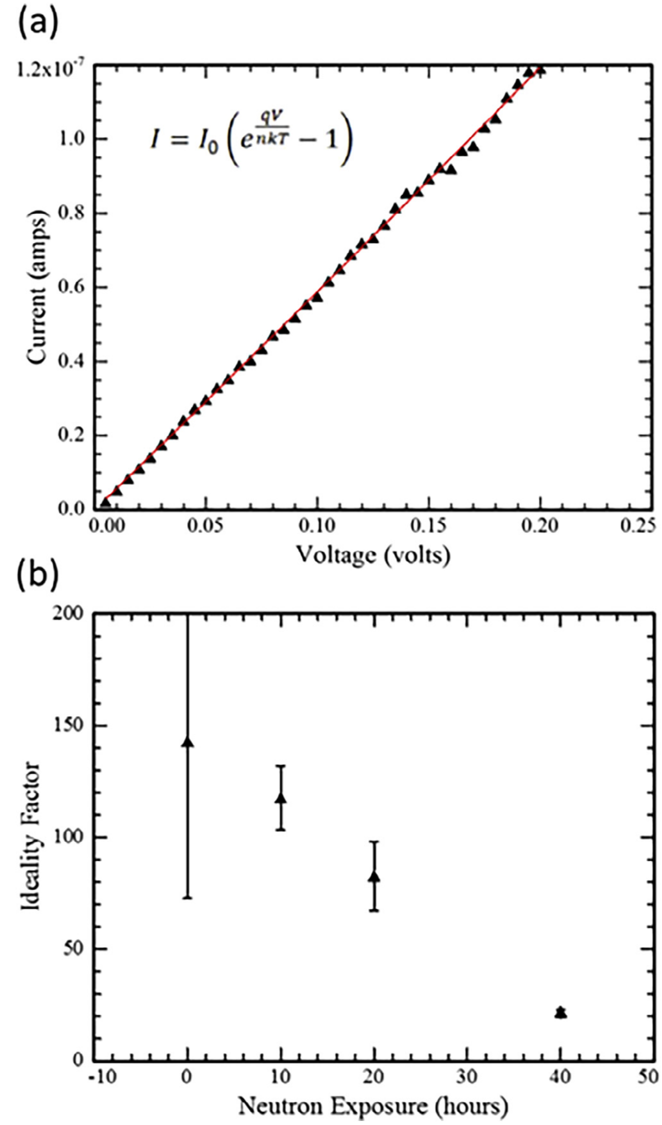

Fig. 2. (a) shows the fitting results (red line) of Eq. (1) (insert in (a)) to the p-n diode current–voltage data to obtain the ideality factor of current due to thermal recombination of carriers in the depletion region. (b) shows the ideality factor as a function of neutron exposure. Neutron fluences of zero, 2.7×10^8, 5.4×10^8, and 10.8×10^8 neutrons/cm^2 correspond to 0, 10, 20, and 40 h of exposure, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The number of neutron reactions with ^{10}B was calculated following Hoglund et. al. [14], assuming a film composition of $B_5C_1H_2$ (determined by elastic recoil detection analysis), a film thickness of 300 nm, a mass density of 1.7 g/cm^3 (determined by x-ray reflectivity), and a reaction cross-section of 3840 barns. The fraction of ^{10}B was taken as 20% of the boron fraction. This analysis indicates that 0.173% of the thermal neutrons were absorbed by ^{10}B, resulting in the production of 1.86×10^6 (α + Li)/cm^2 for a 10.8×10^8 neutrons/cm^2 exposure.

Structural characterization of the p-n device before and after neutron irradiation was performed using high resolution transmission