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Fabrication and characterization of silicon based thermal neutron detector with hot wire chemical vapor deposited boron carbide converter

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ABSTRACT

In order to utilize the well established silicon detector technology for neutron detection application, a silicon based thermal neutron detector was fabricated by integrating a thin boron carbide layer as a neutron converter with a silicon PIN detector. Hot wire chemical vapor deposition (HWCVD), which is a low cost, low temperature process for deposition of thin films with precise thickness was explored as a technique for direct deposition of a boron carbide layer over the metalized front surface of the detector chip. The presence of B-C bonding and ^{10}B isotope in the boron carbide film were confirmed by Fourier transform infrared spectroscopy and secondary ion mass spectrometry respectively. The deposition of HWCVD boron carbide layer being a low temperature process was observed not to cause degradation of the PIN detector. The response of the detector with 0.2 μm and 0.5 μm thick boron carbide layer was examined in a nuclear reactor. The pulse height spectrum shows evidence of thermal neutron response with signature of (n, α) reaction. The results presented in this article indicate that HWCVD boron carbide deposition technique would be suitable for low cost industrial fabrication of PIN based single element or 1D/2D position sensitive thermal neutron detectors.

1. Introduction

In recent years, there has been a considerable interest in the development of solid state semiconductor based neutron detectors as these detectors offer several advantages such as compactness, low operating power, ruggedness, low cost, etc., over conventional gas (BF_3 or ^{3}He) or scintillator based detectors. The research and development effort in this area has been mainly focused to develop substitutes for conventional detectors such as ^{3}He or BF_3 detectors, with improvements in terms of device design and fabrication technology, cost, size, operating voltage/power and adaptability to different applications. Such solid state detectors have been realized by using a suitable converter layer along with a semiconductor detector [1–6] or by forming a converter layer as an integral part of the semiconductor device [7,8]. In the former case, the charged particle due to interaction of neutrons with the converter layer is detected by the semiconductor detector, while in the latter case, the charged particle is released by the interaction of neutrons in the device itself and is subsequently detected. Several semiconductor materials such as Si, GaAs, SiC and diamond have been studied for solid state neutron detectors [1–6]. Heterojunction semiconductor devices with semiconducting form of boron carbide have been also demonstrated as neutron detectors [9]. Silicon based detectors fabricated using well established silicon planar technology have been the preferred choice due to benefits of batch production such as low cost and better uniformity, and ease of segmentation in strips, pads or pixels for 1D or 2D position sensing or imaging. Most common neutron interactions that have been used for thermal neutron detectors are the $^{10}B(n, \alpha)^7Li$ reaction and the $^6Li(n, \alpha)^3H$ reaction due to their high energies of reaction product [10]. Other neutron reactions such as $^{157}Gd(n, \gamma)^{158}Gd$ and the $^{113}Cd(n, \gamma)^{114}Cd$ have been also used

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[11,12]. ^{10}B(n, α)^{7}Li neutron reaction has a microscopic cross section of 3840 barns for thermal neutrons and results in the following reaction products [10]:

$$^{10}B+n\rightarrow\begin{cases}^{7}Li^{*}\ (0.84\ MeV)+{}^{4}He\ (1.47\ MeV)\ \text{(excited state) (94\% probability)}\\ ^{7}Li\ (1.02\ MeV)+{}^{4}He\ (1.78\ MeV)\ \times\text{(ground state) (6\% probability)}.\end{cases}$$

The calculated average range for a 0.840 MeV ^{7}Li ion in pure ^{10}B film is 1.6 μm and the average range for a 1.47 MeV alpha particle is 3.6 μm [1]. Due to limited range of charged particles released by neutron interaction in the converter layer, the neutron detection efficiency in converter based thin film semiconductor neutron detectors is limited by self absorption effects in the converter layer. Hence optimization of converter layer thickness is very important to maximize the efficiency. Various parameters such as energy lost in the converter medium, energy lost in the dead region at the detector entrance window and the electronics low level discriminator (LLD) settings due to electronics noise are also important for improving the neutron detection efficiency.

The converter material is often used in the form of a separate film or deposited over the semiconductor detector using suitable evaporation technique. Pure ^{10}B films though preferred due to its larger cross section for thermal neutrons and higher energies of charged products, is not very suitable for deposition on fabricated silicon detectors. Evaporation of boron was observed to degrade the properties of surface barrier detectors. RF sputtering using a specially developed setup could be used for sputtering of boron only for short durations to prevent heating of detector [13]. In order to explore the possibility of direct deposition of precisely thick neutron converter layer using a low cost process, we have explored feasibility of using Hot Wire Chemical Vapor Deposition (HWCVD) technique. This is one of the established techniques to grow thin films with submicron accuracies at low substrate temperatures. A low substrate temperature possibility is also offered by the other variants of the CVD such as plasma enhanced chemical vapor deposition (PECVD). Considering the requirements of post processing of silicon PIN detector, PECVD was not found suitable as it could have damaged the detector due to plasma effects. HWCVD is also a simple and low cost process compared to PECVD and is suitable for industrial production [14–16]. Due to its unique physical and chemical properties, boron carbide has received great importance recently and it has been used for large number of application in engineering [17,18]. The aim of the present work was to exploit well established silicon technology for low cost industrial production of neutron detectors. Hence, we have used an arrangement in which a HWCVD boron carbide layer was deposited directly over a silicon PIN detector. The silicon PIN device configuration also has 100% theoretical charge collection efficiency for charged particles released by thermal neutron interaction with ^{10}B. In the present work, silicon PIN detectors were post processed for deposition of HWCVD boron carbide converter layer of different thicknesses. The thermal neutron response of the detectors when examined using a nuclear reactor at BARC clearly demonstrates detection of thermal neutrons. The experimental details and results demonstrating thermal neutron response are presented in the subsequent sections of this article.

2. Experimental

2.1. Fabrication of silicon PIN detector

Silicon PIN detectors investigated in this study were fabricated in a 4" bipolar foundry in India as per the design and process flow provided to the foundry. N-type, ⟨1 1 1⟩, 3–5 kΩ-cm, high purity silicon wafers of nominal thickness of 300 μm were used as starting material for the fabrication of detectors. The detectors were designed to have active area of 10 mm × 10 mm and were enclosed in two guard rings. A four layer mask was designed for fabrication of detectors as per the following fabrication steps:

- Field oxidation for thick field oxide of thickness 0.3 μm
- Back phosphorus implantation, anneal and drive in for obtaining a heavily doped N^{+} layer of about 2 μm
- Front side lithography for detector active and guard ring area
- Screen oxide of 40 nm for boron implantation
- Boron implantation at low energies and nitrogen anneal for a shallow P^{+} front side junction of about 0.4 μm
- Lithography for contacts
- Al front side Metallization and metal lithography
- Front side passivation of Phosphosilicate glass (PSG), lithography for pad opening
- Back side Al metallization and annealing

The charged particles released by neutron interaction in the boron carbide lose energy in the dead layer which comprises of P^{+} implant layer, metal layer and passivation layer. In order to reduce the dead layer, the aluminum layer on the front surface was designed in the form of a grid which covered $<5\%$ of the total area. The process parameters for boron P^{+} layer and passivation layer were optimized so as to minimize the dead layer. The complete process flow was tuned to obtain low leakage currents. This is of importance for reduction of detector noise and maximize detection efficiency for detection of charged particles created by n-α reaction in the boron carbide converter. The fabricated wafers were diced and the boron carbide layer was deposited using HWCVD process on the front surface of the PIN detector chips. The deposition was done though a metal mask so as to prevent deposition on bonding pads. The detectors chips were subsequently packaged on ceramic substrates to provide connection to the front P^{+} and back N^{+} contacts.

2.2. Deposition of boron carbide layer using HWCVD technique

In Hot-Wire Chemical Vapor Deposition technique, the precursor material is decomposed by heated filament (tantalum) at very high temperature (1500–1800 °C) and deposited on to the substrate. Fig. 1 shows the HWCVD setup used in the present study for the deposition of the boron carbide layers using ortho-carborane (o-$C_2B_{10}H_{12}$) as precursor. The experiment set up is described in details elsewhere [19]. In the HWCVD tool, the substrate holder, the filament and the gas shower are parallel to each other with the position of heated filament in between substrate holder and gas shower. The distance from the filament to the substrate holder was kept variable from 5–7 cm. In such geometry, the movement of gas molecules is perpendicular to the plane of the filament. Hence, the dissociated molecules of the precursor gas from the heated filament travel towards the substrate and lead to the formation of the thin layer on to the substrate, i.e. front surface of silicon PIN detector. In HWCVD, the precursor is needed in gaseous form. Since ortho-carborane is a solid material, a bubbler (as shown in Fig. 1). was designed to derive the vapor of ortho-carborane molecule. The bubbler was heated at 70–80 °C and the vapor of ortho-carborane generated inside the bubbler was passed into the chamber using argon as a carrier gas. The substrate temperature, filament temperature and gas flow rate are important parameters in HWCVD because they decide the properties of films. HWCVD boron carbide layer was also deposited on bare n-type silicon substrates and corning glass substrate for compositional characterization using FTIR and SIMS. Boron carbide layer were deposited on a number of substrates at 215 mTorr with 10 sccm argon flow. The filament temperature was kept around 1800 °C and substrate temperature was 200 °C. The deposition parameters were optimized to obtain layer of thickness