Boron Filling of Deep Holes for Solid-State Neutron Detector Applications

Kuan-Chih Huang[1], Rajendra Dahal[1], James J.-Q. Lu[1], Yaron Danon[2], and Ishwara B. Bhat[1]

[1]*Department of Electrical, Computer and Systems Engineering, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY USA, 12180*
[2]*Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY USA, 12180*
huangk6@rpi.edu

INTRODUCTION

The demand for highly efficient and portable solid state neutron detectors has increased significantly for homeland security as well as other applications because of the increasing threat of nuclear materials. Solid-state neutron detectors have a number of advantages for such applications over the conventional gas tube detectors. A honeycomb type continuous p-n junction in silicon filled with a converter material, ^{10}B, to detect thermal neutrons has been proposed from the earlier work [1] (Fig. 1). Since the neutron detection efficiency is proportional to the effective surface area of the detector, the device was patterned with honeycomb configuration photolithographically and etched with deep reactive ion etching (DRIE). These holes need to be completely filled with boron to get the highest efficiency of neutron detection. In this article, a new method for filling deep hexagonal holes with boron for use in solid-state neutron detector is reported. Diborane (B_2H_6) was used as the boron precursor in low-pressure chemical vapor deposition (LPCVD) and a multiple deposition and etching process was conducted to improve the boron fill factor.

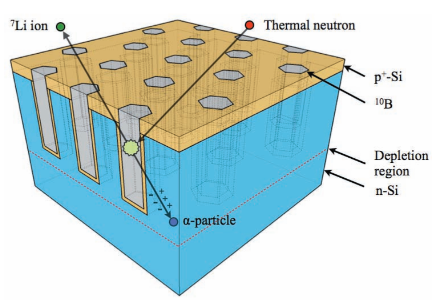

Fig. 1. Schematic design of a honeycomb type solid-state neutron detector.

EXPERIMENTAL METHOD

The process can be separated into six main steps as shown in Fig. 2. A heavily-doped n-type silicon wafer, 4-inch in diameter, was used as a substrate for depositing a lightly-doped n-type epitaxial layer (~50 µm), followed by a heavily-doped p-type epitaxial layer (~1 µm) were deposited (Fig. 2(a)). Silicon dioxide (~1 µm) was deposited and patterned as field oxide in the isolation area (Fig. 2(b)). A layer of thin silicon dioxide (~250 nm) was then deposited on the front side as an etch-stop for DRIE. Then, the silicon wafer was patterned and etched to make deep hexagonal holes with DRIE (Fig. 2(c)). This wafer will be a starting wafer for the boron filling process with the use of LPCVD. Since the continuous deposition of boron in the deep holes leaves behind a large void inside each hole, which reduces the volume of boron inside the hole and hence the detection efficiency significantly, void-free deposition of boron in deep holes with high aspect ratio is technically challenging and needed [2]. In order to solve this problem, the multiple deposition and etching process was used. In this process, boron was deposited using LPCVD into 2 to 3-µm-wide high aspect ratio holes until approximately 1-µm-wide holes remained. The wafer was then coated with photoresist inside the holes as an etch stop layer for the boron etching. After boron was removed from the neck and the top of the holes using inductively coupled plasma reactive ion etching (ICP-RIE), further boron deposition was conducted to increase the boron fill factor. This step was carried out several times until the highest boron fill factor was reached (Fig. 2(d)). Boron was diffused into the n-type silicon to form a continuous p-n junction at high temperature (~900 °C) inside the LPCVD chamber prior to filling the holes with boron. ICP-RIE was used again to etch the boron outside of the hexagonal holes until the heavily-doped p-type silicon was exposed for making a metal contact (Fig. 2(e)). Aluminum with 2% silicon was sputtered on the front side and titanium and aluminum were sputtered on the backside for the metallization (Fig. 2(f)).

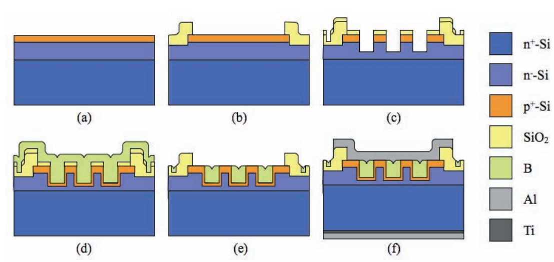

Fig. 2. Six main steps for the fabrication of honeycomb type solid-state neutron detector.

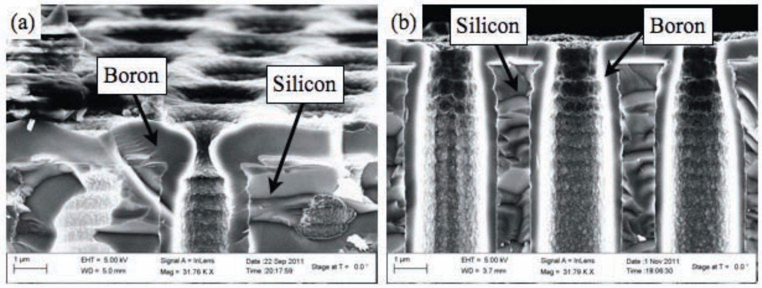

Fig. 3. SEM cross-sectional images of hexagonal holes after (a) boron deposition with LPCVD and (b) boron etching with ICP-RIE.

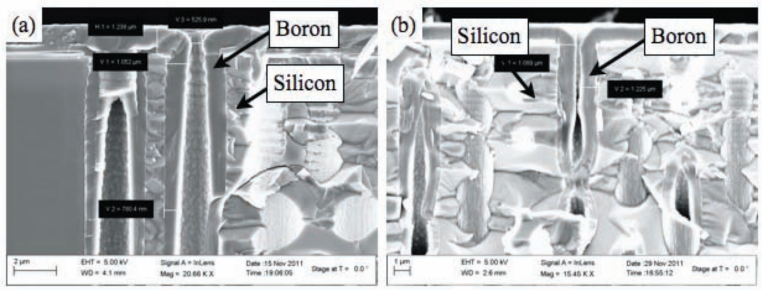

Fig. 4. SEM cross-sectional images of hexagonal holes after (a) the second boron deposition and (b) the third boron deposition with LPCVD.

RESULTS AND DISCUSSIONS

A high fill factor boron deposition in high aspect ratio holes was studied and developed using repeated deposition and etching cycles. Boron was deposited at a temperature of 525 °C, pressure of 250 mTorr, deposition time of 4 hours, and diborane flow rate of 50 standard cubic centimeters per minute. LPCVD with B_2H_6 as the chemical precursor was used and the deposition result is shown in Fig. 3(a). Since most of the boron deposition occurred at around the hole opening, ICP-RIE was used to reopen the holes before further deposition was conducted. A mixture of sulfur hexafluoride and oxygen was used for ICP-RIE. Because the standard process etched boron from the top of the holes as well as from the bottom of the holes, a thin film of photoresist was used as an etch stop layer to avoid the boron etching inside the holes. Fig. 3(b) is the SEM cross-sectional image of hexagonal holes after an ICP-RIE process with the protection of photoresist coating.

An etching step between deposition steps prevents boron from accumulating near the neck allowing more boron to be deposited into the holes. As a result, the boron fill factor inside the holes was improved from 78.7 %, after the first deposition shown in Fig. 3(a), to 87.9 %, after the second deposition shown in Fig. 4(a), and to 90.1 %, after the third deposition shown in Fig. 4(b). A 2 by 2 mm^2 detector with 2.3-μm-wide and 37-μm-deep hole filled with natural boron (19.9% ^{10}B) and 1.5-μm-wide silicon wall shows the best performance to date. Thermal neutron detection efficiency of this detector is 5.0% for the uncollimated neutron beam from ^{252}Cf source placed in the moderator housing. If enriched boron (99% ^{10}B) had been used, higher thermal neutron detection efficiency could be reached.

REFERENCES

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