Large Area Zero Bias Solid-state Neutron Detectors

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INTRODUCTION

Solid-state neutron detectors utilize latest advancement in semiconductors for development of efficient and economical neutron detectors. The recent shortage and price increase of He-3 resulted in more incentive to reach maturity of this technology and enable replacement of gas based neutron detectors. Solid state neutron detectors provide important advantages over current neutron detectors such as operation at low or zero bias, more compact geometry and possibly lower cost. Producing a thermal neutron detector that can replace a He-3 based detector requires high thermal neutron detection efficiency and very low gamma sensitivity that are not easily achieved with solid-state detectors.

Solid-state neutron detectors typically use a converter material with high neutron interaction cross section in which the neutrons interact and produce charge particles (for example ^{10}B(n,α) or ^{6}Li(n,α)). Following a neutron interaction with the converter material these energetic charge particles lose energy as they interact with the surrounding material. If they leave the converter and move into the semiconductor they interact by producing electron-hole pairs that can be collected to produce a measurable current. In some detectors the converter and semiconductor are two different materials, in other cases the semiconductor material itself can have high neutron interaction cross section for example BN [1] or B_5C [2]. Solid-state thermal neutron detectors with high boron content were reported with efficiencies of up to 48% [3], however they are limited in size and scaling to large area requires pixelation which makes the detector electronics costly. Detectors developed at Rensselaer Polytechnic Institute (RPI) use unique continuous junction [4] [5] [6] to achieve very low leakage current which enables operation with low electronic noise and simple scaling to large detection area using a single amplification channel.

CONTINUOUS JUNCTION NEUTRON DETECTORS

The basic concept of a solid-state neutron detector is the planar geometry which includes a converter layer on-top of a Si PN diode. The diode has a depletion layer thickness which is sufficient to stop the most energetic charge particle emitted from the converter. In the case of a B-10 converter with most probable α particle energy of 1.47 MeV this thickness is about 5 μm. In addition the boron layer thickness is limited to the α particle range in the B-10 layer which is about 4 μm. These limitations results in low neutron detection efficiency.

An improvement is the hole geometry shown in figure 1(a). In this geometry a B-10 layer is surrounded by Si walls. In such a device the boron layer can be as thick as desired and the width of the trench (or other type hole) and width of the Si wall can be optimized to maximize the detector efficiency [7]. Charge collection is done by applying voltage to the top *p* layer and the bottom *n* layer. In this geometry the height of the Si wall results in a large surface area between the Si wall and boron where leakage current can develop. This leakage current translate to high intrinsic noise which needs to be discriminated. Scaling such device to large area is problematic because it reduces the signal further while the noise level increases resulting in a higher discriminator setting and loss of detection efficiency.

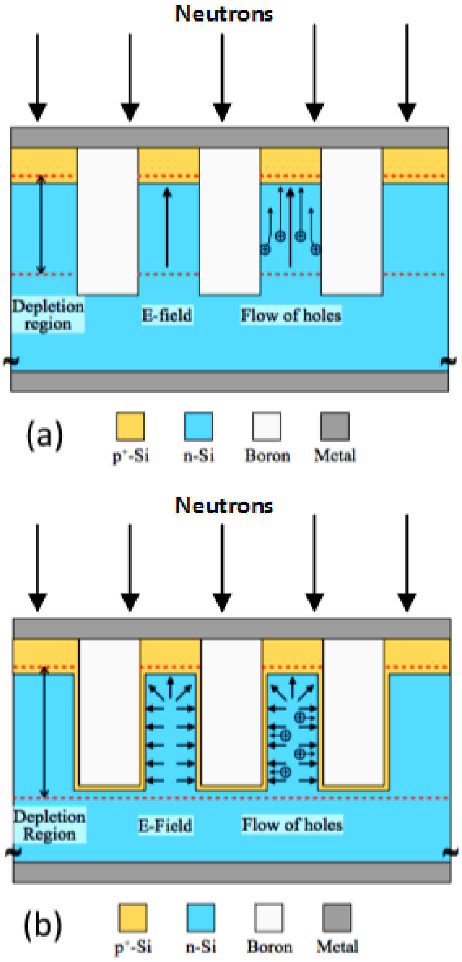

Fig. 1. Schematic diagram showing the origin of reverse leakage current in Si p+-n junction diodes. (a) Minority carrier holes generated in the n-type region as well as from the exposed surface contribute to leakage current, and often surface leakage dominates (b) Minority carriers from only bulk generation contributes since the surface is not exposed.

An novel design developed at RPI uses an appropriately doped Si and a boron diffused *p* layer that surrounds all the Si hole surface as shown in figure 1(b). In this design the p^+ layer isolates the depleted Si layer from the boron in the trench and leakage current is greatly reduced. Such devices have extremely low leakage current per unit area [5] and enabled development of robust high efficiency large area zero bias thermal neutron detectors.

RESULTS

The optimum geometry of a honeycomb structure of Si and B-10 with 45 μm height was determined by GEANT4 [8] simulations [7]. The honeycomb patterned Si was fabricated using the BOSCH process and the B-10 was filled using the LPCVD process [9]. The Si wafer included top eptxial layer that was used to create a 1 μm p^+ layer at the top of the boron pattern. after the boron was filled one contact to the p^+ and n layers were used to collect the signal.
Devices fabricated at RPI like the ones shown in figure 3 were tested using a moderated Cf-252 neutron source. The thermal neutron flux from this source was carefully calibrated using Li-Glass detectors, gold foil activation [1], and was compared to MCNP simulations using the NIST traceable calibration of the Cf-252 source. The Maxwellian averaged flux was determine with better than 5% accuracy at a distance of 8-10 cm from the face of the moderator.

Fig. 2. A picture showing a large area detector with 20 segments each with area of 1 cm^2 that were connected in series-parallel to one preamplifier.

Pulse height spectra from a 1 cm^2 device are shown in figure 3. The data was collected by connecting the detector to an ORTEC 142AH preamplifier with zero detector bias. The Maxwellian averaged efficiency was measured to be 25%.

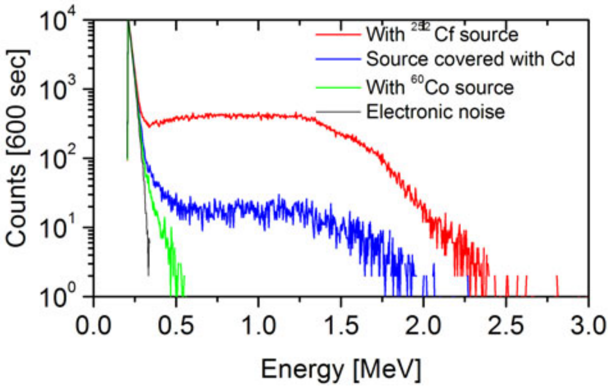

Fig. 3. The measured pulse height spectra shown with: a moderated Cf-252 source, the source covered with Cd (absorbs all thermal neutrons), with a Co-60 source, and the electronic noise (no sources)

A Measurement of a device with 1 cm^2 area was also performed at the RPI LINAC [10] using the time-of-flight method. for these experiments the preamplifier was replaced with a fast CREMAT preamplifier and shaper with overall time constant of 100ns. This was possible due to the fast charge collection time (<100ns) of these detectors. A similar measurement was also conducted with a 1.27 cm thick Li-Glass scintillator detector with a neutron detection efficiency greater than 99% below 10 eV. The results of these experiment allow determination of the detection efficiency as a function of incident neutron energy. A detection efficiency of 28% was obtained for incident neutron energy of 0.0253 eV. The efficiency of this solid-state detector has a $1/\sqrt{E}$ behavior which is expected based of the $1/\sqrt{E}$ behavior of the $^{10}B(n,\alpha)$ reaction. Below 10 eV the efficiency as a function of energy $\epsilon(E)$ can be approximated by equations 1:

$$\epsilon(E) = (1 - exp(-N\sigma_t(E)x))f. \qquad (1)$$

Where N is the nominal B-10 atomic density, x is the nominal thickness of the boron layer and f is the areal fraction of boron in the device, and $\sigma_t(E)$ is the neutron energy dependent total cross section of the B-10 converter. For a measured 1 cm^2 device filled with boron enriched to 93% B-10 it was found that $Nx = 1.952 \times 10^{-4}$ 1/barn and $f = 0.545$. Multiple detector units can be connected together in series to form a large area detector as shown in figure 2. Using 8 units of 1 cm^2 detectors resulted is some loss of efficiency due to attenuation of the current produced as it travels through the other detectors to the preamplifier. The loss in signal amplitude effectively increases the noise level which requires an increase of the discriminator level and thus results in lower efficiency. We were able to scale such detectors from 1 to 16 cm^2 with about 20% loss of detection efficiency.

Simulations were usually done for a perfectly parallel neutron beam which is perpendicular to the detector face. In most applications where the detector is likely to be embedded in a moderator; the neutron entrance angle relative to the detector face covers a wide range of angles which results in a larger intrinsic efficiency [11].

Gamma sensitivity

Usually a neutron environment results in gamma production above ambient background and most applications require detection of neutron with low sensitivity to the background gammas. For the solid-state neutron detector described here interactions of gammas with the active Si layer will result in charge production. It is thus very important to make sure that there is no parasitic active Si area especially on the bottom and sides of the device. Because the detector itself is very thin gamma energy deposition results in low amplitude pulses which can be discriminated with only a small loss in neutron detection efficiency. In figure 3 the gammas from Cf-252 were shown below 0.5 MeV. The sensitivity of a 1 cm^2 area detector with discriminator setting at 0.5 MeV to Co-60 gammas was measured at an exposure rate of 10 mR/h and was found to give be 0.001% of the neutron detection efficiency efficiency.

Radiation Damage

One of the criticisms of solid-state neutron detector as replacement for He-3 detectors is the effect of radiation damage. Every neutron detected results in an alpha particle that can possibly cause radiation damage to the Si semiconductor. In addition fast neutrons can directly cause damage; however since these detectors are typically embedded in a moderator, this issue might be of less concern. To test the effect of neutron damage a detector was used inside the RPI lead slowing down spectrometer (LSDS) [12]. The LSDS is capable of producing high pulsed neutron flux in the energy range from thermal to about 1 MeV which also results in a very intense gamma flux. Usually solid-state devices do not survive this environment for more than a few hours. During the experiment the neutron detector was operating and measuring at rates grater than 10^5 cps. Overall the detector was exposed to about 10^{12} neutrons and survived the test with no observable degradation. More tests are required, however this test indicates that degradation due to radiation is not a concern in low flux applications.

CONCLUSIONS

The solid-state neutron detector discussed here demonstrated a measured thermal neutron detection efficiency of 28%. Improvements in the device fabrication process such as deeper boron filled holes and better adherence to the calculated optimum dimension can increase the efficiency up to 45%. The detectors are easily scalable to large area of 8-16 cm^2 while still using a single preamplifier and providing reasonable efficiency. The gamma detection efficiency was measured to be 0.001% of the neutron detection efficiency and can be improved further by removing unnecessary sensitive Si layers. The fabrication methods of these detectors use conventional clean room technologies that are routinely used in the semiconductor industry and thus large scale production will result in low cost detectors. Such detectors can have many application in low and moderate neutron flux environment.

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