Journal of NUCLEAR SCIENCE and TECHNOLOGY, Supplement 4, p. 407–410 (March 2004)

Development of a Semiconductor Neutron Dosimeter with a PIN Diode

Seungho KIM[1], Namho LEE[1], Jaiwan CHO[1], Geunuck YOUK[2]
[1] *Robotics Lab., Korea Atomic Energy Research Institute, Daejeon, South Korea*
[2] *ServeBot, Inc., USA*

When a Si PIN diode is exposed to fast neutrons, it produces displacement in Si lattice structure of the diode. Defects induced from structural dislocation become effective recombination centers for carriers which pass through the base of a PIN diode. Hence, increasing the resistivity of the diode decreases the current for the applied forward voltage. This paper involves the development of a neutron sensor based on the phenomena of the displacement effect damaged by neutron exposure. The neutron effect on the semiconductor was analyzed, and multi PIN diode arrays with various intrinsic layer(I layer) thicknesses and cross sections were fabricated. Under irradiation tests with a neutron beam, the manufactured diodes have good characteristics of linearity in a neutron irradiation experiment and give results that the increase of thickness of I layer and the decrease of the cross-section of the PIN diodes improve the sensitivity. Newly developed PIN diodes with a thicker I layer and various cross sections were retested and showed the best neutron sensitivity in the condition that the I layer thickness was similar to the length of a side of the cross-section. On the basis of two test results, final PIN diodes with a rectangular shape were manufactured and the characteristics for neutron detectors were analyzed through the neutron beam test using the on-line electronic dosimetry system. The developed PIN diode shows a good linearity to absorbed dose in the range of 0 to 1,000cGy (Tissue) and its neutron sensitivity is 13mV/cGy at a constant current of 5mA, that is three times higher than that of similar commercially developed neutron detectors. Moreover the device shows less dependency on the orientation of the neutron beam and a considerable stability in an annealing test for a long period.

KEY WORDS: PIN diode, neutron, displacement, dosimetry, sensitivity, orientation, annealing

I. Introduction

A personal dosimeter is used for quantitative measurement and evaluation of the radiation effects on the human body. Recently the requirement for a neutron dosimeter has been on the increase as neutron handling in such fields as nuclear power stations, radiotherapy, nondestructive testing, etc. is on an upward trend. In addition, because of the possibility of the use of neutron bombs in local warfare in the Korean peninsula, the demand of neutron dosimeters is expected to rise. Considering these points, it is essential to develop a real-time personal neutron dosimeter that is accurate, convenient, low-priced and small in size[1)]. In general, there are two types of neutron energy discharged from neutron bombs. One of them is energy of an average of 0.8 MeV that occurs from nuclear fission which plays the role of the detonator of a neutron bomb, and the other is an energy of 14 MeV emitted by nuclear fusion inside the main part of the bomb. Both types of energy belong to the range of fast neutron energy.

When the fast neutron is incident upon a silicon PIN diode semiconductor, it collides with the inner silicon lattice, and at that time the neutron energy is transferred to the constituent elements of the lattice and produces scattered recoil nuclei which cause lattice defects. Recoil nuclei with a kinetic energy produces another group of lattice defects, which becomes a trap for electric charges, and consequently changes the I-V (current-voltage) characteristic curve of a PIN diode[2)].

* Corresponding Author, Tel. +82-42-868-2928,
Fax. +82-42-868-8833. E-mail : RobotKim@kaeri.re.kr

In this paper we discuss the increase of the neutron sensitivity of a PIN diode in developing a fast neutron detector using the displacement damage effect of silicon. In addition a highly sensitive personal neutron detector was manufactured through a semiconductor fabrication process, reflecting the results of the neutron tests and simulations according to the device structure. We also discuss the characteristics of the detector such as neutron sensitivity (mV/cGy), angular dependency and annealing.

II. The Effects of Fast Neutron in PIN Diode

When a silicon (Si) PIN diode is exposed to neutron with a certain level of energy, ionization and displacement damage occur simultaneously inside it. The damage is caused by the generation of defects in the form of vacancy and interstitial according to the displacement of the silicon lattice resulting from the collision between the neutron and the silicon lattice. The electron-hole pairs caused by the ionization may be annihilated in a relatively short time depending on the external bias, but the displacement damage effect lasts semi-permanently.

The relationship between the increase of neutron fluence and the reduction of a minority carrier lifetime is as follows.

$$\frac{1}{\tau} - \frac{1}{\tau_0} = K\varphi \quad (1)$$

Here, τ_0 is the initial carrier lifetime, τ is the carrier lifetime after the neutron irradiation, φ is the neutron fluence, and K is the damage constant at base region.

Because the density distribution of the carriers injected into the depletion region is a function of the base width and diffusion length ($L = \sqrt{D\tau}$, L : carrier diffusion length, D : diffusion constant), neutron irradiation reduces the carrier lifetime and the length of diffusion. The external voltage applied to a PIN diode, V_D is expressed [3] as

$$V_D \propto \left(\frac{W}{L}\right)^2 \tag{2}$$

where, W is the diode base width. The applied voltage V_D is inversely proportional to the carrier lifetime τ from the relation of diffusion length L. Consequently, the applied voltage is proportional to neutron fluence. Such a relationship, in which the forward voltage of a diode increases with neutron fluence, is expressed by the rightward shift of the I-V characteristic curve of the device. The amount of electric changes in the characteristic curve shifted by neutron irradiation can be measured by observing the increase of voltage at a constant current or the decrease of current at a constant voltage. It is therefore possible to find the flux or dose of cumulative neutron irradiation simply by measuring the voltage for a constant current or the current for a constant voltage.

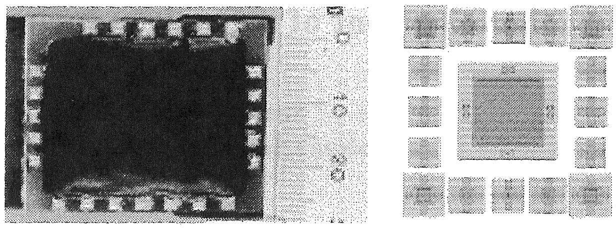
III. Analysis of Neutron Sensitivity according to PIN Diode Structure

1. Manufacturing and Neutron Sensitivity

In the development of a neutron detector, the improvement of sensitivity is essential because the higher sensitivity to unit neutron dose improves the accuracy in measuring neutron dose with a neutron detector. In particular, it is known that the geometric structure of a device is closely related to the sensitivity of a neutron detector. In this study we manufactured different types of devices, and performed irradiation tests in a neutron field and analyzed the results.

In the course of manufacturing the PIN diode device using 350 μm thick high-purity (1000Ω·cm) silicon wafers, a die-shaped PIN diode assembly has been made as shown in **Fig. 1**(a) with four different shapes of effective cross sections (5 x 5, 1 x 1, 0.2 x 0.2, 0.05 x 0.05 mm^2) by using various maskings, and with three kinds of thicknesses (p-n direction) (300, 150, 80μm) by varying the etching process. **Figure 1**(b) shows the internal structure of the manufactured die, which is composed of 17 PIN diodes of different cross sections.

The neutrons irradiation tests were performed on the manufactured devices in a neutron beam with an average energy of 14 MeV which is generated from Be(p,n) reaction. Nearly monoenergetic protons with 35 MeV energy hit a Be target producing neutrons with a energy distribution. The proton beam current (Ip) used in the test was fixed at 40 μA. The contribution from back-scattered low-energy neutrons was approximated to be small compared with the high-energy neutrons directly from the source in this study.



(a) Die photograph (b) Internal structure

Fig. 1 PIN diode assembly outlook and inside structure

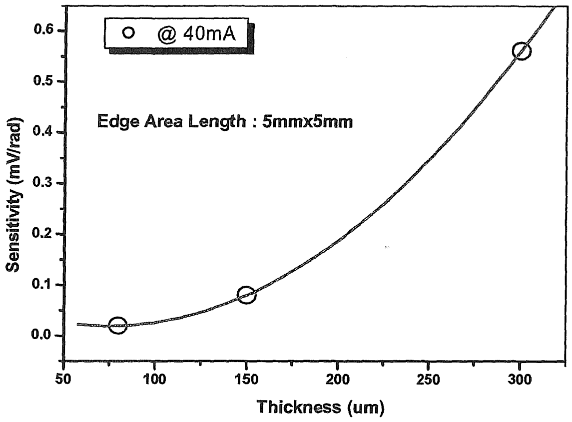


Fig. 2 Changes in neutron sensitivity with the I layer

The displacement damage threshold of a Si lattice is around 25 eV. In order to examine the changes in characteristics by neutron irradiation, the PIN diodes were irradiated with a total 1,000 cGy neutron dose through five steps from 10 cGy only by changing the irradiation time with keeping the dose rate at 6.7 cGy/min, and the diode output characteristics (I-V) were measured and recorded repetitively in each step using a semiconductor parameter analyzer (HP4145B). Neutron dose was measured using a neutron detector (Bicron BC501A liquid scintillator).

The results show that the output current of the PIN diodes changes linearly according to the cumulative neutron dose, and here the change of voltage is 1.52 mV per unit of neutron dose (cGy). Based on the testing results, analysis of neutron sensitivity was performed for various thicknesses of the intrinsic (I) layer and the cross section of the PIN diodes.

Figure 2 is the relationship between the thickness of the I layer and neutron sensitivity when the cross section of the device is constant (5x5mm^2).

It shows that the neutron sensitivity becomes higher when the I layer becomes thicker. **Figure 3** is the analysis of the relationship between the cross section of a device and the neutron sensitivity when the I layer thickness is 300 μm. It shows that the cross section of a device is in an inverse proportion to the neutron sensitivity. From **Figs. 2** and **3**, it can be concluded that the PIN diodes that has thick I layer and narrow cross section are more sensitive to the neutron dose.

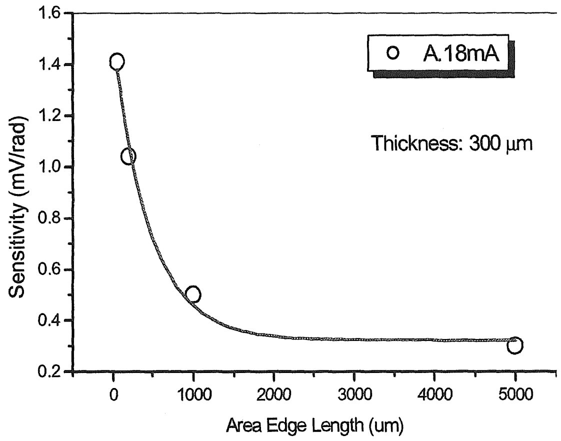


Fig. 3 Changes in neutron sensitivity with the cross section

Table 1 Relation function for transposing

Before	After
$dV_B/d\varphi = f(\tau, J)$, φ : constant	$dV_B/d\varphi = g(d, A)$, φ : constant

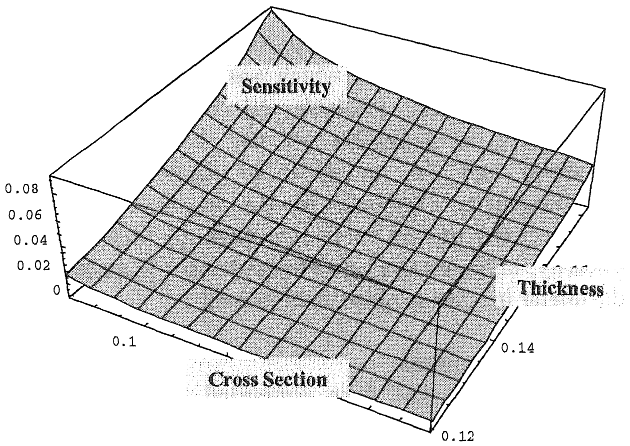


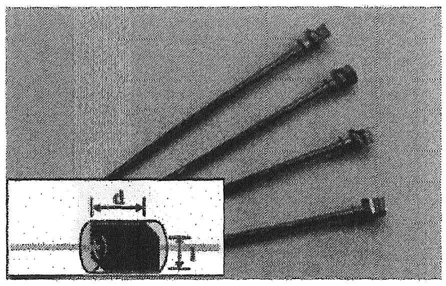
Fig. 4 Characteristics of changes in neutron sensitivity With the thickness and the cross section

2. Simulation of Neutron Sensitivity

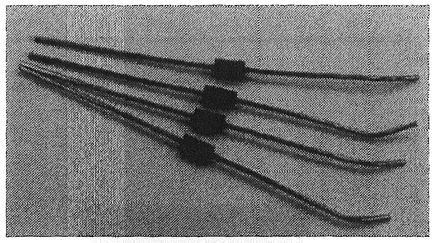
Swartz et al.[4] described the changes in external current-voltage caused by displacement damage when PIN diodes are irradiated with fast neutron. Because the numerical expression describes only the current-voltage changes in the PIN diode and the effects of the parameters inside the devices with the increase of neutron fluence, it is necessary to have a transposition process that introduces the structural variables of the PIN diodes in order to consider the neutron characteristics of a device with variable structures. Swartz's formula was transposed according to the functions in **Table 1**. Here, d is the thickness of the PIN diode, affecting the lifetime of the charges, and A is the cross section of the device, affecting the current itself rather than current density.

The sensitivity was calculated by varying d and A for a constant neutron dose. The correlation between these structure variables and neutron sensitivity is illustrated in **Fig. 4**.

The results of the present simulation shows that the structure with a large thickness (d) and narrow cross section (A) is necessary to make the PIN diodes sensitive to the neutron. The simulated results support qualitatively the results performed with the manufactured device.



(a) Inside structure



(b) Appearance

Fig. 5 Manufactured PIN diodes

IV. Manufacturing High-Sensitivity Neutron Detector

Based on the results of the simulation and neutron tests on the structure of the devices as presented above, we manufactured discrete PIN diodes using a 1.2 mm thick(d) high-purity wafer, whose resistance was 3,000 Ω-cm and length (l) of a side of the cross section was 1 mm, is shown in **Fig.5(a)**. The manufactured device is shown in **Fig. 5(b)**.

V. Neutron Irradiation Test

1. Test Method and its Configuration

PIN diode samples were irradiated by the secondary neutrons produced when an accelerated proton of 35 MeV reacts with the beryllium (Be) target in the cyclotron (MC-50) of the Korea Cancer Center Hospital. The neutron energy has the form of a Gaussian distribution in which the peak energy is 14 MeV and the average value is 6.11 MeV. The proton beam current was set at 40 μA and then, the dose rate of the neutron irradiation was 6.7 cGy per minute. During the experiment, the changes in neutron irradiation as well as the changes in characteristics of the samples caused by neutron irradiation were measured in real-time and the resultant neutron dosage was stored in the computer.

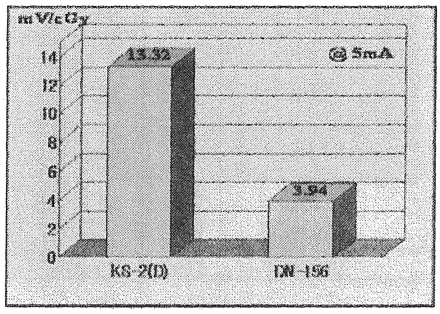


Fig. 6 Neutron Sensitivities

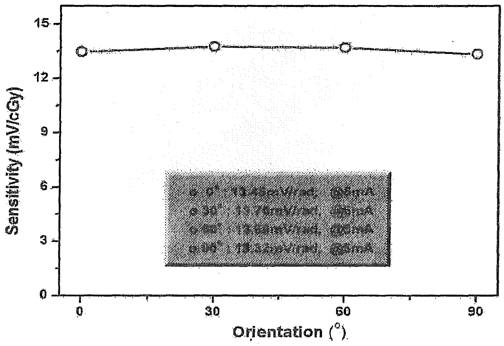


Fig. 7 Orientation dependency

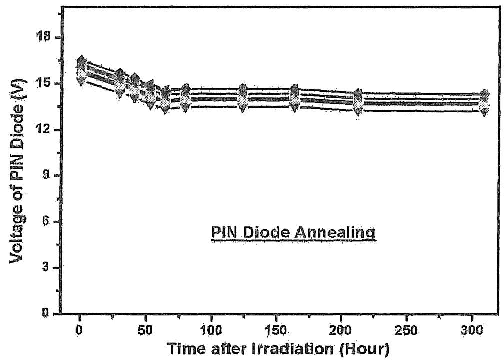


Fig. 8 Annealing characteristic

2. Result of Neutron Test

(1) Neutron Sensitivity

Neutron irradiation test of eight sample PIN diodes developed in this study and two foreign commercial neutron detectors (DN-156, Bicron) were implemented. The changes in the threshold voltage of the samples for a constant current pulse of 5 mA with 10 msec pulse width were recorded online with the irradiated neutron dose. The results show that the developed PIN diodes have a linear characteristic in voltage change to neutron dose, the average sensitivity of 13.32 mV per unit neutron dose (1cGy), and a reliable neutron characteristic that the discrepancies between the devices are less than 7.98 %. **Figure 6** shows that this sensitivity is three times higher than that of the foreign PIN diodes included in the test, which is 3.94 mV/cGy.

(2) Angular Dependency

The changes in sensitivity according to the incidence angle of a neutron upon the developed PIN diode neutron detector were performed to confirm the angular dependency. **Figure 7** illustrates the results of sensitivity for each direction implemented as in the previous test. It suggests that the errors of neutron sensitivities of the PIN diodes measured in this test are less than 3.5 % for all the directions, which shows that the developed PIN diode is almost independent with regards to the direction of the neutron incidence.

(3) Annealing Characteristic

As shown in **Fig. 8**, the initial value of the PIN diodes was annealed at 13% as an average for 308 hours. This change was in the range of the acceptable limit for general neutron dosimeters, and correctable through the software-based offset in the electronic dosimeters. The annealing progresses rapidly until around 70 hours after neutron irradiation but after that time it maintains a relatively stable state.

VI. Conclusion

In this paper we developed a PIN diode as a detector of fast neutron through a semiconductor fabrication process, and analyzed characteristics of the detector particularly concerning on its usability, as a neutron detector through tests in a neutron field. As a personal dosimeter, the developed device showed good linearity from 10 to 1,000 cGy (Tissue), and its sensitivity was 13 mV/cGy at a constant current of 5 mA, which was three times higher than the most advanced available detectors. Furthermore, its dependency is negligible on the direction of neutron incidence, and was proved to be stable in a long-time annealing test. Conclusively, the developed PIN diode devices were proved to be excellent in their sensitivity, linearity, and annealing performance as a personal neutron dosimeter in a fast neutron environment.

Acknowledgement

This research has been supported by the "Dual Use Technology Program".

References

1) M.Sasaki, T. Nakamura, N. Tsujimura, O. Ueda, T. Suzuki, "Development and characterization of real-time personal neutron dosimeter with two silicon detectors, *Nucl. Intrum. Methods*, A418, 465 (1998).
2) George C. Messenger et. al., *The Effect of Radiation on Electronic System*, Van Nostrand Reinhold Company Inc., (1986).
3) O. J. Mengali, E. Paskell, R. W. Beck, and C. S. Peet, "The Use of Diffused Junction in Silicon as Fast-Neutron Dosimeters," *Proc. of 2nd Conf. on Nuclear Radiation Effects on Semiconductor Devices, Materials and Circuits* (1959).
4) John M. Swartz and Marlin O. Thurston, "Analysis of the Effect of Fast-Neutron Bombardment on the Current-Voltage Characteristic of a Conductivity-Modulated P-I-N Diode," *J. Appl. Phys.* 37[2], 745(1966).