Bilateral PIN Diode for Fast Neutron Dose Measurement

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***Abstract*—A silicon-based bilateral diode for fast neutron dose measurement is presented to take advantage of vertical and lateral current distributions and to achieve high uniform current distribution. The structure is designed to place rectangle $p+$ and $n+$ contacts on each side of the n-Si wafer. Diodes with different structure parameters are fabricated and the sensitivity to neutron dose is measured. It is found that, in this research, the increase in the lateral space between the two contacts can effectively increase sensitivity. Furthermore, the decrease of the contact length and the increase of current density can also increase sensitivity. The measured sensitivity data are verified with the model.**

***Index Terms*—Bilateral diode, neutron detector, sensitivity.**

I. INTRODUCTION

NEUTRON detection is applied in fields such as nuclear experiments, space research and the nuclear power industry. The measurement of neutron irradiation dose is significant for personal protection against radiation. Silicon PIN diode can be used as a fast neutron dosimeter when forward biased [1]–[9]. Fast neutron radiation results in decreases of the excess carrier lifetime in silicon by introducing annihilation complexes into the silicon bulk [1][10]. The decrease of the carrier lifetime is related to the neutron radiation dose [1][10]. Under a constant current, the forward voltage drop of the silicon PIN diode will increase after neutron irradiation, which is used to measure the dose of fast neutron irradiation [1]–[9]. The change of silicon resistivity under neutron radiation should be taken into account as well for wide-base silicon PIN neutron dosimeters [3]. The resistivity of high purity n-type silicon changes significantly with fast neutron fluence and the n-type silicon can be converted to p-type silicon given that the neutron fluence is high enough, which indicates it is possible to extend the linear range of operation of PIN fast neutron dosimeters if the diode is made from high resistivity silicon [11].

The sensitivity of a PIN fast neutron diode depends on the diode structure and the initial Si-material. In-depth analytical study on the sensitivity of PIN fast neutron dosimeters reveals that the increase of the intrinsic base width is essential in improving sensitivity [1]. Hence, very thick silicon wafers are required for PIN diodes with large intrinsic base widths. In order to meet the requirement for space application, high sensitivity PIN fast neutron dosimeters is developed by increasing the thickness of diodes to approximately 3.4 mm [5]. The high sensitivity dosimeter with a 5 mm base width is demonstrated [3]. However, the use of very thick silicon wafer poses a challenge to the manufacturing technology. In addition to diode thickness, the cross-sectional area also has noteworthy effects on the sensitivity of PIN fast neutron dosimeters [5][6]. For a constant readout current, the current density should vary according to different diode cross-sectional areas, which also poses large influences on diode sensitivity. The analytical expression, including both diode thickness and cross-sectional area for describing diode sensitivity, is presented in [6].

A great advance in Si neutron dosimeters is the planar-structure PIN diode with a surface $n+$ doping pattern [7][8]. The planar PIN diode has a large effective intrinsic base width without the requiring of excessive silicon wafer thickness. A structure of silicon PIN diode with back side $n+$ doping ring is proposed [9]. The structure is a hybrid of vertical structure and planar structure PIN diodes, which can improve current distribution and take advantage of vertical and lateral current distributions. However, sensitivity is limited by the decrease in current density with increasing back side ring radius [9].

This paper presents a bilateral PIN diode based on high resistivity silicon for fast neutron detection. Instead of the structure with doping rings [9], $p+$ and $n+$ contacts in the shape of rectangle are designed on each side of the wafer with a lateral space between the contacts to optimize current distribution. Diodes with different sizes and parameters are designed and fabricated. The V-I curve of the diode samples are measured before and after irradiation. The neutron dose sensitivity of the diodes is derived. The measured results show that the sensitivity increases with increasing lateral distance between the $p+$ and $n+$ contacts because a larger lateral distance leads to a thicker effective intrinsic layer. In comparison with the PIN diode with back side ring doping [9], the sensitivity of the bilateral PIN diode is improved greatly. The effect of the contact cross-sectional area is also investigated by comparing diodes with different contact lengths, which shows that a smaller contact length can induce larger sensitivity. The measured sensitivity data have been analyzed with the model which indicates that the results are consistent with the theory.

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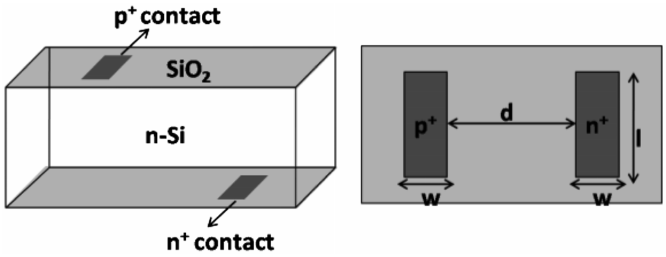

Fig. 1. The structure of bilateral PIN diode and its top view.

II. DIODE STRUCTURE AND EXPERIMENT

The structure of the bilateral diode and its plane projection are illustrated in Fig. 1. The rectangular $\mathrm{p+}$ and $\mathrm{n+}$ doping contact regions are designed on the front and back sides of the silicon wafer. The length and width of the doping contact regions are represented by l and w. The lateral space between the $\mathrm{p+}$ and $\mathrm{n+}$ contacts is denoted by d. The shape and size of the $\mathrm{p+}$ and $\mathrm{n+}$ doping regions are designed to identically to achieve symmetric diode geometry and equal current density distribution at the $\mathrm{p+}$ and $\mathrm{n+}$ contacts. It should also be noticed that the current density is independent of d. Whereas in the diodes with doping ring structure, the current density decreases with the increasing radius of the outside doping ring [8][9]. Additionally, similar as the discussion in [9], this bilateral PIN diode takes advantage of the thick Si wafer and the large lateral space between two contacts because current flows through the thick Si bulk in both lateral and vertical directions. The $\mathrm{p+}$ and $\mathrm{n+}$ contacts are designed on different sides of the wafer instead of on the same side to reduce carrier recombination at the silicon surface which may affect diode sensitivity.

A simulation study is implemented on the bilateral diode to investigate the current distribution under a large current condition by using TCAD Sentaurus [12]. Diodes with different d and l values are fabricated, and the w of all diodes is set to 500μm to investigate the effects of parameter d and l on dosimeter sensitivity. High-purity n-silicon wafers with $3000\ \Omega \cdot$ cm resistivity and 1500μm thickness are applied for dosimeter fabrication. Firstly, 800 nm $\mathrm{SiO_2}$ on the silicon surface is formed at 1000°C. Implantation windows are opened on the $\mathrm{SiO_2}$ by double-side lithography to ensure that the $\mathrm{p+}$ and $\mathrm{n+}$ doping regions are exactly located on each side of the wafer. The following step is ion implantation of boron at a dose of $10^{15}\ \mathrm{cm}^{-2}$ to form the $\mathrm{p+}$ region and ion implantation of phosphorus at a dose of $10^{16}\ \mathrm{cm}^{-2}$ to form the $\mathrm{n+}$ region. Then we perform annealing at 950°C for 0.5 h in $\mathrm{N_2}$ ambient to activate the implanted impurities and to remove the implantation damage from Si bulk. Finally, ohmic contacts are formed by sputtering aluminum onto the Si surface and annealing the wafer at 450°C.

The diodes are exposed to neutron radiation for sensitivity testing. The irradiation source is $^{239}\mathrm{Pu} - \mathrm{Be}$ isotopic neutron source. The total radiation dose is 3672mSv at a radiation rate of 12mSv/h. The V-I data are tested by forward biasing the diodes before and after irradiation with semiconductor parameter analyzer HP 4156B to derive the dosimeter sensitivity to fast neutron radiation.

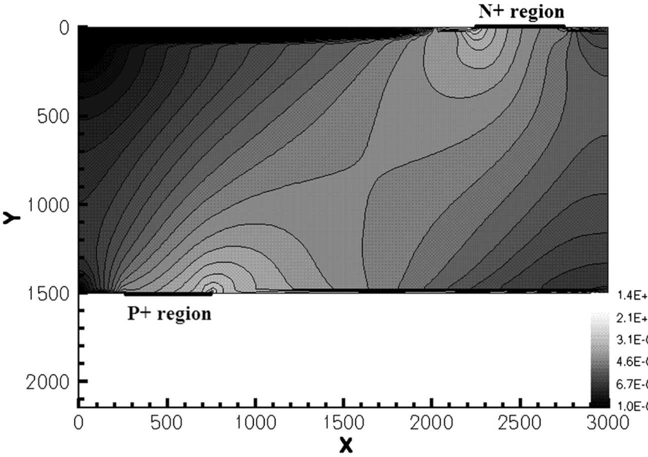

Fig. 2. Current distribution in bilateral structure. The current density values are in units of $\mathrm{A/cm^2}$. The contour line of the current density distribution is also illustrated.

III. RESULTS AND ANALYSIS

The current distribution of the diode under a large current of 1 mA is simulated. The simulated wafer thickness is 1500μm, the width of the $\mathrm{p+}$ and $\mathrm{n+}$ regions is 500μm and the lateral space between the regions is 1500μm. The doping concentrations of the n-silicon, the $\mathrm{p+}$ contact region and the $\mathrm{n+}$ contact region are $1.5 \times 10^{12}\ \mathrm{cm}^{-3}$, $10^{18}\ \mathrm{cm}^{-3}$ and $10^{19}\ \mathrm{cm}^{-3}$ respectively. On both surfaces of the wafer there are $\mathrm{SiO_2}$ layers. The positive charge concentration in the $\mathrm{SiO_2}$ layer is set as $5 \times 10^{10}\ \mathrm{cm}^{-2}$, which can be achieved by thermal oxidation technology. The result is shown in Fig. 2. The illustration shows that the current travels mainly from the p^+ contact region toward the n^+ contact region in the bilateral diode. The effective intrinsic base width h can be approximated as the distance between the $\mathrm{p+}$ and $\mathrm{n+}$ contact regions:

$$h = \sqrt{t^2 + d^2}, \tag{1}$$

where t is the thickness of the Si wafer. It is clear that h is larger than wafer thickness and a larger effective diode base width is achieved. Current density distribution in the sensitive region is quite uniform, thus improving the stability of the diode.

The sensitivity of the fabricated diodes is measured. The increases in voltage drop because of irradiation are achieved by comparing the V–I data before and after irradiation. The increase in voltage drop is divided by the total neutron radiation dose and the dosimeter sensitivity results. The factors affecting dosimeter sensitivity, such as the readout current, the lateral space between the $\mathrm{p+}$ and $\mathrm{n+}$ contacts and the dosimeter length are investigated.

The relationship between dosimeter sensitivity and current is also studied. The result is illustrated in Fig. 3. Fig. 3(a) shows the V–I curve of a bilateral PIN diode before and after irradiation. It is clear to see from the result that the forward voltage drop of the diode increases after irradiation. This phenomenon is mainly related to the decrease of the minority carrier lifetime because of the annihilation complexes caused by irradiation. Figure 3(b) illustrates the derived dosimeter sensitivity against current in high-level injection regions where current is larger than 1 mA. The result shows that sensitivity increases with current.

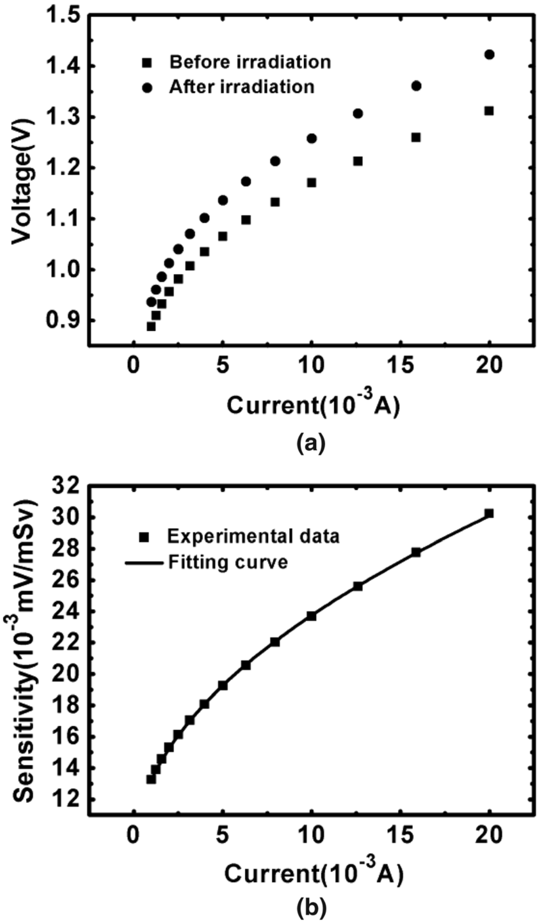

Fig. 3. (a) The V—I data of a bilateral diode before and after irradiation, where d is 1000μm and l is 3000μm. (b) Sensitivity change against current for this diode. The model fitting curve is also shown.

When PIN diodes work in a large current condition, sensitivity is greatly affected by the intrinsic base width and current density [1]–[8]. It has been theoretically concluded that, under high level injection conditions, the voltage drop on PIN diode base and the derived sensitivity is proportional to the square root of current density [1]–[8]. As discussed in [8], under high level injection conditions, the change of dosimeter sensitivity with readout current density can be fitted as follows:

$$S = a + b\sqrt{j}. \tag{2}$$

In (2), S is sensitivity in the unit of mV/mSv, j is current density in the unit of $\mathrm{A}/\mu\mathrm{m}^2$ and a, b are coefficients related to diode structure in the units of mV/mSv and $(\mu\mathrm{m}\cdot\mathrm{mV})/(\mathrm{mSv}\cdot\mathrm{A}^{0.5})$. The theoretical model to explain (2) is derived from circular shape dosimeter in [8]. Similarly, (2) can also be explained by the fundamental analytical model in [1]. It is reasonable to express the coefficient b as

$$b = Bh\left\{1 + \left[\sinh(h/2L) - \frac{\cosh(h/2L)}{h/2L}\right]\left[2\mathrm{arctan}(e^{h/2L}) - \frac{\pi}{2}\right]\right\}, \tag{3}$$

where h is the effective base width, L is the diffusion length, and B is the coefficient independent on h. Equation (3) is based on the sensitivity theory for high level injection in [1].

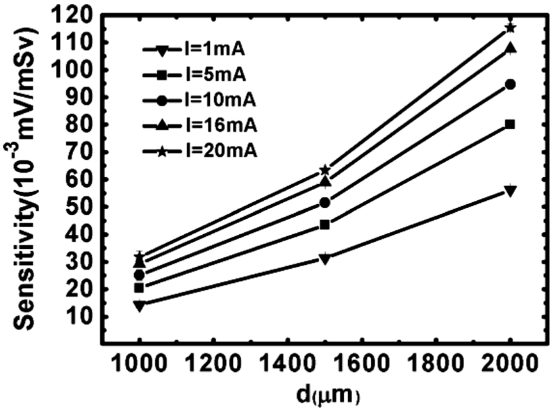

Fig. 4. Sensitivity change against d with $l = 3000\mu$m under different currents represented by different symbols. The lines in the figure are to connect the symbols and serve as a visual guide.

The experimental results of the bilateral diodes under a high level injection condition fit well with (2). The sensitivity data of the diode with d of 1000μm and l of 3000μm is shown in Fig. 3(b) and is fitted as $S = 0.00841 + 187.766\sqrt{j}$.

The relationship between sensitivity and structure parameter d is studied. The results are shown in Fig. 4, where l for all diodes is kept as 3000μm. As expected, sensitivity increases with d greatly. A larger d indicates a wider base width according to (1) and results in higher sensitivity. At a current of 5 mA, the average maximum sensitivity of 0.075 mV/mSv for the bilateral PIN diodes with d of 2000μm is achieved, as is shown in Fig. 4. This value is much higher than the maximum sensitivity of 0.011 mV/mSv for the diodes with back side ring doping [9], which can be attributed to larger effective intrinsic base width and more uniform current density distribution.

In order to analyze how sensitivity increases with current density, coefficient b is investigated. Coefficient a and b in (2) are obtained by fitting the measurement results. The dependence relationship of b on d is shown in Fig. 5(b) and that of a on d is shown in Fig. 5(a). It is obvious that b increases with structure parameter d. The increase of coefficient b indicates that the sensitivity of diodes with larger d value increases faster with the current. The change in b with lateral space d is fitted to (3) by using L as 1.3 mm estimated for the silicon wafer we use. The theoretical fitting curve agrees well with the b values extracted from experiments, as is shown in Fig. 5(b).

The influence of parameter l on sensitivity is also studied and the results are shown in Fig. 6. It is found that under a constant current, sensitivity increases when l decreases. Fig. 7 shows the values of coefficients a and b for different l values. It can be seen in Fig. 7 that the variation of a and b induced by l is much smaller than the variation induced by d shown in Fig. 5.

The decrease of l results in the decrease of the cross section area of the current flow and increases current density under a constant current, which leads to increasing sensitivity with decreasing l. Similar to the model in [6], to describe the impact of cross-sectional area, it is derived from (2) as

$$S = a + b\sqrt{I/wl}, \tag{4}$$

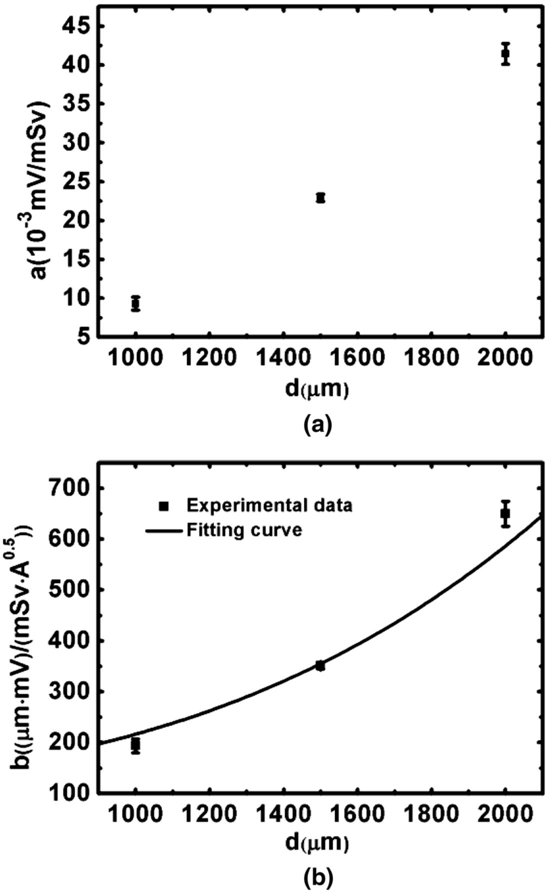

Fig. 5. (a) Influence of parameter d on coefficient a. (b) Influence of parameter d on coefficient b. The curve fitting to (3) is also shown and the fitting coefficient B is 0.37356.

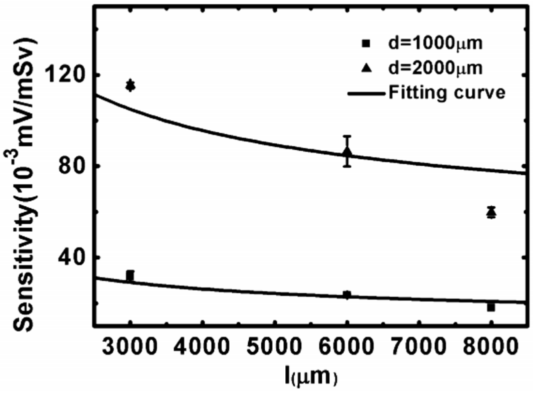

Fig. 6. Sensitivity change against l when $\mathrm{I} = 0.02\mathrm{A}$. The fitting coefficients a and b for $d = 2000\mu\mathrm{m}$ are 0.03556 and 600.5489, and for $d = 1000\mu\mathrm{m}$ are 0.007545 and 187.10393.

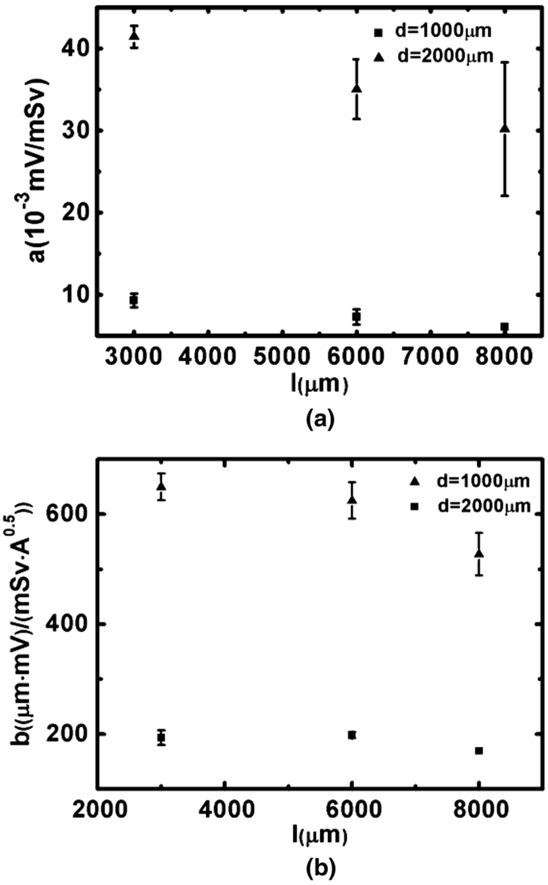

Fig. 7. (a) Influence of parameter l on coefficient a. (b) Influence of parameter l on coefficient b.

where I is the readout current in the unit of A, w and l are in the unit of μm.

The S data shown in Fig. 6 are fitted to (4). The fitting curves are shown in Fig. 6 and the fitting coefficients of a and b are given in the figure caption. It shows that the change of S with l for d of 1000μm can be well explained by (4). The fitting coefficients a and b in Fig. 6 match the values of a and b in Fig. 7.

The increase of resistivity after fast neutron irradiation should also be considered for a wide-base diode in addition to the carrier lifetime decrease as has been discussed in [3]. The change of the resistivity in the central part of the diode should be taken into account to understand the increase of sensitivity with increasing d and decreasing l in Fig. 4 and Fig. 6. In Fig. 5(b), it can be seen that the increasing rate of b with d is underestimated by the fitting curve on the basis of (3), which considers carrier lifetime decrease only. In Fig. 6, the increasing rate of sensitivity with decreasing l for d of 2000μm is larger than that for d of 1000μm. The increasing rate of sensitivity with decreasing l is underestimated by the fitting curves on the basis of (4). These observations are related to the resistivity effect.

IV. CONCLUSION

In this paper, the design of the bilateral diode is presented. The current density distribution in the structure is simulated under large current conditions. The resultant image shows the current flow path and confirms that the structure design enlarges the effective base width to take advantage of the vertical and lateral current distributions. The current distribution is fairly uniform in the sensitive region. Diodes with different geometry parameters are fabricated and the sensitivity to fast neutron dose is measured. It is found that sensitivity increases with increasing current. The sensitivity dependencies on structure parameters are also studied. The sensitivity increases with increasing lateral space between the p+ and n+ contacts and with decreasing doping region length. The measured sensitivity data are verified with the model.

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