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Studies of the Characteristics of a Silicon Neutron Sensor

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Abstract—Electrical characteristics and neutron dosimetry properties of silicon based p-i-n diodes are presented in support of the applications in the sensors for beam monitoring and medical physics. Both the current-voltage (I-V) and capacitance-voltage (C-V) characteristics of silicon planar p-i-n diode sensors with cylindrical geometry have been theoretically modeled and experimentally measured. The shifts of the forward and reverse diode characteristics of the sensors versus the neutron dose have been obtained. It is shown that the neutron irradiation caused shift of the forward voltage of the p-i-n diodes is proportional to the current at which it is measured in the case of the low level injection or to the square root of the current in the case of the high level injection. The C-V characteristics and the full depletion voltages of the diodes have been estimated and experimentally verified. It is shown that the sensitivity of planar cylindrical structures as neutron sensors can be optimized by the selection of the device geometry and the current at which the measurement is performed.

Index Terms—Neutron detectors, p-i-n diodes, sensitivity.

I. INTRODUCTION

DETECTORS for neutron dosimetry based on silicon planar p-i-n structures have important advantages: (i) fabrication by the standard planar technology process which is simpler and cheaper in comparison with manufacturing of single bulk p-i-n diodes; (ii) a variety of different geometry and sizes for controlling neutron sensitivity and a wide range of measurable doses. The principle of measurement of the neutron dose in silicon is based on the effect of non-ionizing energy losses and the creation of radiation damages within the silicon bulk. The neutron dose is determined by either the shift in the diode forward voltage ΔV_f measured at a constant current or the shift of the reverse current-voltage (I-V) characteristics under neutron irradiation. The shift is caused by a reduction in the minority carrier lifetime and a change in the resistivity of the silicon due to the accumulated radiation damage.

The effect of neutron irradiation on the forward I-V characteristics of rectangular p-i-n diodes due to the dependence of the

Fig. 1. Circular planar diodes C1 and C2.

lifetime of the excess carrier τ on the neutron dose was previously studied by Swartz and Thurston [1]. In [2] the influence of the change in the resistivity ρ of silicon was investigated for silicon p-i-n diodes with rectangular geometry. It was shown previously [3] that silicon planar structures demonstrated high neutron sensitivity (from 0.14 to 3.3 mV/cGy for different readout currents) and could be used for the neutron integral dosimetry, for tissue equivalent neutron dosimetry for biological dose monitoring. Small sizes of these structures allow measuring neutron beam profiles [3].

The present paper provides a study of the possibility of using circular planar p-i-n structure as neutron sensors. The current-voltage (I-V) and capacitance-voltage (C-V) characteristics and the sensitivity of circular p-i-n structures are modeled. Comparisons with the results of experimental measurements are undertaken.

Comparison of a linear array of rectangular diodes and circular p-i-n diodes was performed in [3]. The circular structures are preferable because of avoiding edge effects. The distribution of the electric field is more complicated in the case of the rectangular structures and the edge effects should be taken into account. Circular structures also can be used for dosimetry in mixed neutron-gamma fields due to the better charge collection efficiency [4].

II. CIRCULAR SENSORS

Circular p-i-n diodes (Fig. 1) were fabricated by the planar technology on 300 μm thick n-Si wafers with the resistivity of

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1 kOhm-cm. Concentric p^+ and n^+ regions were formed by the ion implantation on the upper surface of the silicon.

Implantation energies and doses were 30 KeV and $7 \cdot 10^{14}$ ion/cm² for boron and 60 KeV and $3 \cdot 10^{15}$ ion/cm² for phosphorus, respectively. The backside n^+ layer was formed by phosphorus implantation with the energy 60 KeV and the dose $3 \cdot 10^{15}$ ion/cm². The 1 μ m thick aluminum layers were formed to make ohmic contacts with the n^+ and p^+ regions.

The C1 structure was irradiated up to the dose of 10 Gy ($2 \cdot 10^{11}$ n/cm²) and the C2 structure was irradiated up to the dose of 20 Gy ($4 \cdot 10^{11}$ n/cm²) by fast neutrons with average energy about 20 MeV on the Fast Neutron Therapy facility at Harper hospital in Detroit. The neutron beam intensity was $5 \cdot 10^{11}$ n-cm⁻²·s⁻¹ of equivalent 1 MeV neutrons in Si [3]. We have used a Keithly digital bridge for I-V and C-V measurements that allows obtaining the accuracy of 2%.

III. FORWARD CURRENT-VOLTAGE CHARACTERISTICS

A. Model and Theory

The sensor sensitivity is determined by the irradiation caused shift of the I-V characteristics of the planar structures. Detailed analysis of the I-V characteristics of the p-i-n diode with rectangular geometry under neutron irradiation was carried out in [3] where the approximation of the high level carrier injection was assumed. The calculation for the circular geometry is similar to those performed in [1].

The voltage across the diode is the sum of the voltage drops across the p^+ -n and n- n^+ junctions, respectively, and the voltage drop across the diode base. The voltage drops across the diode junctions is given by

$$V_{p+n} + V_{nn^+} = \frac{kT}{e} \ln \frac{p(r_1)p(r_2)}{n_i^2}, \quad (1)$$

where $p(r_i)$ is the concentration of holes, n_i is the intrinsic charge-carrier concentration in Si.

The voltage drop on the diode base can be obtained by the standard procedure from the continuity equations, expressions for the electron and the hole currents and Poisson equation [2]

$$\begin{aligned} V_b &= - \int_{r_1}^{r_2} E_r dr \\ &= \frac{1}{2\pi d e \mu_p} \int_{r_2}^{r_1} \frac{I_0}{r(p+bn)} dr + \frac{kT}{e} \int_{r_2}^{r_1} \frac{\vec{\nabla}(p-bn)}{p+bn} dr, \end{aligned} \quad (2)$$

where $I = 2\pi r d J$ is the p-i-n diode current, d is the diode thickness, r_1 is the radius of the p^+ -n junction, r_2 is the radius of the n- n^+ junction, n, p are the electron and hole concentrations, respectively, $b = \mu_n/\mu_p$, μ_n and μ_p are the electron and hole mobility, respectively.

In the quasi-neutrality approximation ($\Delta n = \Delta p$) for the voltage on the base for the planar cylindrical p-i-n diode in the case of the long base ($r_2 - r_1 \gg d$) one can obtain

$$V_b = - \frac{1}{2\pi d e \mu_p} \frac{I}{p_0 + bn_0} \int_{r_1}^{r_2} \frac{dr}{r(1+P(r))} - \frac{kT}{e} \frac{1-b}{1+b} \ln \frac{1+P(r_2)}{P(r_1)}, \quad (3)$$

where $P(r) = \Delta p(r) \cdot (1+b)/(p_0 + bn_0)$, n_0 and p_0 are the equilibrium electron and hole concentrations, respectively. The density of the injected carriers $\Delta p(r)$ in the diode base can be obtained from the diffusion equation with the corresponding boundary conditions [5], [6]

$$\frac{1}{r} \frac{d}{dr} \left(r \frac{d}{dr} \right) \Delta p(r) - \frac{\Delta p(r)}{L_a^2} = 0, \quad (4)$$

where $L_a = \sqrt{D_a \tau}$, $D_a = 2D_n/(b+1)$ is the coefficient of the ambipolar diffusion, D_n is the coefficient of the diffusion of the electrons, τ is the lifetime of the excess carriers.

The solution of (4) is given by

$$\Delta p(r) = A \cdot I_0(r/L_a) + B \cdot K_0(r/L_a) \quad (5)$$

where $I_0(r/L_a)$ and $K_0(r/L_a)$ are the modified Bessel function of the zeroth order of the first and second type, respectively, A and B are the coefficients that can be obtained from the corresponding boundary conditions [5], [6].

The expressions for the I-V characteristics can be simplified in the following two cases:

- 1) In the case of the high level injection the results of calculations of the I-V characteristics for cylindrical planar diodes are similar to the case of the linear diode [1], [2]. In this case, according to [1], [2], the relation between the current and the hole concentration at the junctions are the following

$$\begin{aligned} \Delta p(r_1) &= \left(\frac{b}{(b+1)} \frac{p^+ a I}{2\pi e D_n r_1 d} \right)^{1/2} \\ \Delta p(r_2) &= \left(\frac{b}{(b+1)} \frac{n^+ c I}{2\pi e D_n r_2 d} \right)^{1/2} \end{aligned} \quad (6)$$

where a, c are the thicknesses of the highly doped n^+ and p^+ regions of the diode, respectively.

Using (5) and (6) one can obtain two linear equations for the calculation of the coefficients A and B . From (3), (4) and expressions for the coefficients A and B one can obtain the voltage drop across the diode base

$$V_b(I) = \frac{kT}{e} (\ln(\eta) + C\sqrt{I}), \quad (7)$$

where the coefficient C is given by

$$C = I_d^{-1/2} \int_{z_1}^{z_2} (zF(z))^{-1} dz, \quad (8)$$

Fig. 2. The I-V characteristics for the C1 structure. $V_0 = 0.515 + 0.069\sqrt{I} + 0.0412 \ln(I)$, $V_{Dn} = 0.516 + 0.241\sqrt{I} + 0.0447 \ln(I)$.

Fig. 3. The I-V characteristics for the C2 structure. $V_0 = 0.585 + 0.632I + 0.0453 \ln(I)$, $V_{Dn} = 0.633 + 2.852I + 0.0508 \ln(I)$.

where $z = r/L_a$, $I_d = kT\mu_p(b+1)2\pi dp^+a/r_1$,

$$F(z) = \frac{(K_0(z_2) - \eta K_0(z_1))I_0(z)}{I_0(z_1)K_0(z_2) - I_0(z_2)K_0(z_1)} + \frac{(\eta I_0(z_1) - I_0(z_2))K_0(z)}{I_0(z_1)K_0(z_2) - I_0(z_2)K_0(z_1)},$$

$$\eta = ((r_1 n^+ c)/(r_2 p^+ a))^{1/2}.$$

The I-V characteristic in this case can be written as follows

$$V(I) = \frac{kT}{e} (\ln(I/I_s) + \ln(\eta) + C\sqrt{I}), \quad (9)$$

where I_s is the saturation current of junctions.

- 2) In the case of the low level injection the dependence of the voltage drop across the diode base is proportional to the current I (quadratic term in I can be neglected) and the I-V characteristic can be written as follows

$$V(I) = \frac{kT}{e} \ln(I/I_s + 1) + IR_s, \quad (10)$$

where $R_s = (2\pi e\mu_p)^{-1}(p_0 + bn_0)^{-1} \ln(r_2/r_1)$ is the diode base resistance.

The shift of the I-V characteristics under the neutron irradiation is determined by the dependence of τ , L_a , n_0 , p_0 on the absorbed neutron dose [1], [2].

The experimental I-V characteristics for the C1 and C2 structures before and after neutron irradiation as well as the corresponding theoretical approximations based on (9) and (10) are shown in Figs. 2 and 3. The sizes of marks in the figures include the experimental errors.

B. Sensitivity

The diode sensitivity is determined by

$$S = -\frac{kT}{e} \frac{1}{I_s} \frac{dI_s}{d\Phi_n} + \frac{dV_b}{d\Phi_n}, \quad (11)$$

where Φ_n is the total fast neutron dose.

Fig. 4. Dependence of the C1 diode sensitivity on the measurement current. The $S = -0.7 + 17.3\sqrt{I}$ fit is shown by the dashed line.

Fig. 5. Dependence of the C2 diode sensitivity on the measurement current. The $S = 0.99 + 128.9I$ fit is shown by the dashed line.

Thus, the diode sensitivity for the cases of the high level and the low level injection, described above, is proportional to $\sqrt{I}$ or I , respectively. Measured sensitivities of the diodes were approximated by the expression $S = a_1 + b_1\sqrt{I}$ for the diode C1 and $S = a_2 + \Delta R_s I$ for the diode C2 which agree with the theoretical model (Figs. 4 and 5). The sensitivities were in the range from 1 to 10 mV/Gy.

IV. REVERSE CURRENT-VOLTAGE AND CAPACITANCE-VOLTAGE CHARACTERISTICS

The neutron dose can also be determined from the irradiation caused shift of the reverse I-V characteristics. Under condition where the generation current in the depletion region Ω is dominant, the I-V characteristics can be written as

$$I_{\text{gen}} = \frac{e n_i}{2\tau_0} (1 + \alpha \Phi_n \tau_0) \Omega(V), \quad (12)$$

where τ_0 is the initial minority carrier lifetime, α is the degradation coefficient of the lifetime, n_i is the intrinsic concentration of charge carriers. The sensitivity is given by

$$\frac{dI_{\text{gen}}}{d\Phi_n} = \frac{e n_i \alpha}{2} \Omega(V). \quad (13)$$

Thus, the sensitivity is determined by the dependence of the depletion region on the applied voltage and is independent of the neutron dose.

The width of the depletion region w can be estimated by the following equation which is the result of the solution of the Poisson equation for the circular geometry

$$V = \frac{kT}{2e} \frac{1}{L_d^2} \left(r_1 w - \frac{1}{2} w^2 + (r_1 + w)^2 \ln \frac{r_1}{r_1 + w} \right), \quad (14)$$

where $L_d^2 = (\varepsilon kT)/(4\pi e^2 N_d)$ is the Debye length.

In the case of a wide depletion region, when $w \gg r_1$, neglecting the terms of higher orders of r_1/w , one can obtain

$$V = -\frac{kT}{2e} \frac{w^2}{L_d^2} \left(\frac{1}{2} + \ln \frac{w}{r_1} \right). \quad (15)$$

Thus the dependence w on V is close to the experimentally observed for the C2 structure ($w \sim \sqrt{V}$).

In this case the full depletion voltage is given by

$$V = -\frac{kT}{2e} \frac{(r_2 - r_1)^2}{L_d^2} \left(\frac{1}{2} + \ln \frac{r_2 - r_1}{r_1} \right). \quad (16)$$

The I-V and C-V characteristics of the diodes under reverse bias and their approximations are presented in Figs. 6 and 7. The sizes of marks in the figures include the experimental errors. The estimated sensitivity for $\alpha = 100 \text{ rad}^{-1}\text{s}^{-1}$ is approximately $5 \cdot 10^{-10} \text{ A/rad}$. This allows the sensors to measure the dose exceeding 10 rad.

V. CONCLUSION

The I-V and C-V characteristics of circular planar sensors and the sensitivity of these characteristics to the neutron irradiation have been studied. Satisfactory agreement with experimental data was obtained.

Varying the applied voltage, material and the geometry of the proposed planar cylindrical structures allows altering the sensi-

Fig. 6. Reverse I-V characteristics. The $I = I_0(e^{\alpha V} - 1) + C V^\beta$ fit is shown by dashed lines. The fitting parameters are C1 : $I_0 = 1.59 \cdot 10^{-9}$, $C = -6.52 \cdot 10^{-10}$, $\beta = 0.5$ C2 : $I_0 = 4.26 \cdot 10^{-11}$, $C = -3.48 \cdot 10^{-10}$, $\beta = 0.5$.

Fig. 7. C-V characteristics. The $C = A + b/\sqrt{|V|}$ fit is shown by dashed lines. The fitting parameters are C1 : $A = 2.75$, $b = 5.1$ and C2 : $A = 2.4$, $b = 1$.

tivity of the diodes to the neutron irradiation. The sensitivity of the sensors can also be controlled by tuning the current at which the measurement is performed.

The advantages of the planar technology and the small sizes of the devices make these sensors suitable for the applications in portable dosimeters for the medical and radiation protection purposes.

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