THE EFFECT OF NEUTRON IRRADIATION ON SILICON PHOTODIODES

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ABSTRACT

Neutron radiation testing was performed on a total of 125 silicon photodiodes to investigate the changes in the device parameters after neutron exposure. Californium-252 source was used to irradiate these photodiodes with 1 MEV equivalent neutrons having fluences in the range of $5x10^{11}$ to 10^{14} N/cm^2. The photodiode forward voltage drop, ideality factor and series resistance were found to increase after neutron exposure. The increased series resistance was found to cause a degradation in diode photocurrent linearity. An empirical expression for post neutron changes in photodiode linearity is presented. Neutron induced changes in the photodiode shunt resistance and dark current have been modeled using simple expressions. These expressions allow device designers to estimate changes in photocurrent linearity, shunt resistance and dark current after neutron exposure. No post neutron change in the UV quantum efficiency of diodes without recombination in the front region was observed. This suggests that neutron irradiation does not affect the Si-SiO$_2$ interface recombination velocity of p-n junction diodes.

INTRODUCTION

Silicon photodiodes are being used routinely in military systems in ring laser gyros, rubidium frequency standards, fiber optic links, laser range finders, position sensors and ocean communication systems. This has led to testing of the reliability and radiation hardness aspects of silicon photodiodes [1-9]. Reliability aspects of more advanced photodiodes have recently been reviewed [1]. In this paper the changes in the device parameters and characteristics of several types of photodiodes after exposure to 1 MeV equivalent neutrons having fluences in the range of $5x10^{11}$ to 10^{14} N/cm^2 are reported.

Earlier investigators [2-9] have found changes in the photodiode characteristics such as responsivity, shunt resistance dark current, risetime, capacitance and 1/f noise after exposure to neutrons and various ionizing radiations. This work deals mainly with the effect of neutron irradiation on the photodiode series resistance, current linearity, shunt resistance, dark current and the forward I-V characteristics.

TEST STRUCTURES

All the photodiodes used in this investigation were of planar type made on n as well as p-type starting wafers ranging in resistivity from 1 ohm-cm to 5000 ohm-cm. The photodiodes had an active area of 1 cm^2. Some photodiodes fabricated on p-p+ epitaxial wafers were also included in this study. The diode fabrication and principal structural details have been adequately described elsewhere [10,11]. The diodes investigated were of the following types.

1. POSITION SENSING PHOTODIODE: The position sensing photodiode (UDT FIL C10D) used in this work has n-type 400 ohm-cm bulk resistivity rectangular sheet, which has ohmic contacts formed around the p-type active area. More details on the position sensing photodiodes are given in Ref. 12.

2. PHOTODIODES WITHOUT CARRIER RECOMBINATION IN THE FRONT REGION: Historically, high responsivity UV-enhanced photodiode were made by inducing an n-type natural inversion layer on p-type silicon [13]. However, the ionizing radiation decreases the charge associated with this inversion layer leading to a decrease in the current linearity of inversion layer photodiodes [11]. Photodiodes recently fabricated by us using a defect free n-type impurity diffusion into p-type silicon have demonstrated better stability than the inversion layer photodiode with no noticeable difference in the internal quantum efficiency [10,11]. These diodes were found to be extremely efficient to detect photons from the UV, vacuum UV, far UV and soft X-ray spectrum [14]. As there are several military, space, scientific and medical applications of these photodiodes [14,15], these diodes were also included in this study. UDT FIL UV100 and FIL 6230 photodiodes investigated here represent the inversion layer and phosphorus diffused diodes, respectively.

3. NUCLEAR RADIATION DETECTORS: These diodes are made on greater than 5000 Ω-cm n-type silicon and are used in a fully depleted configuration. They are used for detecting heavy ions, minimum ionizing particles, X-rays and extremely high energy particles. Because of these unique applications, neutron exposure studies on these diodes are extremely useful. Additional details on silicon

nuclear radiation detectors are available in the literature [16]. UDT RD100 is the radiation detector examined here.

4. CONVENTIONAL SILICON PHOTODIODES: In addition to the above special purpose photodiodes, p on n as well as n on p conventional silicon photodiodes were also exposed to neutrons. Photodiodes fabricated on p-p+ epitaxial wafers with p-type epitaxial layer resistivity of 25 Ω-cm and a thickness of 15 microns were also included in this study. A schematic of a typical photodiode investigated is shown in Figure 1

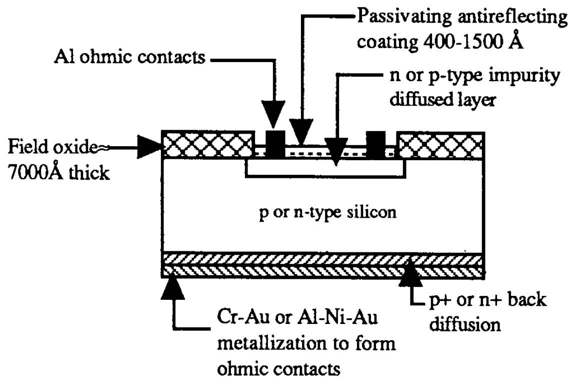

Fig. 1: Schematic of a conventional photodiode

ELECTRO-OPTICAL CHARACTERIZATION

All the photodiodes were characterized at room temperature for shunt and series resistance, dark current, responsivity and photocurrent linearity. The shunt resistance is measured by applying 10 mV DC voltage across the diode in the forward and reverse direction and measuring the corresponding currents. The shunt resistance is then calculated to be 10 mV divided by the average current measured.

Series resistance was measured on a curve tracer by taking the inverse slope of the I-V characteristic at 200 mA. Series resistance was also measured on a few representative diodes from the complete forward I-V characteristics. The series resistance was calculated from the difference between the theoretically extrapolated characteristics and the measured characteristics at high current levels [17]. The difference between these two series resistance methods was found to be less than 15% for pre-neutron devices.

Photodiode responsivity was obtained by spectral response comparison relative to a silicon photodiode standard traceable to the National Institute of Standards and Technology. Details on the responsivity apparatus are given in Reference 10. All the responsivities reported in this work were obtained without any reverse bias across the diode.

The linearity of the photodiodes was measured by the a.c./d.c. method [18]. In this method, the photodiode under test is exposed to small a.c. optical signal from a light emitting diode along with a large variable d.c. optical flux from a tungsten incandescent lamp. The maximum current for which the diode is linear (I_{lin}) is defined to be the d.c. photocurrent value at which the a.c. signal has dropped by 2%.

NEUTRON TEST FACILITY

Neutron irradiation was performed at the IRT Californium-252 neutron facility. Neutrons were provided by four Californium-252 sources having a neutron to gamma ratio of 10^9 neutrons per rad (Si) of gamma radiation. Some devices exposed to neutrons with a gamma shield did not show appreciable differences compared with the devices exposed without a gamma shield. Hence, most of the photodiodes reported in this work were irradiated with neutrons without the gamma shield.

RESULTS AND DISCUSSION

Figure 2 shows the before and after neutron exposure linear plot of the forward I-V characteristic of a photodiode. As seen from this figure, neutron exposure increases the static and dynamic resistance of the diode. The increase in these resistances was found to be a function of the resistivity and type of the starting silicon wafers used to fabricate the photodiodes. The neutron exposure induced increase in the forward voltage drop at a given current for p-type starting wafers was found to be less than that for n-type wafers. The major reason for this increased forward voltage drop is neutron induced decrease in the minority carrier lifetime which causes insufficient conductivity modulation in the diode base region [19].

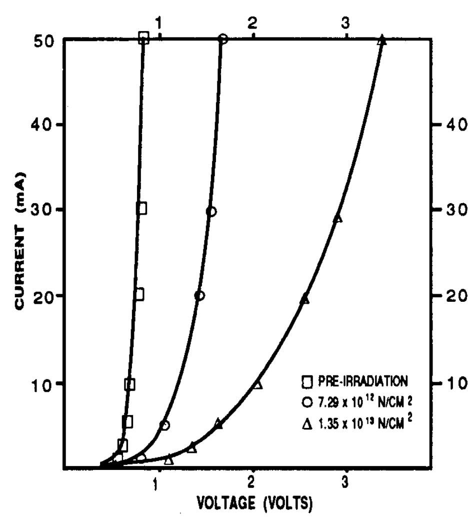

Fig. 2: The effect of neutron exposure on the forward characteristic of photodiode fabricated on 5000 ohm-cm n-type wafers (UDT RD 100)

The I-V characteristics of a photodiode made on 100 ohm-cm p-type wafers is shown in Figure 3. This photodiode (UDT FIL 6230) was found to be the most resistant to all the neutron induced changes observed among non-epitaxial diodes tested. The pre-neutron diode characteristic of Figure 3 obeys the standard p-n junction theory as the diode ideality factor (n) values observed are 1 and 2 for moderate and high currents respectively. The series resistance calculated from this characteristic is 0.75 ohm which compares favorably with the value 0.9 ohm obtained by the direct measurement on the curve traces. This correlation was also observed on the other types of photodiodes (UDT RD100, UDT FIL C10D) before neutron exposure.

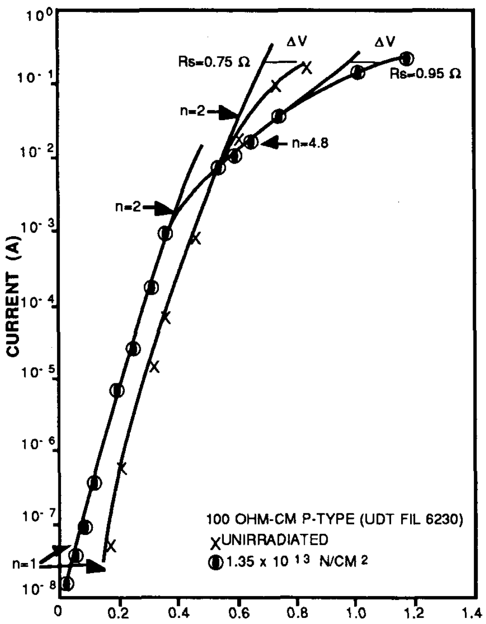

Fig. 3: Forward I-V characteristics of a photodiode showing series resistance calculation and the change in the diode ideality factor with neutron exposure.

However, interpretation of the post-irradiation series resistance measurement from the forward I-V characteristics is not as clear. As seen from Figure 3, the post neutron photodiode does follow the standard p-n junction theory up to moderate current levels with slopes of n=1 and n=2. Series resistance calculated from the difference between the extrapolated n=2 characteristic and the observed characteristic was several times higher than the resistance directly measured on the curve tracer. This discrepancy was also observed on the other photodiodes tested. As seen from Figure 3, the post neutron characteristics may be approximated by a slope of n=4.8 and then a measurement of the series resistance can be made. The value of 0.95 ohms obtained by this method agrees with the value of 1.25 ohms obtained from the direct curve tracer method.

The diode ideality factor greater than 2 has been reported recently for neutron irradiated AlGaAs/GaAs heterojunction bipolar transistors [20]. These investigators attributed the larger value of n to the neutron induced traps causing tunneling assisted trapping and nonuniform distribution of Shockley-Read-Hall recombination levels. In our opinion, the basic recombination mechanism in the post neutron devices is the same as in unirradiated devices because the post neutron devices tested do show n=1, n=2 at moderate current levels. We strongly feel that the ambipolar constants D_a and τ_a are changing with the injection level at high current levels causing the increase in the n value. Further studies are required to verify this hypothesis. Nevertheless, it is important to note here that this increase in n should be incorporated during the post neutron modeling of bipolar devices [21].

The series resistance (R_S) of the photodiodes increases with neutron fluence as shown in Figure 4. The increased series resistance is caused by the increase in bulk resistivity of silicon [22] due to the neutron induced decrease in the dopant density and carrier mobility. This increased bulk resistivity also increases the positioning resistance of a position sensing photodiode as shown in Figure 5.

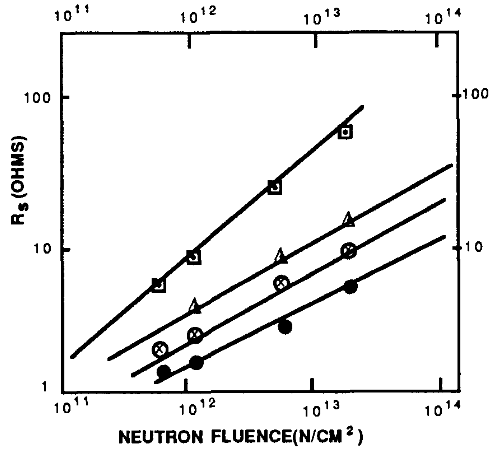

Fig. 4: The effect of neutron exposure on series resistance of photodiodes

- ◘ 400 Ω-cm n-type, position sensing photodiode (Rso=4Ω)
- ⊗ 400 Ω-cm n-type (Rso=2Ω)
- Δ 5000 Ω-cm p-type (Rso=4.4Ω)
- ● 5000 Ω-cm n-type (Rso=1.1Ω)

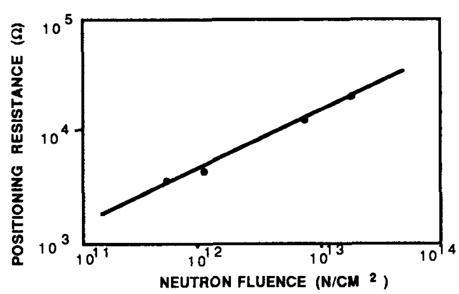

Fig. 5 : Change in the positioning resistance of the position sensing (UDT FIL C10D) photodiode after neutron exposure .

No noticeable series resistance change was observed on the photodiodes made on 10 ohm-cm or lower resistivity wafers. This observation is consistent with the observation of Stofel et al [23], who did not notice any change in the series resistance of solar cells made on p-type 5-10 ohm-cm silicon wafers after neutron exposure.

The post neutron increase in the series resistance of a photodiode causes the current linearity to degrade as shown in Figure 6. The mathematical treatment of the photodiode linearity is quite complex and has been given in Reference 18. From Figure 6, an empirical relation for post neutron linearity may be written as:

$$\Delta I_{lin} = K_l \ \ln (\varnothing/\varnothing_c) \qquad (1)$$

where, ΔI_{lin} is the decrease in the linearity,
K_l is a constant,
$\varnothing$ is the neutron fluence and
$\varnothing_c$ is a critical neutron fluence required to change the device linearity.

It may be concluded from Figure 6 that $\varnothing_c$ and K_l are a function of starting wafer resistivity and type. More the initial linearity of the device smaller would be $\varnothing_c$ and larger would be K_l for a given resistivity and type. Table 1 gives the values of constants $\varnothing_c$ and K_l obtained for various types of diodes. The values of these constants along with equation (1) will be useful to predict the neutron induced changes in the linearity of similar types of photodiodes.

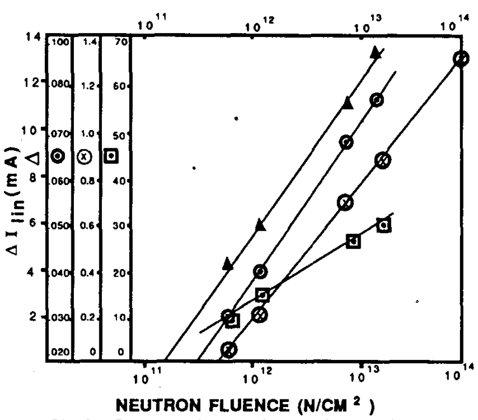

Fig 6: Decrease in the photodiode linearity vs neutron fluence.
▣ p-p+ epitaxial, 25 ohm-cm, I_{lino} =75 mA
▲ 400 ohm-cm n-type (UDT PIN 1223), I_{lino} =14 mA
⊗ 400 ohm-cm n-type (UDT FIL C10D), I_{lino} =80 µA
⊘ 100 ohm-cm n-type (UDT FIL 6230), I_{lino} =1.5 mA

TABLE 1

DIODE TYPE	$\varnothing_c$ (N/CM²)	K_l (mA)
UDT PIN 1223	1.4×10^{11}	2.82
UDT FIL C10D	3×10^{11}	.0146
UDT FIL 6230	4.6×10^{11}	0.252
P-P+ EPITAXIAL	1.4×10^{11}	6.55

It is interesting to note that the changes in the series resistance and decrease in the current linearity were reported earlier for the inversion layer photodiodes after exposure to intense 254 nm UV radiation [10]. To the best of our knowledge, this is the first time that degradation in these parameters has been observed after neutron irradiation.

Figure 7 shows the decrease in shunt resistance (R_{sh}) of photodiodes after neutron exposure. The shunt resistance of a photodiode is determined by the reverse saturation current, I_o of the p-n junction diode. The reverse saturation current for a p-n junction diode is dominated by the thermal generation current and may be expressed as [17]:

$$I_o = q\, A\, n_i\, x_d / 2\tau_g \qquad (2)$$

where, q is an electron charge,
A is the active area of the diode,
n_i is the intrinsic carrier concentration,
τ_g is the effective carrier generation lifetime and
x_d is the depletion region width.

Thus, ΔI_o, the neutron induced change in the reverse saturation current, is proportional to $\Delta(1/\tau_g)$ which is defined as:

$$\Delta \left(\frac{1}{\tau_g}\right) = \frac{1}{\tau_g} - \frac{1}{\tau_{go}} \qquad (3)$$

where, τ_g and τ_{go} are post and pre irradiated effective carrier lifetime values respectively. The neutron induced change in the carrier lifetime has been well studied and is expressed as [5]:

$$\frac{1}{\tau_g} - \frac{1}{\tau_{go}} = K\varnothing \qquad (4)$$

where, K is the damage constant and $\varnothing$ is the neutron fluence.

As $\Delta(1/R_{sh})$ is proportional to ΔI_o one may write,

$$\Delta\left(\frac{1}{R_{sh}}\right)=\frac{1}{R_{sh}}-\frac{1}{R_{sho}}=K_{sh}\,\varnothing \qquad (5)$$

In the above equation R_{sho} and R_{sh} are the pre and post neutron shunt resistance values, and K_{sh} is the shunt resistance damage constant. Table 2 gives the K_{sh} values obtained for various types of photodiodes from Figure 7.

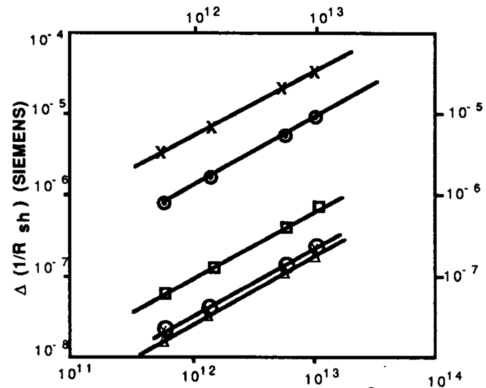

Fig. 7: The effect of neutron exposure on the shunt resistance.
X 5000 ohm-cm n-type (UDT RD100)
◎ 400 ohm-cm n-type (UDT FIL C10D)
◻ 100 ohm-cm p-type (UDT FIL 6230)
⊗ P-P+ epitaxial
Δ 5 ohm-cm p-type

TABLE 2

DIODE TYPE	K_{sh} (cm^2/N-ohm)
UDT RD 100	4.95×10^{-18}
UDT FIL C10D	1.24×10^{-18}
UDT FIL 6230	6.58×10^{-20}
P-P+ EPITAXIAL	2.67×10^{-20}
5 OHM-CM P-TYPE	2.3×10^{-20}

For a p-n junction diode the reverse current will be independent of reverse voltage if avalanching and tunneling effects are absent [17]. Thus, the neutron induced changes in the dark current (reverse current at a specified voltage without any photogeneration) are the same as those in the reverse saturation current. Therefore, ΔI_d, the post neutron change in the dark current, may be written as:

$$\Delta I_d = K_d\,\varnothing \qquad (6)$$

Where K_d is the dark current damage constant. The change in the dark current with neutron fluence has been plotted in Figure 8. From this figure, values of K_d for different types of photodiodes have been obtained and are tabulated in Table 3.

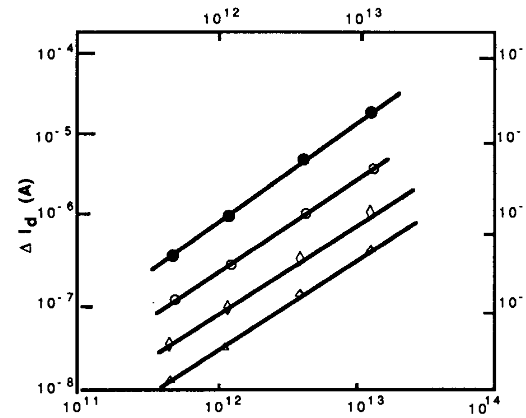

Fig. 8: Increase in the photodiode dark current vs. neutron fluence.
● 5000 ohm-cm n-type (UDT RD100) 100 volts bias
○ 400 ohm-cm n-type (UDT FIL C10D) 25 volts bias
◊ 400 ohm-cm n-type (UDT PIN 1223) 10 volts bias
Δ 100 ohm-cm p-type (UDT FIL 6230) 5 volts bias

TABLE 3

DIODE TYPE	K_d (nA/N)
UDT RD 100	2.05×10^{-9}
UDT FIL C10D	4.08×10^{-10}
UDT PIN 1223	1.65×10^{-10}
UDT FIL 6230	2.38×10^{-11}

Using the model proposed by J.R. Srour et al [24], the generation-lifetime-damage-coefficient value was calculated and was found to be 5.8×10^{-8} cm^2/N-sec for the RD 100 photodiodes which are fabricated on 0.355 mm thick, 5000 ohm-cm, n-type silicon wafers. This value is about 1.5 times better than the damage coefficient values reported by Srour et al [24].

The post exposure change in the responsivity of photodiodes has been known for a long time, and has been well documented [4,8,9]. However, there exists considerable discrepancy in the change in responsivity with neutron fluence. For example, Figure 9 shows the normalized responsivity at 940 nm as a function of neutron fluence for photodiodes made on 400 ohm-cm n-type wafers by United Detector Technology. It is extremely difficult to explain the large responsivity drop of UDT PIN 020 as reported in Ref. 8. The smaller post neutron responsivity change in UDT PIN 5D is due to a large applied reverse bias which widens the depletion region in the bulk silicon making the neutron induced minority carrier lifetime reduction less important.

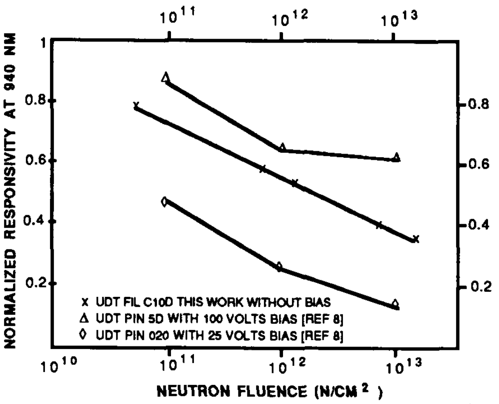

Fig. 9: The effect of neutron fluence on the 940 nm normalized responsivity of photodiodes fabricated on 400 ohm-cm n-type silicon

Figure 10 shows the effect of neutron exposure on the 632.8 nm responsivity of several photodiodes. As evident from Figures 9 and 10 the neutron induced responsivity change at shorter wavelengths is not as severe as that occuring at larger wavelengths. The shorter the wavelength of light, the less is the penetration depth of photons in silicon, making the effect of the minority carrier lifetime reduction less important. As evident from Figure 10, diodes fabricated on epitaxial wafers show less degradation of responsivity after neutron exposure. This happens because of the lower initial diffusion length in epitaxial materials which is controlled by the epitaxial layer thickness. Also note that photodiodes fabricated on p-type silicon have less neutron induced responsivity change compared to the diodes fabricated on n-type silicon. This is a direct result of the lower minority carrier lifetime damage constant of p-type silicon [5].

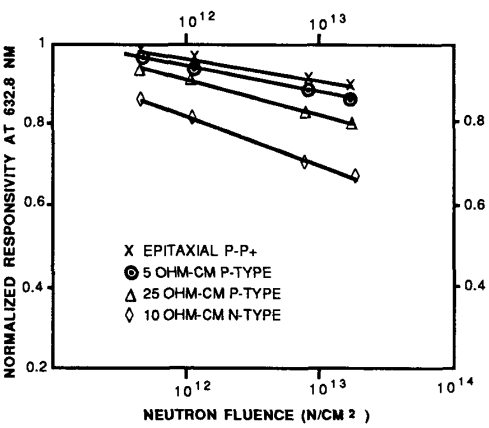

Fig. 10: The effect of neutron irradiation on normalized 632.8 nm responsivity

Figure 11 supports the well known interpretation that the neutron induced changes occur only in the bulk of the semi-conductor. Both types of devices characterized in Figure 11 are known to have no recombination in the front region [10,13]. As no change in responsivity was observed on these devices after exposure to 2 x 10^{13} neutrons, this suggests that the surface recombination velocity remains unaffected by the neutron exposure to this level.

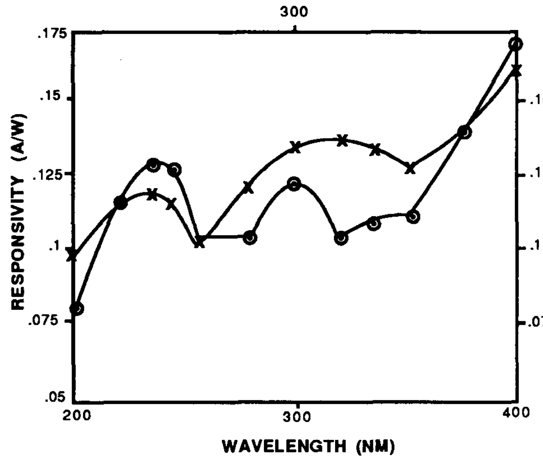

Fig. 11: Typical pre and post neutron (2x10^{13} neutrons) irradiated responsivity plots of n on p photodiodes with no recombination in the front region
⊚ Inversion layer photodiode, 1200Å SiO_2 (UDT FIL UV100)
X Phosphorus diffused photodiode, 400Å SiO_2 (UDT FIL 6230)

CONCLUSIONS

Neutron induced bulk resistivity changes were found to increase the series resistance of photodiodes fabricated on 20 ohm-cm or larger resistivity starting wafers. This change in the bulk resistivity of wafers increases the positioning resistance of a position sensing photodiode. A post neutron diode ideality factor much greater than 2 has been observed which probably has been caused by the variation of the ambipolar constants D_a and τ_a with injection level in the neutron irradiated silicon. The observed post neutron increase in diode voltage drop is caused mainly by insufficient conductivity modulation of the diode base region owing to the decreased minority carrier lifetime. Neutron induced changes in the photodiode linearity have been reported for the first time, and an empirical expression to model these changes has been provided. Simple mathematical equations are derived to explain the post neutron behavior of photodiode shunt resistance and dark current. From the observed post neutron characteristics, damage constants required in these expressions are obtained. The values of these damage constants along with their appropriate expressions are extremely useful in predicting neutron induced changes in the current linearity, shunt resistance and dark current of similar types of photodiodes. The generation lifetime damage constant obtained for 5000 ohm-cm n-type silicon was found to be 1.5 times better than the damage constant reported in the literature. No surface induced changes were observed in the 100% internal UV quantum efficiency photodiodes after neutron irradiation.

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