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CHANGES IN ELECTRICAL PROPERTIES OF HIGH RESISTIVITY SILICON CAUSED BY FAST NEUTRON DAMAGE*

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P^+-n^--n^+ silicon radiation detectors made of high resistivity Si material ($\rho \geq 2$ kΩ-cm) were irradiated to a neutron fluence of a few times of 10^{13} n/cm^2. Dependence of detector leakage current, reverse bias capacitance, and effective doping concentration of the Si substrate on the neutron fluence have been systematically studied. Models using several defect levels in the band gap describing the frequency dependent C-V effect and electrical field profile at high neutron fluence ($\phi_n > 10^{13}$ n/cm^2) are proposed in this study.

INTRODUCTION

High resistivity silicon materials are widely used in high energy physics community as radiation and particle detectors. The most common detector configuration is the p^+-n^--n^+ implanted junction diode device. For a 300 μm thick detector fully depleted at a reverse bias between 30 V to 150 V, the resistivity of the n-type Si must be between 2 k to 10 k Ω-cm, which leads to a net doping concentration of less than 2×10^{12}/cm^3. Displacement damage caused by fast neutron (E > 100 keV) radiation has been a major concern for high resistivity silicon detectors working in a high radiation environment anticipated for the Superconducting Super Collider (SSC) and the Large Hadron Collider (LHC), where the annual fluence of fast neutrons can be as high as 10^{13} n/cm^2. At this neutron fluence, concentrations of various defects in the band gap can be close to or exceed the net doping concentration, causing problems unexpected in low resistivity silicon materials. In this work, effects of fast neutron radiation (up to the fluence of a few times of 10^{13} n/cm^2) on the electrical properties of high resistivity silicon detectors, such as leakage current, capacitance-voltage (C-V) characteristics, and possible type inversion (n→p) have been systematically studied.

EXPERIMENTAL

Fast neutrons from 10 keV to 2.2 MeV with $\bar{E}$ = 1 MeV were obtained from the ^{7}Li(p,n) reaction using 4 MeV protons from a van de Graaff accelerator at the University of Lowell. The p^+-n^--n^+ ion-implant junction detectors used in this study were made on n-type <111> Si wafers, with resistivities ranging from 2 kΩ-cm to 10 kΩ-cm. A multi-frequency HP 4192 LF Impedance Analyzer was used for capacitance-voltage (C-V) measurements at various frequencies. All C-V measurements were performed with the HP 4192 LF Impedance Analyzer in a series mode to take into account the high series resistance ($R_s \geq 1$ kΩ).

Keywords: Neutron radiation damage, radiation detector, high resistivity silicon, frequency-dependent capacitance, donor removal and/or compensation, type-inversion, electrical field distribution

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RESULTS AND DISCUSSIONS

The detector leakage current (I) has been found to increase linearly with the neutron fluence ϕ_n up to 10^{14} n/cm^2 due to degradation of minority carrier lifetime. A damage coefficient α, defined as $\Delta I = \alpha V \phi_n$ with V being the depleted volume and ϕ_n being the neutron fluence (n/cm^2), can be determined from experimental data. Data shown in Fig. 1 result in $\alpha = 9.48 \times 10^{-17}$ A/cm at 24°C. A consensus value of $\alpha = 8 \times 10^{-17}$ A/cm is realized for 20°C and 1 MeV kerma corrected.

For detectors irradiated to high neutron fluence ($\phi_n > 10^{12}$/cm^2), the C-V characteristics become frequency dependent as it is shown in Fig. 2. A model using two acceptor-like trap levels shown in Fig. 3 is developed to describe the frequency dependence and dopant compensation effects.[1] In this model, the effective doping density, N_{eff}, is compensated by the somewhat shallow acceptor-like level E_{t2}, i.e.,

$$N_{eff} = N_D^0 - N_A^0 - N_{t2} \quad \text{with} \quad N_{t2} = \gamma \phi_n \tag{1}$$

where γ is the introductory rate of N_{t2}.

In reality, donor removal due to the formation of E-center, P-V (phosphorus-vacancy complex), that removes the phosphorus from the substitution site is very important. Equation (1) therefore can be modified as

$$N_{eff} = N_D^0 e^{-\beta\phi n} - N_A^0 - \gamma\phi_n \tag{2}$$

where β is the donor removal rate. Figure 4 shows C(ω, V) curves calculated from the model. A good agreement between the experiment data and calculation is illustrated in Fig. 5.

When the neutron fluence ϕ_n is close to or greater than 10^{13} n/cm^2, the defect concentrations can be close to or exceed the dopant concentration (10^{12}/cm^3). This could lead to so called *type-inversion* (n$^-$→p) and possibly cause a basic structural change in the detector. This change of type could make some detector configurations, such as the silicon drift chamber detector that uses a potential well created by a p$^+$-n-p$^+$ structure to collect electrons, not workable.

Type inversion, however, has now become an interesting but complicated problem. Contradictory conclusions have been reached by different groups based on different measurements. In this work, MOS capacitor techniques and back-to-back diode techniques have been used. Figure 6 shows the C-V characteristics of MOS capacitors with n-type Si substrate under various fluence of neutron radiations. It is clear that up to the neutron fluence of 2.15×10^{13} n/cm^2, the MOS capacitor still exhibits the characteristics of a n-type Si substrate, suggesting no type-inversion. The decrease of C_{ox} at high frequency is caused by the increase of R_s with neutron radiation. The increase of C_{min} at f = 10 kHZ, on the other hand, is due to the decrease in response time of the minority carrier τ_R with neutron radiation, which is in turn related to minority carrier lifetime τ_p as in the following [2]:

$$\tau_R = \frac{1}{\sqrt{2}} \left(\frac{N_D}{n_i} \right) \left(\tau_{Tn}\, \tau_{Tp} \right)^{1/2} \left(1 - \frac{v_1}{U_B} \right)^{1/2} \tag{3}$$

Since the transition frequency for minority carrier to response to the measurement is proportional to $1/\tau_R$, i.e.:

$$f_t \propto \frac{1}{\tau_R} \quad (4)$$

One would expect f_t to go up with the neutron fluence as it is shown in Fig. 6.

Back-to-back diode I-V characteristics shown in Figs. 7 and 8 also indicate that the junction is still in the front, i.e., still p^+-n junction for the neutron fluence to above 1.2×10^{13} n/cm^2.

However, Lindstroem et al., [3], using an α-source that has a range of 20 μm in Si, have found in their charge collection experiments that more charge has been collected when the α-source was placed in the back of the detector than that when the α-source was placed in the front when a high resistivity ($\rho \geq 5$ kΩ-cm) p^+-n^--n^+ detector was irradiated to above 8×10^{12} n/cm^2. This result indicates more electrical field in the back than that in the front and a shift of junction from front to back or type-inversion was suggested. Our data of α-particle induced current pulse (*I(t)*) measurement on detectors irradiated also to above 1×10^{13} n/cm^2 also show high field on the back of the detector. However, a similar high field has also shown existed on the front side, indicating junctions may be on both front and back side of the detector but with only less than half of the charge collected (see Fig. 9). Our resistivity data (Fig. 10) through series resistance (R_s) value of the C-V measurement show that detector substrate resistivity saturates between 6×10^{12} to 1.5×10^{13} n/cm^2 indicating an intrinsic or near intrinsic bulk instead of inversion. Data of our measurement of resistivity on a $n^+/n/n^+$ resistor also show the resistivity saturates at a value of 255 kΩ-cm at $\sim 1.5 \times 10^{13}$ n/cm^2. Based on these observations, a model of $p^+/n/i/p/n^+$ structure is proposed in this study. As it is shown in Fig. 11, a donor-like level(s) on the n-side and an acceptor-like level(s) on the p-side are controlling the band bending and therefore the field in the structure with little or no E-field in the bulk. Free carriers created by α-particle travel in the E-field and get trapped by shallow traps in the low or no E-field bulk before being collected. This model can explain the MOS C-V data, back-to-back diode data and α-source results.

In conclusion, changes of electrical properties of high resistivity Si detectors due to fast neutron radiation have been found total-dose dependent. At low doses, $\phi_n < 10^{12}$ n/cm^2, the Shockley-Read-Hall generation and recombination process via various defect levels is the dominant mechanism that contributes to the increase of detector leakage current (or decrease of minority carrier lifetime). At intermediate dose, 10^{12} n/cm$^2 \leq \phi_n < 10^{13}$ n/cm^2, donor-removal becomes important and concentrations of acceptor-like defect levels are high enough to affect detector C-V characteristics. At high dose, $\phi_n \geq 10^{13}$ n/cm^2, the Si bulk may become intrinsic or near intrinsic and donor-like defect level(s) and acceptor-like defect level(s) may become dominant to control the electrical field in the front side and back side of the detector, respectively. There is no clear evidence, however, for classic type-inversion or non-inversions. More work is needed to resolve this problem.

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2. E. H. Nicollian and J. R. Brews, *MOS (Metal Oxide Semiconductor) Physics and Technology*, (John Wiley & Sons, New York), p. 144 (1982).
3. G. Lindstroem, et al., Presented at the Intl. Conf. on Calorimetry in High Energy Physics, (World Scientific Publ. Co., Singapore), in press.

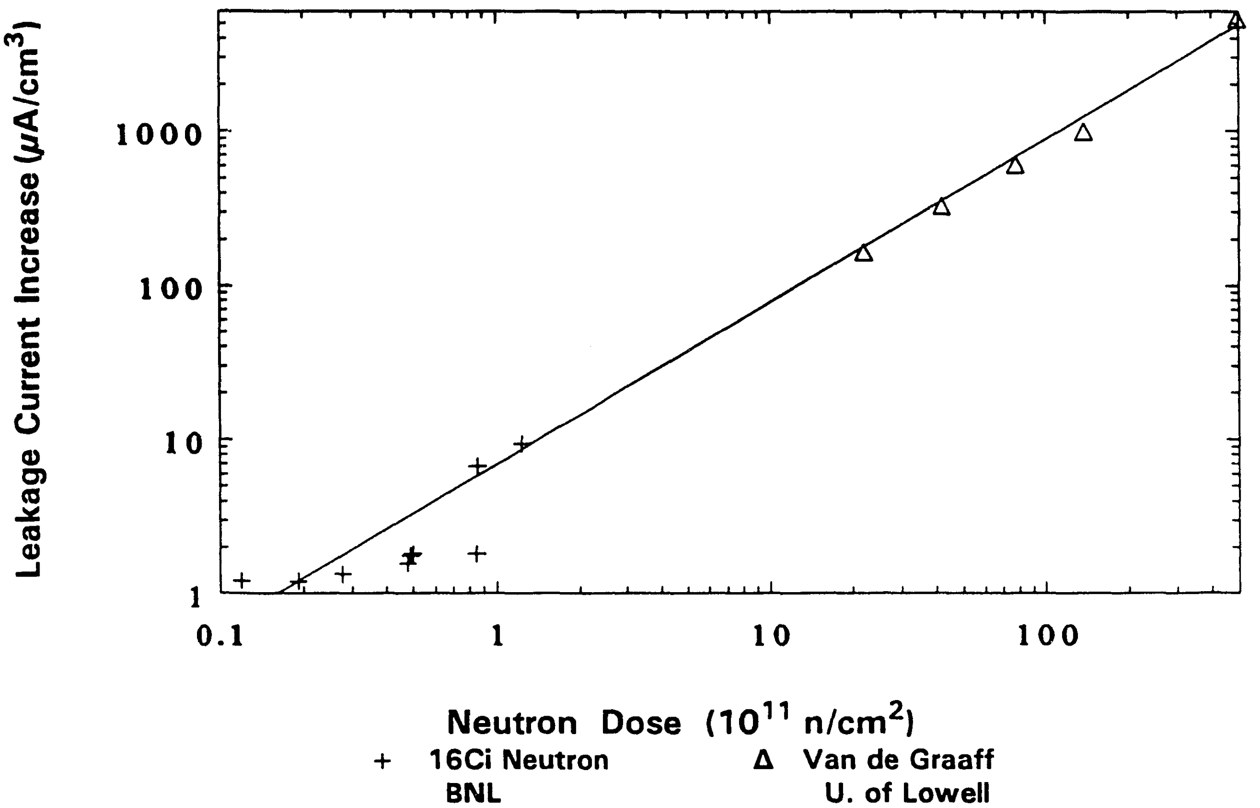
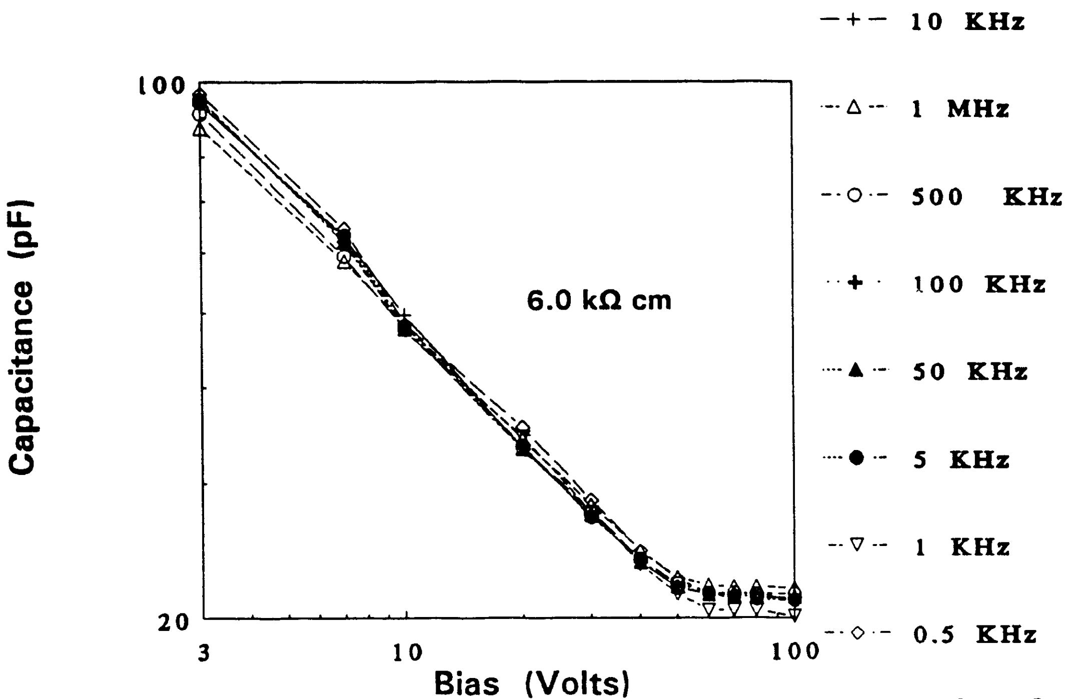
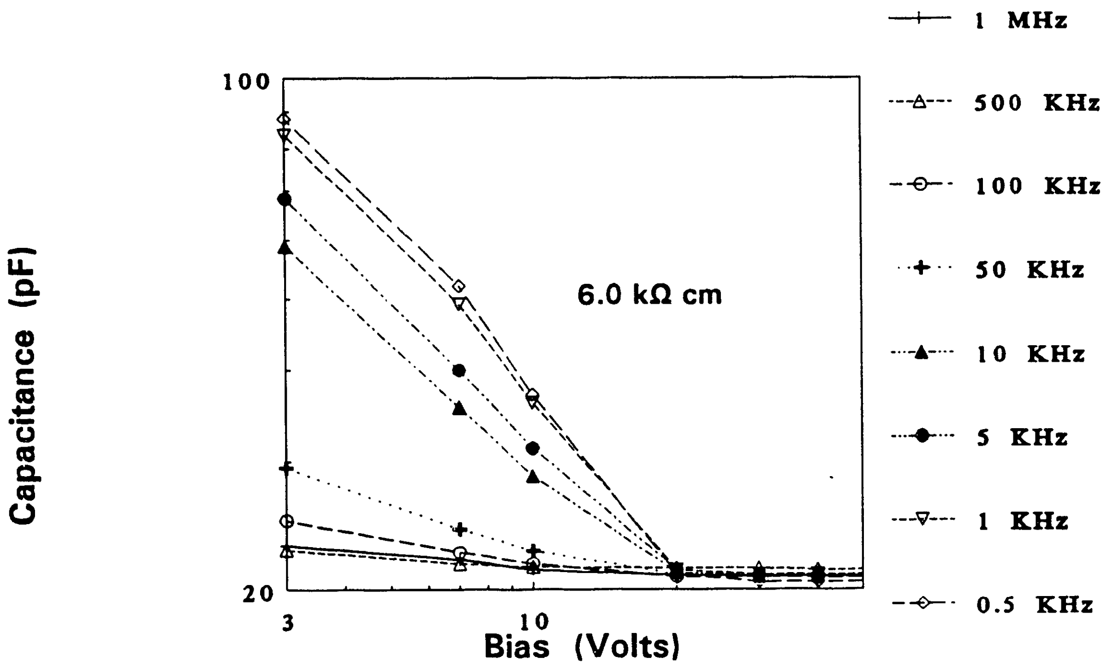


Fig. 1. Increase of detector volume leakage current with fast neutron fluence up to 5×10^{13} n/cm^2. A linear fit is also shown.



a) Neutron irradiated to the fluence of $7.0 \times 10^{10}/cm^2$



b) Neutron irradiated to the fluence of $7.8 \times 10^{12}/cm^2$

Fig. 2. Detector C-V characteristics at various frequencies of detectors irradiated to the neutron fluence of a) $7.0 \times 10^{10}/cm^2$; and b) $7.8 \times 10^{12}/cm^2$.

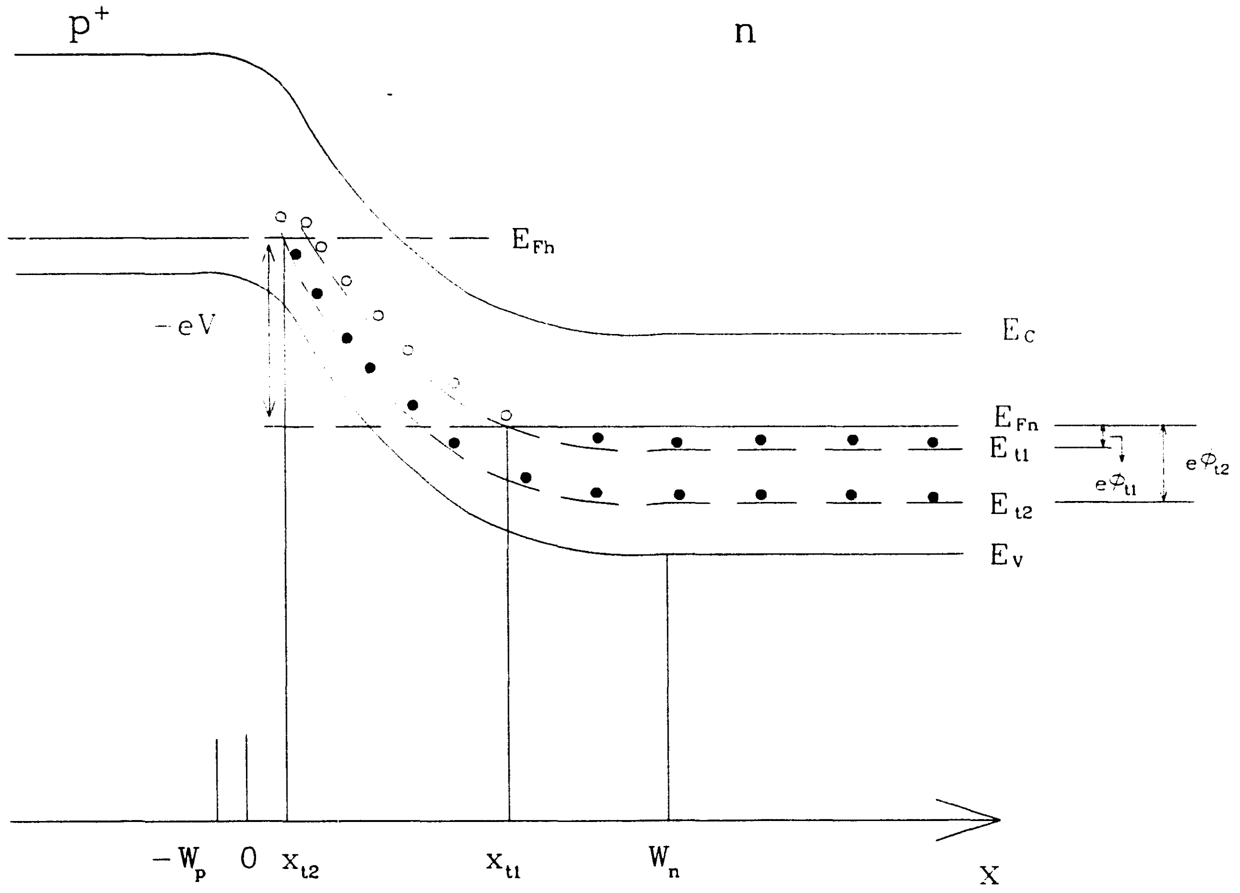
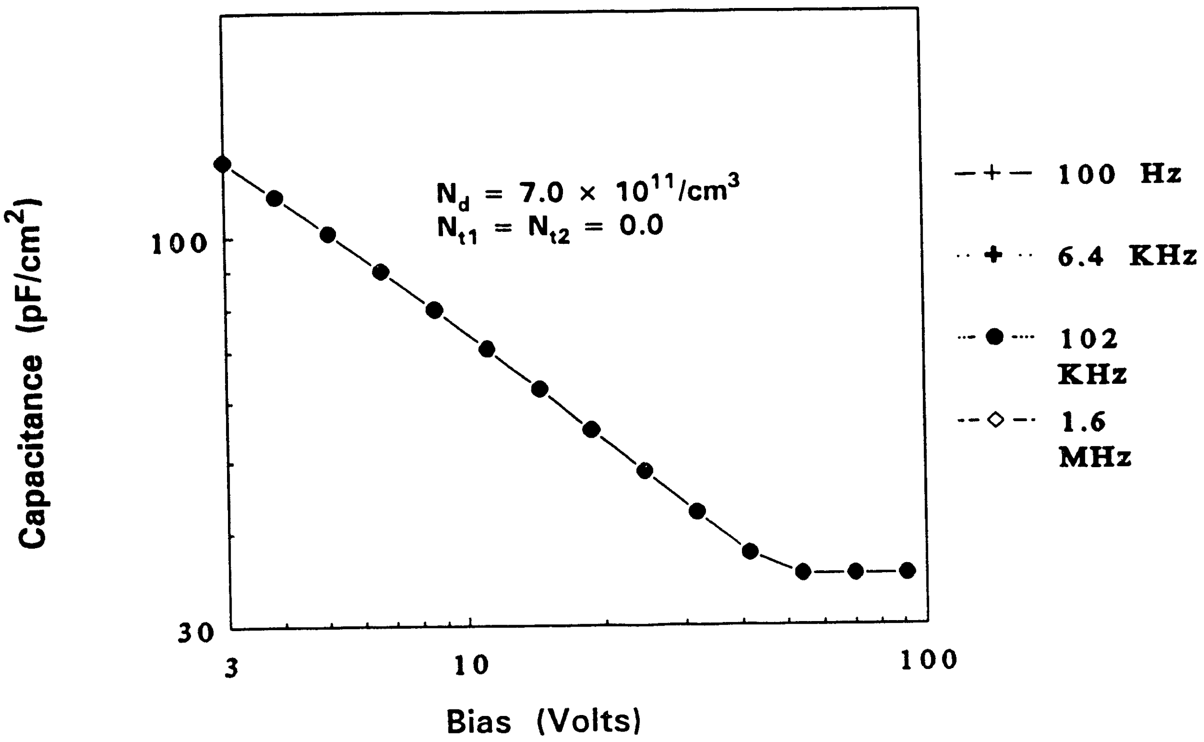
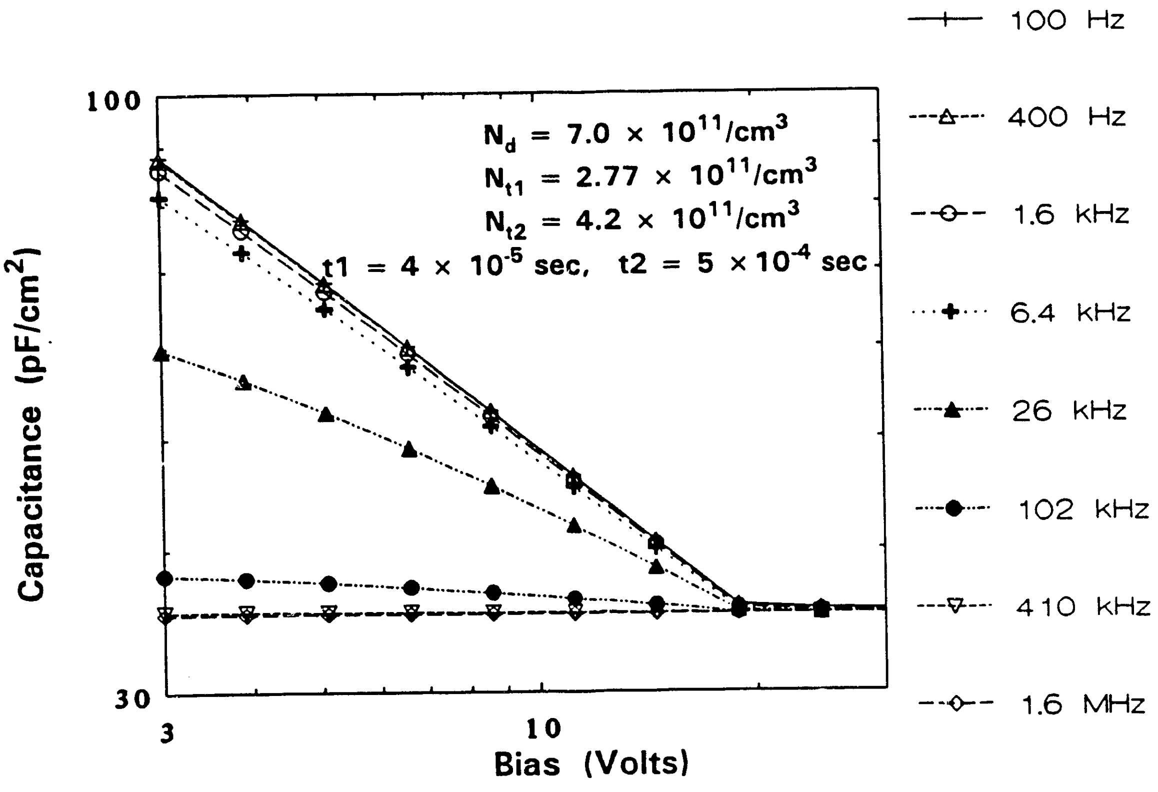


Fig. 3. **Energy band diagram for the proposed two-level model describing the observed frequency-dependent C-V effects.**



a) No defect (control)



b) With defects

Fig. 4. Calculated frequency-dependent C-V characteristics with a) No defects (control); and b) two defect levels.

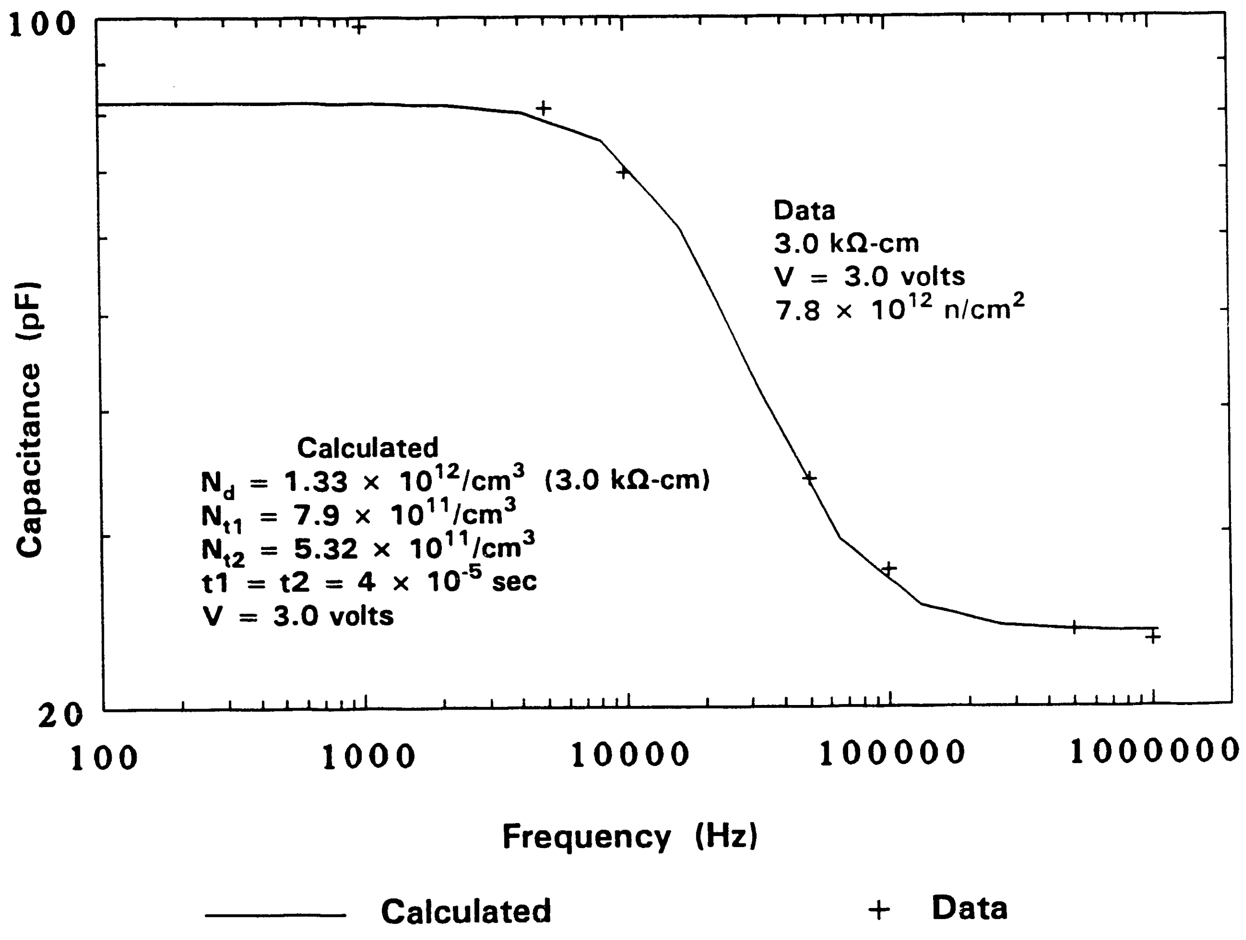


Fig. 5. Comparison between calculated and measured C-*f* data.

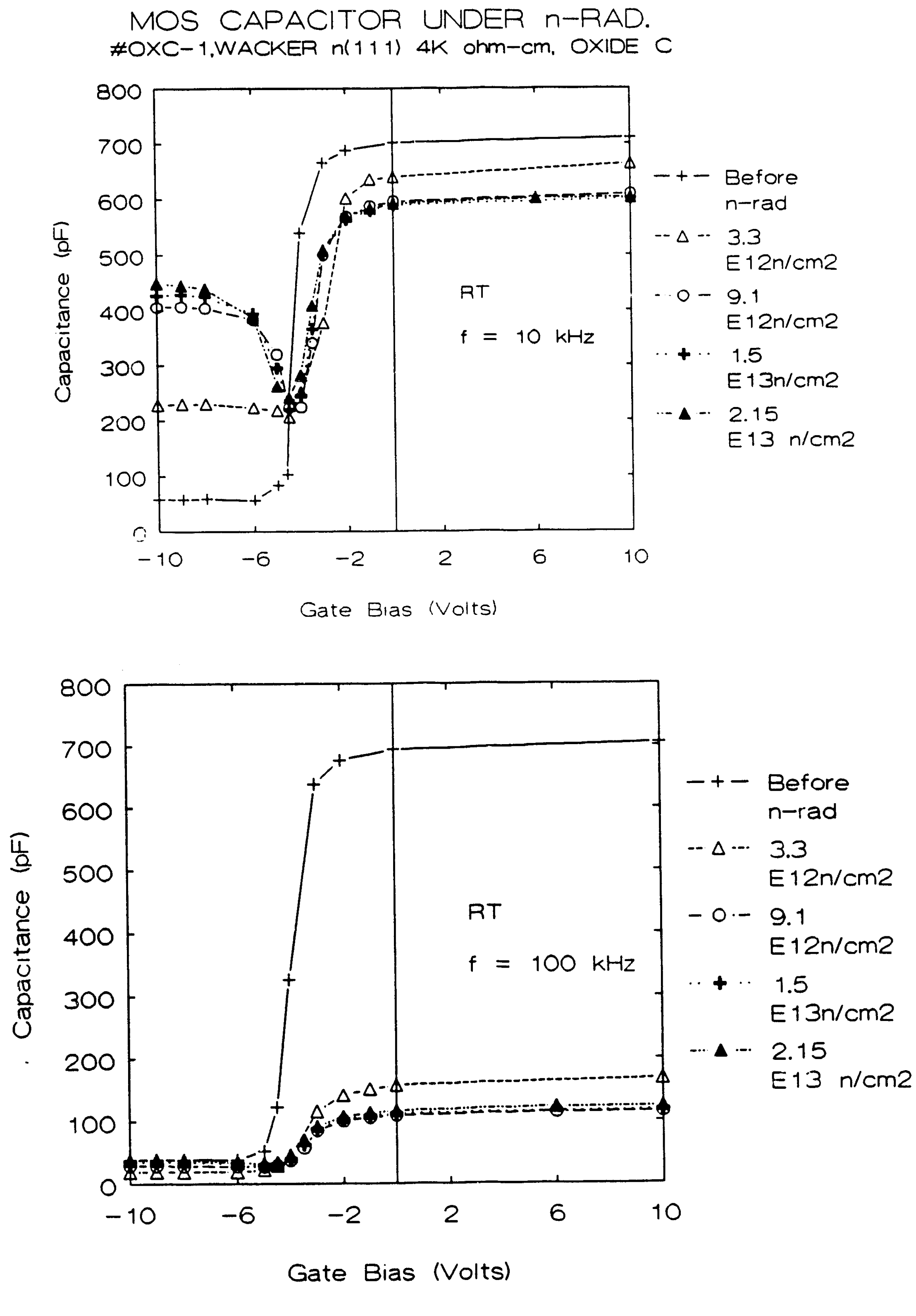


Fig. 6. **C-V characteristics of an Al/SiO_2/n-Si MOS capacitor after consecutive neutron radiations up to 2×10^{13} n/cm^2. SiO_2 here is OXC (Oxide C (1100°)).**

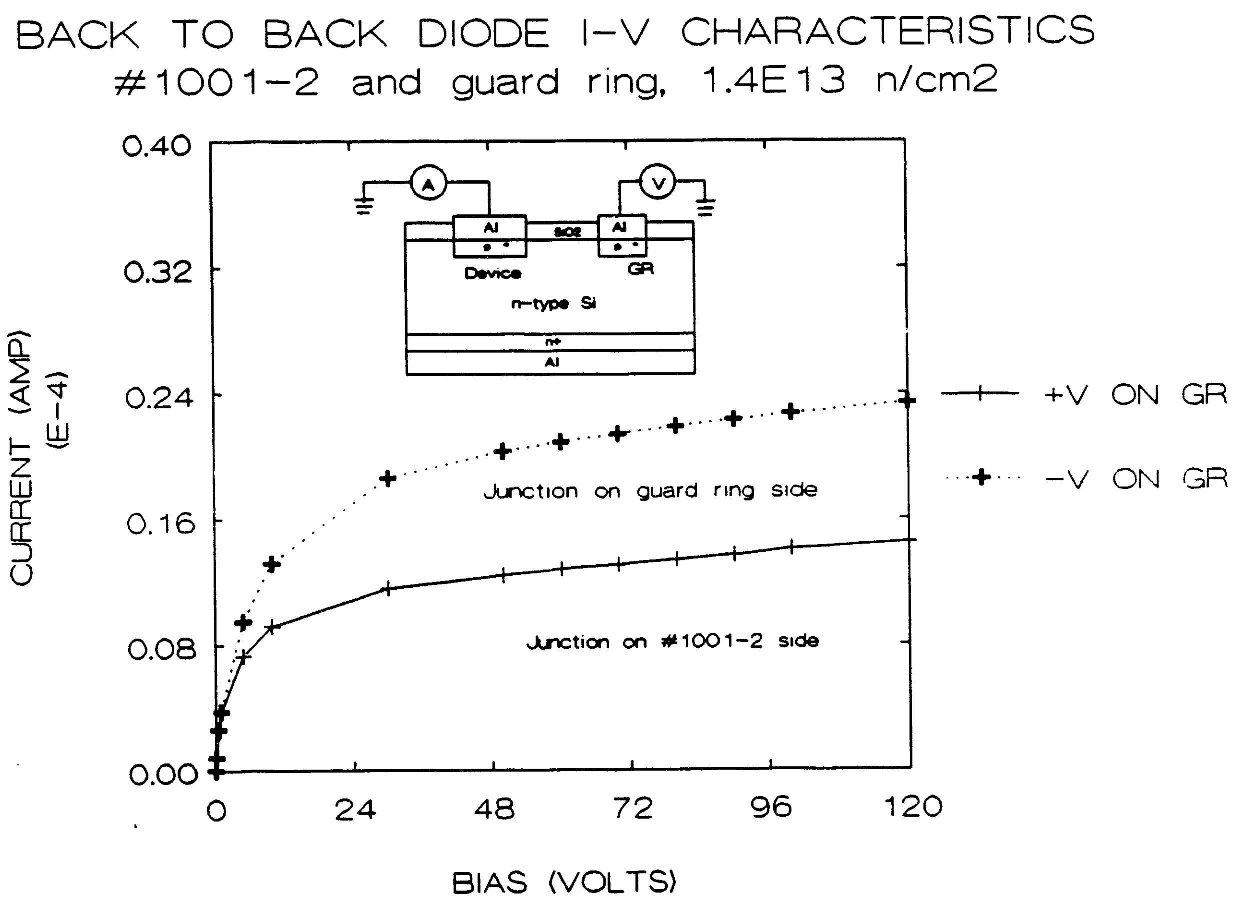


Fig. 7. I-V characteristics of the back-to-back diode configuration after n-radiation. Detectors are made on OXC (Oxide C (1100°C)).

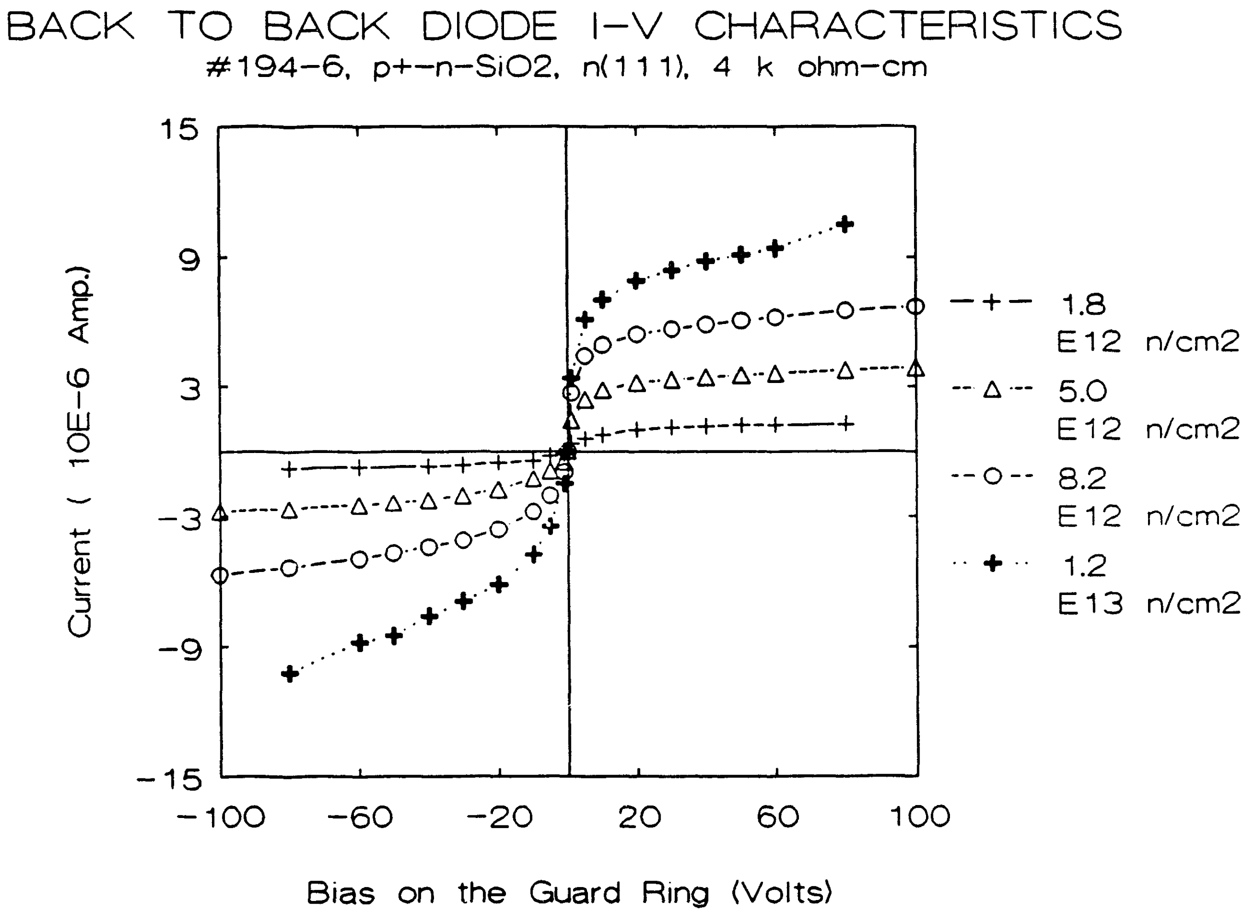


Fig. 8. I-V characteristics of the back-to-back diode configuration with SiO_2 on the back side after n-radiation. Detectors are made on OXC (Oxide C (1100°C)).

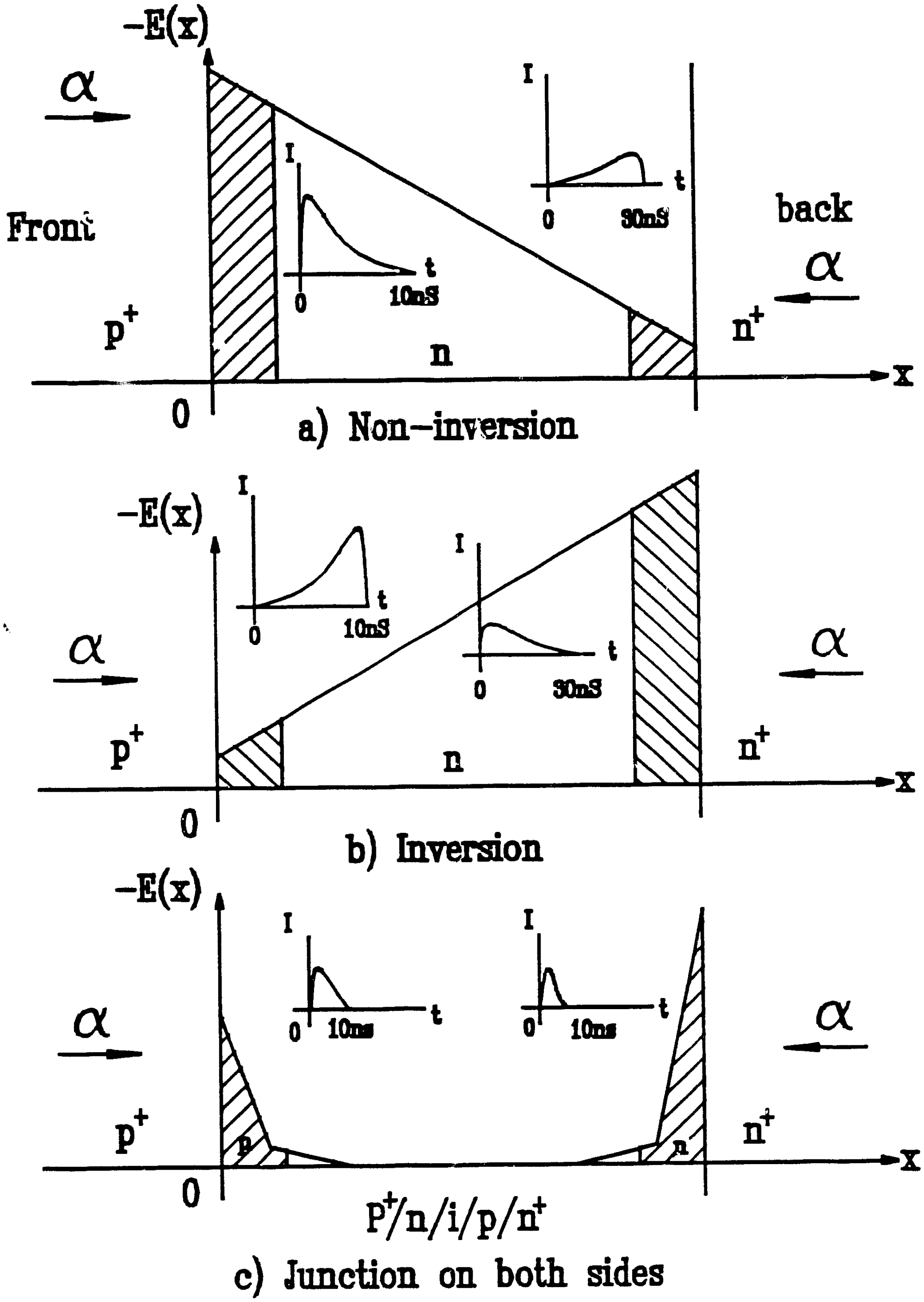


Fig. 9. Schematic of the electrical field profiles in the Si detector for three different configurations. Corresponding current pulses respond to α-particle on the front and back of the detector are also shown.

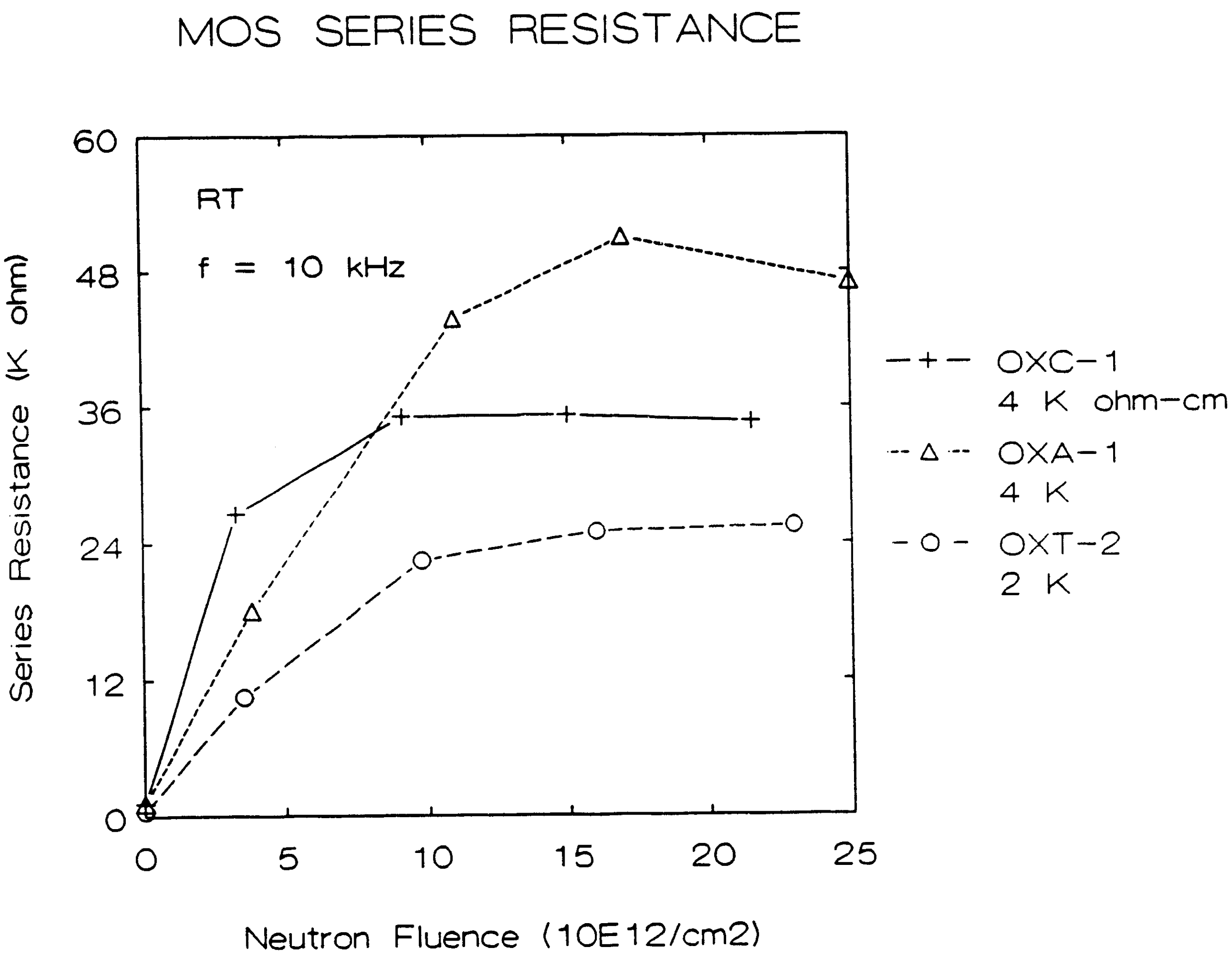


Fig. 10. **Series resistance R_s of MOS capacitors measurement as a function of neutron fluence.**

$$V_A = V_{An} + V_{Ap}$$

N_{TD}, E_{TD} : Donor type traps

N_{TA}, E_{TA} : Acceptor type traps

$$N = p \cong n_i = 1.0 \times 10^{10}/cm^3$$

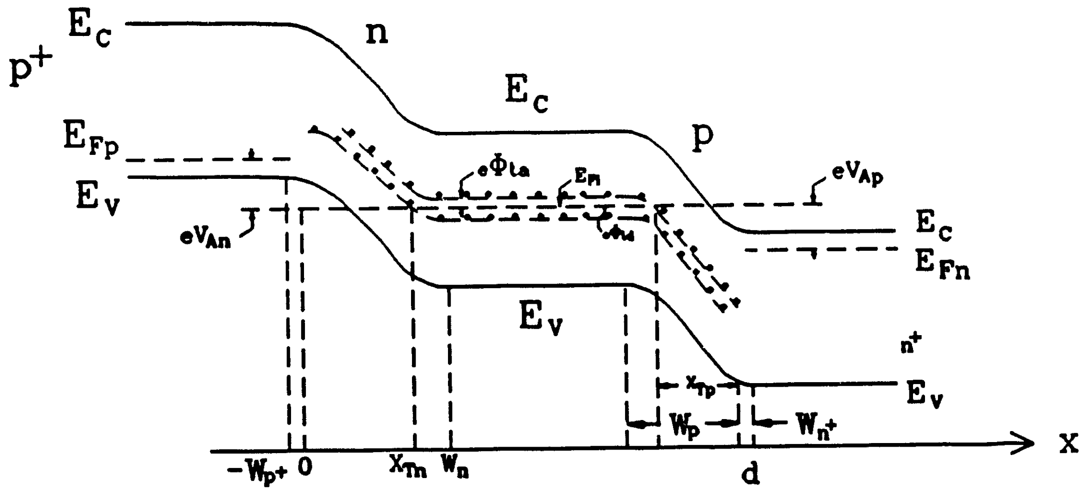


Fig. 11. Proposed p^+-p-i-n-n^+ band diagram for a detector irradiated to high neutron fluence ($\phi_n \geq 10^{13}$ n/cm^2).

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