Current-Voltage and Impedance Characteristics of Neutron Irradiated Silicon Detectors at Fluences Up To 10^{16} n/cm^2

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Abstract

The effect of neutron irradiation at very high fluences up to $\phi \sim 10^{16} \text{ n/cm}^2$ on the rectifying properties of silicon high energy detectors was studied. It was shown that at critical fluences, $\phi_{c1} \sim 10^{12} - 10^{13} \text{ n/cm}^2$ and $\phi_{c2} \sim 1.2 \times 10^{14} \text{ n/cm}^2$, abrupt changes of the forward current, rectifying factor and other parameters, appear. Measurements of impedance (Z) as a function of frequency (f) show that, after strong irradiation, the real and imaginary part of Z and losses depend on f . They may be related to a decrease of lifetime of free carriers, due to traps caused by high irradiation.

1. Introduction

Lowly doped ($5 \times 10^{11} < N_D < 10^{12} \text{ cm}^{-3}$) silicon detectors, Schottky or $p^+ - n - n^+$ type diodes, are an important tool in high-energy physics experiments. The main advantages of these detectors are: a) they withstand fluences (ϕ) of particles (mainly neutrons) and b) they can easily be integrated in overall electronic circuits, employed in collider experiments. For ϕ up to $10^{12} - 10^{13} \text{ n/cm}^2 = \phi_{c1}$, where ϕ_{c1} is a critical fluence, no significant detector damages are observed and, therefore, the detector is suitable for collider experiments. Measurements of I-V, C-V, and DLTS were performed and the data have shown negligible irradiation effects [1-4], for $\phi < \phi_{c1}$. For $\phi > \phi_{c1}$, the radiation damage causes abrupt changes of the reverse bias leakage current. The leakage current, which appears in the reverse biased ($I_r - V_r$) characteristics, makes DLTS and C-V measurements unreliable.

The $I_f - V_f$ characteristics, with only limited investigation in literature [5], could lead to the understanding of radiation damage factors. In our earlier paper [4], the forward bias characteristics ($I_f - V_f$) were measured and a contribution to the better understanding of the changes of the silicon parameters (resistivity, lifetime of carriers, diffusion length) due to the radiation damage was obtained. It was shown that the rectification ratio of the detector ($Rec = I_f/V_f$ at V_{fmax} diminished from $Rec = 10^4$ for a non irradiated detector, to $Rec = 30$ at $\phi \simeq 10^{14} \text{ n/cm}^2$. The detector resistance, R , increased about 40 times for $\phi \simeq 10^{14} \text{ n/cm}^2$, as compared with R , for nonirradiated ones. As a consequence, the $p^+ - n - n^+$

device behaves as a $p^+ - \nu - n^+$ (ν - near intrinsic n) one. From these measurements, the diffusion length was calculated. The decrease of the rectification factor (Rec) and the increase of resistance R , obtained from $I_f - V_f$, indicated that significant damage appeared. But, from these results, it was not obvious if at higher fluences ($\phi > 10^{14} \text{ n/cm}^2$), the process of damaging continues up to complete damage $Rec = 1$ or it is stopped at $Rec > 1$.

In this paper new data of I-V characteristics of silicon detectors for higher neutron fluences $10^{14} < \phi < 10^{16} \text{ n/cm}^2$ were obtained and the changes of the physical parameters of the Si and the detector junction, analyzed.

2. Experiments, Results and Discussions

The detectors of the $p^+ - n - n^+$ type were made of single crystal silicon, of resistivity $4 - 6 \text{ k}\Omega$. The p^+ and the n^+ doping was made by implanting boron and phosphorous impurities, respectively. The wafers of $400 \mu\text{m}$ thickness were of the FZ type, cut in the (111) direction. For the electrical measurements of the I-V characteristics and impedance (Z) an H-P system was used. The irradiation was performed at the Triga reactor RC/1 of the National Organization for Alternative Energy (ENEA) at Casaccia, Rome. The energy range of the reactor is between 24.8 keV and 10 MeV, with a mean energy of 0.885 MeV and a flux of $6.475 \times 10^{11} \text{ n/cm}^2\text{s}$. In less than four hours, a fluence of about 10^{16} n/cm^2 was obtained, when the reactor worked at 1 MW.

In Fig. 1, I_f as a function of V_f , for fluences $1.2 \times 10^{12} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$, is shown. It can be seen that the $I_f - V_f$ characteristics, for ϕ between 5.9×10^{14} and $8.9 \times 10^{15} \text{ n/cm}^2$ are different than that for $\phi_{c1} < 1.2 \times 10^{14} \text{ n/cm}^2$. This indicates that, in addition to the drop of conductivity (I/V) due to irradiation [4], at the first critical ϕ_{c1} (between 10^{12} and 10^{13} n/cm^2) at the second critical fluence (ϕ_{c2}), (larger than $1.2 \times 10^{14} \text{ n/cm}^2$), another drop appears, which changes not only the value of the current at the same V , but also the shape (the exponential type of dependence). This seems to indicate that after a strong reduction of rectification of the detector a new type of damage is being induced, which does not continue too much to decrease the rectification. The analyses of these last strongly modified curves have shown that, at higher voltages, a linear shape of dependence of I_f , as a function of V_f , appears.

Fig. 1: $I_f - V_f$ characteristics of Si detectors, irradiated at fluences of $1.2 \times 10^{12} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$.

In Fig. 2, this linear part Eq. (1), for the three highest fluences ϕ of $(1.2, 4.2, \text{ and } 8.9) \times 10^{15} \text{ n/cm}^2$ is shown. From Eq. (1), the value of resistance R_f can be defined as $1/\text{slope}$ of the straight line of Eq. (1):

$$R_f = 1/\alpha \quad (2)$$

For $V = 0$, $I_f(0) = \beta$ is obtained, which should be zero, when the detector is not rectifying anymore, behaving as an ohmic material. If $V = V_{f0}$, is the minimum value V on the straight line, Eq. (1), and

$$\alpha \cdot V_{f0} \gg \beta \quad (3)$$

β can be neglected in Eq. (1).

Thus, the detector behaves nearly as an ohmic

material.

Fig. 2: $I_f - V_f$ characteristics of Si detectors, irradiated at fluences $1.2 \times 10^{15} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$.

In Figs. 3a and 3b, β and α as a function of ϕ , respectively, were drawn. In Fig. 3a, the value β varies between $(1.0 \text{ to } 1.7) \times 10^{-4} \text{ A}$, smaller than $\alpha V_{f0} = 3.75 \times 10^{-4} \text{ A}$, but not negligible. This indicates that the device maintains a certain rectification, even at the highest used fluence. Since the variations of β and α are very small and taking into account that $\alpha \sim 1/R_f$, the average resistance was calculated ($R_f = 4.5 \times 10^4 \Omega$). This value corresponds to a resistivity of $\sim 2.8 \times 10^5 \Omega \text{ cm}$, which is almost equal to the intrinsic resistivity ($\rho_i = 2.55 \times 10^5 \Omega \text{ cm}$).

Fig. 3a: Values of β from relation (1) versus fluences $1.2 \times 10^{15} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$.

Fig. 3b: Values of α from relation (1) versus fluences $1.2 \times 10^{15} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$.

The reverse biased characteristics of the dependence of current I_r as a function of voltage V_r were also measured and drawn for fluences $10^{13} < \phi < 10^{16} \text{ n/cm}^2$. Unlike the characteristics measured for $\phi < 10^{13} \text{ n/cm}^2$ [4], for these high fluences, an important leakage current appeared which, for sufficient applied bias (200 – 300V), reach the value of the forward current. Same as in the forward bias case, at a large applied reverse voltage, a linear dependence of the I_r on V_r , but with a different slope and intersection with the I_r axis, was found:

$$I_r = aV_r + b \quad (4)$$

where $a = 1/R_r$ (R_r is the reverse resistance) and for $V_r = 0, b = I_r$. The values R_f and R_r were obtained from the measured forward and reverse currents and employing Eqs. (1), (2), and (4) for several fluences at which the detectors were irradiated. The obtained dependencies of R_f and R_r on fluences $10^{13} < \phi < 10^{16} \text{ n/cm}^2$, are shown in Fig. 4. A relatively rapid decrease of R_r and in-

Fig. 4: Forward and reverse resistances (R_f, R_r) versus fluences $1.2 \times 10^{13} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$.

crease of R_f up to $\phi = 1.2 \times 10^{15} \text{ n/cm}^2$, followed by a change of slope to a slower variation of both R_f and R_r , up to $\phi = 10^{16} \text{ n/cm}^2$, can be seen. Since R_f increase and R_r decrease with increasing fluence, it could have been expected that extrapolating the straight lines of the larger slopes of R_f and R_r for higher ϕ , an intersection may eventually appear, where $R_f = R_r$. This would indicate that total damage of rectification (ohmic material), is possible, for that intersecting value of fluence, ϕ_i . Extrapolating the high slope lines to higher fluences, up to the intersection ϕ_i , a value of ϕ , of the order 10^{16} n/cm^2 was obtained. However, $R_f = R_r$ was practically not obtained, since the change of slopes of the lines R_f and R_r as a function of ϕ to smaller ones appear for $\phi < 10^{15} \text{ n/cm}^2$. Concerning the small slopes of R_f and R_r , respectively, a similar extrapolation gives an intersection at much higher fluences than above, which may not be practically realized. This means that small rectification will be maintained at all practical values of ϕ .

This may be due to contacts or interface asymmetric damages.

More information about the change of rectification, due to neutron irradiation, can be obtained, by using rectification factor (Rec) as the ratio between the forward and reverse currents ($Rec = I_f/I_r$) at a given $V_r = V_f = V = 10V$ (the maximum forward voltage, where no heating was observed), as a function of fluence $1.2 \times 10^{14} \text{ n/cm}^2 \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$. As can be seen (Fig. 5), the rectification factor decreases abruptly as a function of fluence between $1.2 \times 10^{14} \leq \phi \leq 5.9 \times 10^{14} \text{ n/cm}^2$, followed by a smaller drop up to $\phi = 1.2 \times 10^{15} \text{ n/cm}^2$ and a constant Rec for $\phi \geq 1.210^{15} \text{ n/cm}^2$ ($Rec \sim 8$). This result confirms the assumption that, after irradiations with large fluences ($\phi \geq 10^{15} \text{ n/cm}^2$), small rectification is maintained, which is, probably, due to contact damage or interface rectification.

Fig. 5: Rectification factor Rec versus fluences $1.2 \times 10^{14} \leq \phi \leq 8.9 \times 10^{15} \text{ n/cm}^2$.

Another type of measurements which may enable one to obtain data on the connection between strong fluences of irradiation and the characteristics of the detectors, is the variation of the impedance (Z) as a function of ϕ and the frequency f (Fig. 6).

Fig. 6: Impedance (Z) versus frequency (f) (reverse bias $V_r = 160V$).

These measurements were performed for an applied

reverse bias of $-160V$ and various of f 's between 1 to 500 kHz. As can be seen, Z decreases with increasing f , for all values of ϕ . Saturation (constant Z) is achieved for $f > 400$ kHz for all values of $\phi > 10^{14}n/cm^2$.

In order to obtain more detailed information, we now studied the real and imaginary part of the ac impedance, R_{ac} and capacitance (C), respectively, and the losses ($tg\delta$).

The dependence of R_{ac} and C on frequency f is shown in Fig. 7a,b,c,d. For $\phi = 1.2 \times 10^{13}n/cm^2$ (Fig. 7a), a maximum R_{ac} appears at $f \sim 50$ kHz and for $f > 50$ kHz, R_{ac} decreases and tends to saturate for $f > 450$ kHz. For $\phi > 10^{14}n/cm^2$, R_{ac} decreases for all values of f (no more maxima appear) and the same tendency of saturation at high frequencies is observed. For the highest used fluence ($8.9 \times 10^{15}n/cm^2$) a similar decrease of R_{ac} as a function of f occurs (Fig. 7c), but the saturation appears at a lower frequency (~ 250 kHz). The maxima of R_{ac} , which appear at low f and low fluence $\phi < 1.2 \times 10^{12}n/cm^2$, are probably due to storage effects which appear in undamaged diodes at these frequencies.

For $\phi = 1.2 \times 10^{12}n/cm^2$, the capacitance C is constant for all measured frequencies between 1 and 500 kHz (Fig. 7b). Comparing the values C and R in Fig. 7a,b and c, an interesting behavior can be observed. At higher fluences ($\phi > 10^{13}n/cm^2$), C becomes frequency dependent, similarly to R (Fig. 7b). At the highest measured fluence ($8.9 \times 10^{15}n/cm^2$), the shape of characteristics of both C and R on f , is almost constant (Fig. 7c). The value for which C reaches saturation, for $f > 450$ kHz, is $8pF$, which is the same for all ϕ , also for values of ϕ where $C(f) = \text{const.} = 8pF$ (Fig. 7a). This value of C corresponds approximately with $C = \epsilon A/d$, where A is the area of contacts, d is the thickness of the wafer, and ϵ is the dielectric constant of silicon. The increase of the value of C from $8pF$ to about $12pF$ at $f = 1$ kHz for $\phi = 1.2 \times 10^{14}n/cm^2$, is followed by a decrease with increasing f , back to the $8pF$ for $f \geq 500$ kHz, (Fig. 7b). For the highest fluences $\phi = 8.9 \times 10^{15}n/cm^2$ (Fig. 7c), the capacitance C increases to about $70pF$ for $f = 1$ kHz, followed by a fast decrease to the same value, measured for a non-damaged detector of $8pF$. This shows that the value $f \times \tau > 1$ of the diode has changed due to the decrease of free carriers life-time, τ , by the created traps caused by irradiation. By increasing f the product $(f \times \tau)$ is again $f \times \tau > 1$, where the capacitance is $C = 8pF$ [6-8].

An interesting behavior which resulted from the R_{ac} and C measurements at $\phi < 10^{14}n/cm^2$ was

that unlike the value of C , which for an applied reverse bias $V_r > 20 - 80V$ is constant and independent on applied frequency. R_{ac} is dependent on frequency for the reverse bias $V_r = 160V$. To verify this difference in behavior, we plotted in Fig. 8, R_{ac} as a function of reverse bias V_r , and frequency of 100 kHz and the maximum applied frequency $f = 500$ kHz for a detector irradiated to $\phi = 1.2 \times 10^{12}n/cm^2$. As can be seen, R_{ac} increases with increasing V_r and saturation is observed for $V_r > 120V$, as was observed for $C = C(V_r)$, for samples irradiated at $\phi < 10^{13}n/cm^2$ [6]. This shows that the real impedance, similar to the capacitance, attains saturation when the capacitance attains full depletion.

As shown in Fig. 8, a change of the slope of curve R_{ac} as a function of V_r appears at about $V_r = 40V$ and saturation, at about $V_r = 120V$, is seen.

Fig. 7a: Capacitance (C) and real impedance R_{ac} versus frequency (f), (reverse bias $-160V$), irradiation fluence $\phi = 1.2 \times 10^{12}n/cm^2$.

Fig. 7b: Capacitance (C) and real impedance R_{ac} versus frequency (f), (reverse bias $-160V$), irradiation fluence $\phi = 1.2 \times 10^{14}n/cm^2$.

Fig. 7c: Capacitance (C) and real impedance $R_{r,ac}$ versus frequency (f), (reverse bias $-160V$), irradiation fluence $\phi = 8.9 \times 10^{15} n/cm^2$.

Fig. 8: Real impedance $R_{r,ac}$ versus applied bias V , for fluence $\phi = 1.2 \times 10^{12} n/cm^2$.

Fig. 9 shows $R_{r,ac}$, at the highest measured frequency (500 kHz), as a function of ϕ . For $10^{12} < \phi < 1.2 \times 10^{13} n/cm^2$, R decreases from 10 to 8 $M\Omega$ and

Fig. 9: Real impedance (R_{ac}) versus fluence ϕ for reverse bias $-160V$ at frequency $f_{r,ac} = 500$ kHz

from this value R_r decreases abruptly to $80 k\Omega$ for $\phi = 4.6 \times 10^{14} n/cm^2$, remaining practically constant up to the highest fluence ($8.9 \times 10^{15} n/cm^2$). From this minimum constant value of $R_{r,ac}$, a value of $\rho_{r,ac} = 5 \times 10^5 \Omega cm$ is obtained. This value is still

higher than the intrinsic resistivity ρ_i , but not significantly, demonstrating that a small space charge is maintained for the highest employed fluence applied to the detector.

As shown in our previous paper [4], at $\phi \sim 10^{12}-10^{13} n/cm^2$, an abrupt change of several physical parameters occurs, due to damage. The observed changes of $R_{r,ac}$ and C confirm the results in [4].

In Fig. 10, the linear dependence of $R_{f,ac}$ on $\phi > 10^{13} n/cm^2$ for the maximum measured frequency ($f_{max} = 500$ kHz), is shown. For $\phi_{max} = 8.9 \times 10^{15} n/cm^2$, $R_{f,ac} = 18 k\Omega$ is obtained, which is of the same order of magnitude as R_f of the dc measurements (Fig. 3b). Unlike $R_{r,ac}$, the resistance $R_{f,ac}$ shows a small increase with increasing ϕ (the slope $dR_{f,ac}/d\phi$ is very small). This shows that, for $\phi \geq 4.6 \times 10^{15} n/cm^2$, a new type of damage was induced in the device, which may again suggest the above considered hypothesis that damage to the contacts, or interface states are produced and play a role in the characteristics of the detector.

Fig. 10: Real impedance $R_{f,ac}$ for forward bias $0.5V$ versus fluence ϕ at frequency 500 kHz.

Capacitance C , as a function of ϕ , with f as a parameter, is shown in Fig. 11. The value of C at

Fig. 11: Capacitance (C) versus fluence (ϕ) for frequencies f : 20, 100 and 500 kHz.

$f_{max} = 500$ kHz, is practically independent on

fluence, for all values of ϕ . For $f < 500$ kHz and $\phi > 10^{13} \text{ n/cm}^2$, C depends on ϕ , but for $\phi < 10^{13} \text{ n/cm}^2$, C is practically constant for all values of ϕ . This suggests, similar as was found in Fig. 7a,b,c, that the lifetime τ decreases with neutron fluence and the factor $f \times \tau$ is larger than 1 only for $f > 100$ kHz. For $f < 100$ [6-8].

In Fig. 12 the losses ($tg\delta$) as a function of fluence, are shown. It can be seen that for $\phi > 10^{13} \text{ n/cm}^2$, the losses increase with fluence. Functions $C(\phi)$, and $tg\delta$ are of similar shape but, unlike C , $tg\delta$ depends on ϕ , for $f = 500$ kHz. Fig. 13 shows $tg\delta$ as a function of f with fluence as a parameter, is represented. As can be seen, maxima of losses appear for $\phi > 10^{14} \text{ n/cm}^2$. This is due to the fact that at these fluences both C and $R_{r,ac}$ depend on f , (Fig. 7b,c).

Fig. 12: Losses $tg\delta$ versus fluence ϕ for frequencies $f = 100$ and 500 kHz.

Fig. 13: Losses versus frequencies for fluences $\phi = 1.2 \times 10^{12}$, 1.2×10^{13} , 1.2×10^{14} , 4.6×10^{14} , 1.2×10^{15} , and $1.9 \times 10^{15} \text{ n/cm}^2$.

3. Conclusions

a. The strong damage of neutron fluences (ϕ) on

silicon detectors is confirmed and explained.

- b. Critical fluences (ϕ_c) for $\phi_{c1} > 10^{12} - 10^{13}$ and $\phi_{c2} > 4 \times 10^{14} - 10^{15} \text{ n/cm}^2$, were observed. For $\phi > \phi_{c1}$, the damage may be due to defects induced in the bulk of Si and for $\phi > \phi_{c2}$, the surface (contacts or interfaces), damage may be significant.
- c. Due to the surface damage (ϕ_{c2}), the rectification Rec remains larger than 1, but of the order of unity ($\text{Rec} = 8$ for $\phi \sim 10^{16} \text{ n/cm}^2$).
- d. Both the dc and ac electrical measurements confirm the above conclusions of rectification decrease and existence of two critical fluences at which the damage may be mainly in bulk and surface, respectively.
- e. From the ac measurements of $Z(f)$, $R_{r,ac}(f)$, $C(f)$ and $tg\delta$, at different fluences, a decrease of the lifetime (τ) with ϕ is to be taken into consideration. This may be the cause of the dependence of Z , C , and $tg\delta$ on f , at low frequencies.

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