Study of Current Voltage Characteristics of Irradiated Silicon Detectors

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Abstract

Current-voltage (I-V) characteristics of non-irradiated and irradiated $p^+ - n - n^+$ detectors, with neutron fluences (ϕ) up to $10^{14} n/cm^2$ were measured and the obtained data were analyzed. The $I_f - V_f$ characteristics confirmed the existence of a critical fluence boundary ($\phi_b > 5 \times 10^{11} n/cm^2$), similar to those found by other types of measurement (DLTS, C-V).

We found that at ϕ_b the rectification ratio is reduced drastically, but a large reverse voltage can, nevertheless, be applied.

The series resistivity (ρ) calculated from the $I_f - V_f$ characteristics, for both non-irradiated (NI) and irradiated detectors, shows that for NI detectors the resistivity is of the order of that of the silicon bulk ($1200 \Omega cm$). The resistivity (ρ) for irradiated devices increases (with increasing values of ϕ , of up to $10^{14} n/cm^2$), up to $\sim 4 \times 10^3 \Omega cm$.

As a result of the increase of ρ with ϕ , the $p^+ - n - n^+$ becomes a $p^+ - \nu - n^+$ device. This study explains the rather good charge collection efficiency in spite of strongly affected physical properties.

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Introduction

Properties of silicon detectors make them amenable for collider experiments. Recently, intensive investigations of silicon detectors have been performed at very high neutron fluences (ϕ), in view of their future application in large colliders (such as the LHC - Large Hadron Collider) experiments. The fluences (ϕ), to which silicon detectors will be exposed, are of the order of $10^{13} - 10^{14} n/cm^2$, or more. New investigations on the degradation of the characteristics of the device, as a function of ϕ , are currently in progress [1-5].

One of the topics under investigation is the variation of the current-voltage (I-V) characteristics of detectors, with irradiation, mostly for the reverse current. The increase of reverse current, I_{rev} , due to ϕ , results in an appreciable leakage current. Despite that, the collection efficiency is only slightly decreased.

Studies of leakage current, for various values of ϕ , were performed and models, attempting to explain the impact of irradiation on the parameters of silicon detectors, were published [6-8]. Also, information on the damage, caused by irradiation in the bulk of the silicon, and the influence on the electrical properties (mobility, concentration), were obtained [9-11].

Studies of silicon detector properties were performed, in order to obtain information on the Capacitance-Voltage (C-V) characteristics, for non irradiated and irradiated detectors. Data on space-charge concentration, depletion width, and full depletion voltage [4,7,8], were obtained. Measurements, employing Deep Level Transient Spectroscopy (DLTS), were performed, in order to obtain energetic localized states values and concentration of many of the generated deep levels by irradiation [4,7,8,12]. Mainly irradiation with neutrons was thoroughly investigated, since the strongest damage is caused by it.

All this intense scientific activity has not yet resulted in a clear answer to the problems of irradiation damage. Also, the influence on charge collection efficiency for this type of detectors (for future colliders) is not yet clarified.

So far, less attention was paid to the forward-bias part of the I-V characteristics, $I_f = f(V_f)$. But I_f may provide important information on the bulk and contact/series resistance (R_s), generation recombination of carriers, and saturation current, I_s , since it can be expected that the high fluences of irradiation modify these parameters and, thus, may contribute important information on the deterioration of the detector characteristics, caused by neutron

irradiation.

In this paper, data on forward and reverse I-V characteristics, before and after irradiation, with fluences of between 5×10^{11} to $10^{14} n/cm^2$, are presented. The impact of fluence (ϕ) on the generation recombination current (mainly the forward recombination), the diffusion current of I_f , series and/or contact resistance R_s , and rectification ratio I_f/I_{rev} (forward to reverse current), is discussed. It is shown that irradiation with neutrons decreases the equilibrium majority concentration (n) and the $p^+ - n - n^+$ device is transformed in a $p^+ - \nu - n^+$ one. The ambipolar diffusion length (L_a) was calculated from the relation of I_f as a function of V_f for a $p^+ - \nu - n^+$ device and the average value of L_a was found.

Conclusions about the impact of neutron irradiation on the I-V characteristic of the detector and on its performance as a radiation detector, will be given.

Theoretical Comments

The usual silicon radiation detectors, employed in collider experiments, are of the $p^+ - n - n^+$ junction type. Typical for these detectors is the relatively thick bulk n-silicon ($400 - 500 \mu m$), of very low doping (of the order of $10^{12} cm^{-3}$). Their I-V characteristics after irradiation at various ϕ , were studied. Observed changes are explained by generation of carrier traps, due to levels (recombination - generation radiation-induced centers) in the semiconductor. This can contribute to the understanding of the damage produced by irradiation.

Assuming that the $p^+ - n - n^+$ device behaves as a real diode, the relation given by [14] for this case is:

$$I = I_0 \exp(\beta V) + I_{re} \exp\left(\beta \frac{V}{2}\right) \quad (1)$$

where I_0, I_{re} are the diffusion and the recombination saturation currents, respectively, and $\beta = q/kT$ (where q is the electron charge, k is the Boltzmann constant, and T absolute temperature).

For silicon and other semiconductors with an energy gap $E_g > 1 eV$ [14], for small values of V, $I_{re} > I_0$. For large values of V, where the diffusion current increases steeply, the relation is reversed and $I_{re} < I_0$.

Eq. (1) can be approximated for forward bias

$$I = I_s \exp(\beta V/n), \quad (2)$$

where I_s is the saturation current of the real diode and n is the emission coefficient or ideality factor. Representing current I_f , in a semilogarithmic scale, as a function of V_f , corresponding to Eq. (1), two linear regions will appear (a) for low values of V_f , a straight line with a slope corresponding to $n=2$ and the extrapolation for $V = 0$ gives I_{re} and (b) for large values of V_f , the slope corresponds for silicon $n = 1.2 - 1.3$ and the extrapolation of I_f at $V = 0$, gives the value of I_0 .

For higher values of V_f , the influence of the series bulk resistance is more significant and will lead to a decrease of the slope of the linear dependence of I_f vs. V_f , in semilogarithmic scale.

For a further increase of V_f , the device may enter a high injection state, where the concentration of the minority carriers p , becomes comparable to the n -doping ($\sim 10^{12} \text{ cm}^{-3}$). This may occur in this type of detectors, since the n -doped silicon is only about two order of magnitude higher than that of the intrinsic concentration, n_i . This may change $I_f = f(V_f)$ from an exponential to a power dependence ($I \sim V^m$)

$$I_f = aV_f^m + b \quad (3)$$

where most of the voltage drop is on the series and/or contact resistance, with an ohmic-like behavior.

For high neutron fluence irradiation, defects, generated in the silicon, cause the resistivity of bulk silicon to increase, corresponding mainly to a decrease of the majority carrier concentration n . It can, thus, be assumed that the $p^+ - n - n^+$ device will behave rather as a $p^+ - \nu - n^+$ type device. Therefore, part - V_i - of the applied bias V appears as a voltage drop across the ν material. In this case, the value of V_i will not depend on the current, but on $W/2L_a$, where W is the width of the ν material and L_a the ambipolar diffusion length [13,15]. This can be explained by the fact that the increase of I_f is caused by the

increase of electron- and hole-concentration, over the equilibrium values n and p in the bulk silicon. Thus, a corresponding increase of the bulk silicon conductivity occurs, maintaining the potential drop V_i on W independently on the current [15].

For the $p^+ - \nu - n^+$ device, applying the well known theory [15,16], the current is:

$$I = (q \cdot D_a \cdot n_i / W) \cdot f(W/2L_a) \cdot \exp(\beta V/2) = I_s \exp(\beta V/2) \quad (4)$$

where D_a is the ambipolar diffusion constant, n_i the intrinsic concentration of carriers, and $I_s = (qD_a n_i / W) f(W/2L_a)$.

The function $f(W/2L_a)$ is independent on current and was calculated for both $W/2 < L_a$ and for $W/2 > L_a$. For $W/2 = L_a$ the function attains its maximum value $\{f(1) \max \sim 0.3\}$ [14,15]. Eq. (4) is similar to the I-V relation of a $p^+ - n - n^+$ device, but the saturation current is, in this case, a function of q, n_i, L_a and D_a , which are important parameters for the $p^+ - \nu - n^+$ junctions. The value of the slope of $I_f \sim f(V_f)$ is $1/2$ (in semilog representation).

Data obtained from the measured I-V characteristics, introduced in relation (4), have enabled to estimate a value of the diffusion length $L_a \simeq 200\mu m$.

Experiments and Results

The investigated silicon detectors were of the $p^+ - n - n^+$ type. The resistivity of the bulk silicon single crystal was 4 to 6 $k\Omega cm$. The p^+ and n^+ doping was made by implanting ions of boron and phosphorus, respectively. The wafers were of FZ silicon, cut in the $\langle 111 \rangle$ direction and thickness of about $400\mu m$.

The I-V characteristics were measured with Hewlett Packard equipment. The reverse current (I_{rev}) was measured at reverse maximum bias (V_{rev}) of about 300V and no signs of breakdown were observed. At this doping the breakdown voltage is several thousand volts. Non-irradiated and irradiated (at fluences between 5×10^{11} and $10^{14} n/cm^2$) samples were measured.

The $I_f - V_f$ characteristics, measured for non- and irradiated ($10^{11} \leq \phi \leq n/cm^2$) detectors are shown in Fig. 1.

An obvious difference between $I_f = f(V_f)$ of detectors non-irradiated and irradiated at $\phi < 5 \times 10^{11} \text{ n/cm}^2$ and those irradiated at $\phi > 5 \times 10^{11} \text{ n/cm}^2$ can be seen. Thus, at $\phi \simeq 5 \times 10^{11} \text{ n/cm}^2$, a boundary occurs, indicating a significant change of physical properties of the device. So far, physical changes at this fluence were observed employing DLTS or C-V measurements.

From the I-V data, the following parameters were studied: (1) ideality factor n , (2) rectification ratio, I_f/I_{rev} , for the same value of V (forward and reverse), corresponding to the maximum value of I_f , (3) the same rectification ratio I_f/I_{rev} for the maximum measured values of V_f and V_{rev} and (4) the series (bulk) and/or contact resistance.

Applying the calculations from [15,16] (see Eq. (4) above) for the $p^+ - \nu - n^+$ device, an average of L_a for all fluences was estimated.

Assuming that I_f varies with V_f , as given in Eq. (2), we represent in Fig. (2) $\log I_f \sim \beta V_f/n (\beta \simeq q/kT)$. Three linear regions can be seen. From the slopes of these straight lines three values of n ($n_1 = 1.2, n_2 = 2.0, n_3 = 4.0$) were obtained. The maximum applied voltage, $V_{f,max}$, was about 0.55V.

Since the value of n_3 is higher than the predicted value for silicon in that region ($1.2 \leq n_3 \leq 1.3$) this indicates a deviation from the theoretically predicted behavior (Eq. (2)).

For this type of detector, of $0.5 \times 0.5 \text{ cm}^2$, the reasons for this deviation may be the low doping ($10^{12}/\text{cm}^3$) and large wafer thickness of the silicon ($\sim 400 \mu\text{m}$), which contributes to the increase of the series resistance (R_s). The reverse current was about 10^{-8} A and constant, up to the maximum measured value of $V_{rev} (\sim 300 \text{ V})$. This indicates a very low leakage current (good rectifier). Although the forward current does not follow exactly the theoretically predicted behavior (2) the diode is a good rectifier with small and constant I_{rev} .

A typical $I_f - \beta V_f/n$ characteristic of an irradiated sample (at 10^{14} n/cm^2), is shown in Fig. 3. The I-V characteristic of the irradiated sample indicates that I_f depends *exponentially* on V_f up to the maximum bias $\beta V_f \simeq 5$. The first linear region of $\log I_f \sim \beta V_f/n$, corresponds to the predicted relation (4) for a $p^+ - \nu - n^+$ device [14,15] where $n = 2$. For values $\beta V_f > 5$, the corresponding n is large and I_f is a function of V_f^m (Eq. (3)). The low value of $\beta V_{f,max}$ for which I_f is still exponential, shows that after the highest irradiation ($\phi = 10^{14} \text{ n/cm}^2$), R_s becomes the main factor which determines I_f .

From Fig. 4 it can be seen that, unlike in the non-irradiated sample, a current (I_{rev}) in the irradiated one, dependent on V_{rev} (with leakage current), appears. In spite of the high leakage current, rectification is maintained, since for $I_f \simeq I_{rev}$, V_f/V_{rev} is about 600.

In order to obtain more information about the behavior of these detectors, the rectification ratio $R_{ec} = I_f(V_{f,max})/I_{rev}(V_{rev} = V_{f,max})$ for the non-irradiated and irradiated (up to $10^{14}n/cm^2$) samples, was calculated and presented (Fig. 5). R_{ec} increases slowly from the non-irradiated ($R_{ec} \simeq 10^4$) to the irradiated sample, at $\phi = 5 \times 10^{11}n/cm^2$ ($R_{ec} = 5 \cdot 10^4$). Between $\phi = 5 \times 10^{12}$ and $10^{14}n/cm^2$, R_{ec} decreases sharply to 16. To avoid errors caused by measurements of reverse current ($V_{rev}) \leq 1V$, we introduced a new rectification ratio $R_{ec1} = I_f(0.45V)/I_{rev}(290V)$. The dependence R_{ec} on ϕ is shown in Fig. 6. As can be seen, the value R_{ec1} is 10^4 for the non-irradiated case and decreases to about $R_{ec1} = 1$ at maximum irradiation ($\phi = 10^{14}n/cm^2$). This value corresponds to the observed critical value at which the capacitance (C) begins to be a function of frequency ω [5,8]. For values of $\omega > 120kHz$, C does not depend anymore on the applied bias [5,8]. Furthermore, DLTS measurements have shown a similar critical value of irradiation ϕ over which no more DLTS measurements can be performed [17].

It is well known that reverse bias of irradiated diodes gives leakage current, but the appearance of the critical value of the ratio I_f/I_{rev} was not observed previously since no systematic study of I_f as a function of V_f were made. Since I_f , for high fluences is practically equal to the corresponding I_{rev} ($R_{ec1} = 1$), the ratio $V_{rev}(300V)/V_f(0.45V) \simeq 600$. This may be an indication that, after strong irradiation, although the device is not a good rectifier anymore, the resistance and the breakdown voltage are nevertheless large. Taking also into account the reduction of the majority carriers due to irradiation [8,11], it may well be that the device behaves like $p^+ - \nu - n^+$ device.

Assuming that for large neutron fluences interface states at the $p^+ - \nu$ and $\nu - n^+$ are created, in addition to bulk traps, a change of the nature of the contacts may occur, e.g., the ohmic $\nu - n^+$ contact may become a rectifying one. An asymmetric space charge may appear at the $p^+\nu$ and $n + \nu$ contacts, and the detector behaves like an asymmetric, long $p^+ - \nu - n^+$ device [13,14,16].

For the region where the series resistance is dominant, V_f/I_f depends linearly on $1/I_f$.

By extrapolating at $1/I_f \rightarrow 0$ (very large currents) the obtained finite value V_f/I_f , is the series resistance R_s , from which the resistivity of bulk silicon can be calculated.

In Fig. 7 the best fit of a straight line dependence of $R = V_f/I_f$, obtained for the smallest experimental $1/I_f$, is shown. From this line for $1/I_f = 0$, $R_s \simeq 195\Omega$ is obtained.

In Fig. 8, the same $R_s = V_f/I_f$ (for large V_f) as a function of $1/I_f$ for an irradiated sample at $\phi = 10^{14}n/cm^2$, is shown. For $1/I_f = 0$, $R_s \simeq 8.27k\Omega$ was obtained.

The $\log I_f$ as a function of $\log V_f$ characteristic (for $V_f > 1V$), for the same sample $\phi = 10^{14}n/cm^2$) is shown in Fig. 9. It is a straight line, with a slope of about 1.2, which shows that for $V_f > 1V$, the resistance of the detector is practically ohmic since in this interval $R_s \simeq \Delta V_f/\Delta I_f$. The value obtained for R_s was about $5.0k\Omega$, the same order of magnitude as that obtained from Fig. 8. This is acceptable, taking into account the errors which occur in such procedures.

The resistivity of the non-irradiated sample, (ρ_{NI}) was calculated from $R_s = 195\Omega$ and a value $\rho_{NI} = 1.210^3\Omega cm$ was obtained. The corresponding concentration is n_{NI} is $3.4 \times 10^{12}cm^{-3}$ which is in agreement with the one of the silicon wafer. The average resistivity calculated from $R_s \simeq 5.00$ and $8.3k\Omega$ ($R_{ave} = 6.6k\Omega$) of the irradiated device $\phi = 10^{14}n/cm^2$) is $\rho_{ave} = 4.14 \times 10^4\Omega cm$. For this ρ_{ave} , the obtained concentration of carriers $n = 10^{11}cm^{-3}$, is only one order of magnitude less than the intrinsic value (n_i) of silicon ($n_i = 1.15 \times 10^{10}cm^{-3}$). This confirms, that after strong irradiation, the concentration of free carriers, n , is approaching that of *intrinsic*, thus, the $p^+ - n - n^+$ is already a $p^+ - \nu - n^+$ device.

Based on these results and using Eq (4) of a $p^+ - \nu - n^+$ device, we calculated the values of the function $f(W/2L_a)$ from $I_s = (qD_a n_i/W)f(W/2L_a)$. For this purpose, experimental curves of $\log I$ as a function of V_f , for irradiated samples, were employed. Introducing the thickness of the Si wafer $W = 400\mu m$, $D_a = 1.5cm^2/sec$ [14], and $n_i = 1.15 \times 10^{10}cm^{-3}$ in I_s , the value of $f(W/2L_a)$ was found. From the curve of $f(W/2L_a)$ as a function of W/L_a , given in [14] for a $p^+ - \nu - n^+$ device, L_a was found. The found average value L_a is $200\mu m$, which is of the order of the wafer thickness.

Conclusions

In this paper, the I-V characteristics of detectors of type $p^+ - n - n^+$ were measured and the impact of neutron fluences ($10^{11} \leq \phi \leq n/cm^2$), on forward and reverse currents, studied. The main contributions of the investigation are:

1. The I-V characteristics of non-irradiated devices show a very small reverse current ($I_{rev} < 10^{-8} A$) which remains constant for measurements of up to $V_{rev} \simeq 300V$. For large forward bias, V_f , the value of ideality factor n is 4.0 which deviates from the accepted value of $1.2 \leq n \leq 1.3$ for silicon (no diffusion region appears). This may be due to a large contribution of the bulk resistance. The maximum obtained current for $V_f = 0.55V$ is of the order of $10^{-4} A$.

I_f of the irradiated device ($10^{14} n/cm^2$) increases exponentially for low values of I_f ($n = 2$), followed by a non-exponential region. Unlike the non-irradiated devices, the irradiated ones show a leakage current at V_{rev} . For an irradiated sample ($\phi = 10^{14} n/cm^2$) at $V_{rev} \simeq 300V$, a current I_{rev} of the order of $10^{-4} A$ was measured. This I_{rev} value is near to the I_f value, at $V_{f,max} = 0.55V$. This shows that after irradiation a behavior, typical for a $p^+ - \nu - n^+$ device, is observed.

2. The rectification ratios $R_{ec} = I_f(V_{f,max})/I_{rev}(V_{rev} = V_{f,max})$ and $R_{ec1} = I_f(V_f = 0.45V)/I_{rev}(V_{rev} = 300V)$ have shown that for the non-irradiated device, the rectification factor R_{ec} is about three and for R_{ec1} , about four orders of magnitude larger than for irradiated ($10^{14} n/cm^2$). This shows that, although the rectification factor decreases (up to $R_{ec1} = 1$) by irradiation, a large voltage $V_{rev} > 300V$, can still be applied, without causing damage. I_f for $V_{f,max} = 0.45V$ is of about the same value as I_{rev} for $V_{rev} \max \simeq 300V$. This indicates that some rectification is maintained, although the leakage current increased dramatically ($R_{ec1} = 1$). The dependence of rectification ratios on irradiation show a strong change for $\phi > 10^{12} n/cm^2$. This confirms that this irradiation produces anomalous behavior of the characteristics of this device.
3. The series (and/or contact) resistance R_s was calculated for $1/I_f = 0$, from the V_f/I_f characteristics as a function of $1/I_f$, for non irradiated and irradiated (at

$\phi = 10^{14}n/cm^2$) detectors. The value of R_s for a non-irradiated detector, was 195Ω (which corresponds to about $\rho_{NI} = 1.2k\Omega cm$). This value is of the same order of magnitude like that of the resistivity of bulk silicon wafer, used in the fabrication of the detectors. The corresponding average resistivity of the irradiated detector ($\phi = 10^{14}n/cm^2$) was $\rho_{ave} = 4.14 \times 10^4\Omega \times cm$ ($n = 10^{11}cm^{-3}$). This shows that the strong fluences reduce the concentration of free carriers by about one order of magnitude and bring the concentration n , nearer to $n_i = 1.15 \times 10^{10}cm^{-3}$. This confirms again that the $p^+ - n - n^+$ device became a $p^+ - \nu - n^+$ device.

4. From Eq. (4) and from the values of $I_f \simeq f(V_f)$ of irradiated devices, the ambipolar diffusion length (L_a) was calculated and an average value of $L_a = 200\mu m$ was found.

The main contribution of this paper was to show that, in spite of the leakage current which deteriorated the rectifying properties after neutron irradiation, the detector behaved like a $p^+ - \nu - n^+$ device [15,16]. Thus, it was, nevertheless, able to sustain sufficiently high bias voltage in order to maintain good charge collection efficiency, which is important for future colliders.

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Figure Captions

Fig. 1 : I_f vs. V_f characteristics for non-irradiated and irradiated samples.

Fig. 2 : Forward I_f vs. qV_f/kT characteristics of non irradiated sample.

Fig. 3 : Forward I_f vs. qV_f/kT for an irradiated ($10^{14}n/cm^2$) sample.

Fig. 4 : Reverse current I_{rev} vs. V_{rev} for an irradiated ($10^{14}n/cm^2$) sample.

Fig. 5 : Rectification ratio $R_{ec} = I_f(V_{f,max})/I_{rev}(V_{rev} = V_{f,max})$ vs. fluence (ϕ).

Fig. 6 : Rectification ratio $R_{ec1} = I_f(V_{f,max})/I_{rev}(V_{rev} = 300V)$ vs. fluence (ϕ).

Fig. 7 : Straightline region of series resistance ($R = V_f/I_f$ for the highest values of V_f), vs. $1/I_f$ for non-irradiated sample: $R = (0.456 \times 1/I_f + 195)\Omega$.

Fig. 8 : Straightline region of resistance ($R = V_f/I_f$) vs. $1/I_f$ for irradiated ($\phi = 10^{14}n/cm^2$) sample: $R = (0.193 \times 1/I_f + 8.3 \times 10^3)\Omega$. By extrapolating to $1/I_f = 0$, R equals the series resistance, $R_s = 8.3k\Omega$.

Fig. 9 : $\log I_f$ vs. $\log V_f$ of irradiated ($\phi = 10^{14}n/cm^2$) sample: $(\log I_f = 1.18 \log V_f - 4)$.

(Fig. 1)

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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Fig. 9