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TEMPERATURE DEPENDENCE OF RADIATION DAMAGE AND ITS ANNEALING IN SILICON DETECTORS

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Abstract

The radiation damage resulting from the large particle fluences predicted at the Superconducting Super Collider will induce significant leakage currents in silicon detectors. In order to limit those currents, we plan to operate the detectors at reduced temperatures (~0° C). In this paper, we present the results of a study of temperature effects on both the initial radiation damage and the long-term annealing of that damage in silicon PIN detectors. Depletion voltage results are reported. The detectors were exposed to approximately $10^{14}/cm^2$ 650 MeV protons. Very pronounced temperature dependencies were observed.

I. INTRODUCTION

Silicon detectors at future collider facilities such as the Superconducting Super Collider (SSC), will be exposed to large fluences of both neutral and charged particles resulting in considerable bulk radiation damage. In order to reduce the increase in leakage current associated with that damage, the proposed operating temperature of the silicon detectors in the SSC Solenoidal Detector Collaboration (SDC) experiment is 0°C. The temperature dependence of the leakage current follows the relation [1]

$$I_{Leak}(T_2) = I_{Leak}(T_1)\left\{\frac{T_2}{T_1}\right\}^2 \exp\left\{\frac{-E}{2k}\left(\frac{T_1-T_2}{T_1T_2}\right)\right\} \tag{1}$$

where T_1 and T_2 are the temperatures in degrees Kelvin and k is the Boltzmann constant. We have found that the constant E is essentially independent of the bias voltage [2]. A fit to I_{Leak} versus $T^2 \exp\{-E/2kT\}$ gave E = 1.2eV. That compares well with the values found elsewhere in the literature [3,4,5].

In order to explore any potential complications of operating detectors at 0°C, we irradiated two sets of detectors. One set was kept close to 0° C during the exposure and annealing period, while the other was maintained at room temperature throughout (~27°C during the exposure, and ~23°C during the annealing period). We monitored the full depletion voltage and leakage current of the detectors during the irradiation period and over the subsequent annealing period.

II. EXPERIMENT

A 647 MeV proton beam at the Clinton P. Anderson Meson Physics Facility (LAMPF) was utilized for the irradiation. The detectors received maximum fluences of approximately 10^{14} p/cm^2 over a period of five days. Measurements of the leakage current (I-V) and of the capacitance (C-V) as a function of the bias voltage were taken nine times during the run when the beam was turned off. Those measurements were typically taken a few hours after the beam was turned off. We have continued the I-V and the C-V measurements to the present (~450 days after irradiation) to investigate and compare the annealing behavior of the "cold" and "warm" detectors. The proton fluences were determined by activation measurements of aluminum foils that were placed on the detectors. The reaction used was $Al^{27}+p \rightarrow Na^{22}+X$.

Table I: Detector radiation exposure information

Device	total dose [p/cm^2]	absolute error [%]	statistical (relative) error [%]	average temp. [°C]
pd20	8.49×10^{13}	10.2	2.0	26.9
pd27	8.35×10^{13}	10.2	2.0	1.4
pd28	9.55×10^{13}	10.2	1.8	1.4
pd29	7.46×10^{13}	10.2	2.1	1.4

The silicon detectors were n-type 1723-06 PIN photodiodes manufactured by Hamamatsu. The photodiodes are $1cm^2$ in area and 200µm thick. Their maximum depletion depth is 170µm. Table I summarizes the exposures received by the detectors. All detectors were reverse-biased at 80V during irradiation.

The relation between the applied bias voltage V_b and the depletion thickness d is given by

$$\begin{aligned} d &= \chi\sqrt{V_b} \qquad &&\text{if } V_b \le V_D, \text{ and} \\ d &= d_D \qquad &&\text{if } V_b \ge V_D \end{aligned} \tag{2}$$

where V_D is the full depletion voltage, and d_D is the full depletion depth. The proportionality constant χ is:

$$\chi = \sqrt{\frac{2\varepsilon_s}{e|N_{eff}|}} \tag{3}$$

where e is the charge of electrons, ε_s is the permittivity of silicon, and N_{eff} is the effective dopant concentration.

The depletion voltage was determined by measuring the capacitance of the detector as a function of the applied bias voltage. The depletion layer capacitance C per unit area of a silicon detector is given by

$$C = \frac{\varepsilon_s}{d} \tag{4}$$

From equations (2) and (4) it follows that

$$\begin{aligned} C &= \frac{\varepsilon_s}{\chi}(V_b)^{-1/2} \qquad &&\text{if } V_b \le V_D, \text{ and} \\ C &= \frac{\varepsilon_s}{d_D} = \text{const} \qquad &&\text{if } V_b \ge V_D \end{aligned} \tag{5}$$

The measured C-V curves were fit in two sections: the first, where $V_b \le V_D$, were fit to a power law relation $C = aV_b{}^n$ [with n initially close to -0.5 as expected from eq. (5), but at higher fluences n becomes dependent on the frequency of the measurement and the fluence]; and the second, where $V_b \ge V_D$, were fit by a linear relation ($C = a'+b'V_b$). The intersection of the two fitted curves is the value which we quote as the depletion voltage. An example of that is shown in Fig.1. The capacitance measurements were done at a frequency of 10 kHz.

III. RESULTS

The dependence of the depletion voltage on the proton fluence received is shown in Fig.2. As the fluence increases, the depletion voltage decreases until it reaches a minimum at about 0.75×10^{13} p/cm^2 for the cold detector, and 1.25×10^{13} p/cm^2 for the warm detector. At that point type inversion occurs: the bulk silicon of the detectors changes from n-type to p-type. At higher fluences the depletion voltage rises again. The increase occurs more rapidly for the cold detector than for the warm device. At a fluence of 9.5×10^{13} p/cm^2, the depletion voltage of the cold detector has reached 77V, which is about twice the depletion voltage of the warm detector at the same fluence.

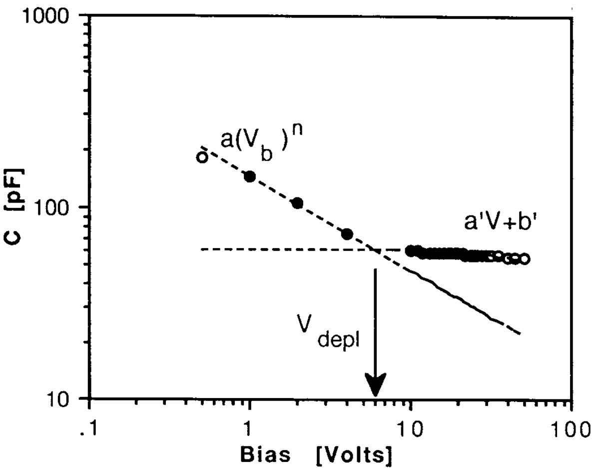

Fig. 1: Capacitance as a function of bias voltage of a Hamamatsu photodiode after a fluence of 5.9×10^{12} p/cm^2. The intersection of the two fitted curves (dotted lines) gives the depletion voltage, as indicated by the arrow. Open circles are not included in the fits.

We have previously found [2,6] that the relation between N_{eff} and the proton fluence ϕ is approximately given by

$$N_{eff} = N_0 \exp(-c\phi) + \beta\phi \tag{6}$$

where N_0 is the initial dopant concentration (negative for n-type material), and c and β are constants. Combining equations (2), (3) and (6), yields

$$|N_{eff}| = |N_0 \exp(-c\phi) + \beta\phi| = \frac{2V_D\varepsilon_s}{ed_D{}^2} \tag{7}$$

at full depletion. Using this relation to fit the values of N_{eff} derived from the depletion voltage values shown in Fig.2, we find the constants $\beta = 0.018$ cm^{-1} and $c = 1.67 \times 10^{-13}$ cm^2 for the warm detector and $\beta = 0.037$ cm^{-1} and $c = 1.1 \times 10^{-13}$ cm^2 for the cold detector. The fits are shown in Fig. 3.

The results observed can be explained by the two terms in eq. (6). The first term represents an exponential decrease of the initial dopant density through the removal of the donors in the n-type bulk material. The second term involves an increase in the number of acceptor sites, the magnitude of which is directly proportional to the total fluence. The value of β gives the number of activated acceptor sites created by one incident particle while passing through a unit thickness of material (1cm). We find that for large total fluences, the effective dopant density is largely determined by the linear term. The large difference in the values of β for the warm and cold detectors most likely involves the more rapid, that is short-term, annealing of the acceptor sites created in the warm detector rather than a more rapid creation of those sites in the cold detector.

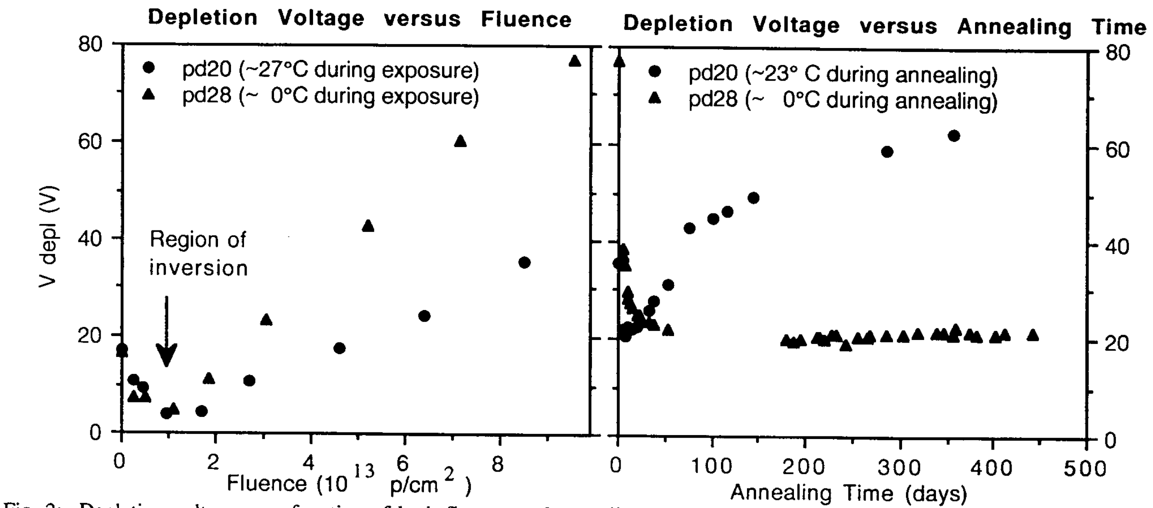

Fig. 2: Depletion voltage as a function of both fluence and annealing time for warm and cold detectors. The two detectors received roughly equal total fluences.

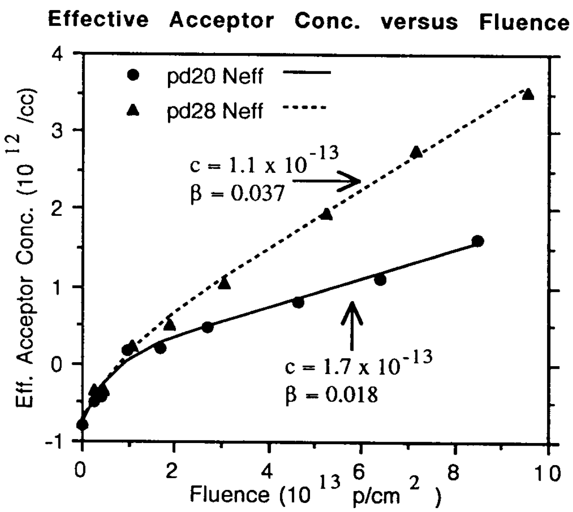

Fig. 3: The effective acceptor concentration as a function of the fluence for warm and cold detectors. A negative value refers to n-type material. The formula fit was $N_{eff} = N_0 \exp(-c\phi) + \beta\phi$.

Fig. 2 also shows that the depletion voltage and therefore the effective dopant-concentration fall very quickly in the early stages of the annealing period. Fits of the function

$$N_{eff} = N_0 + N_A \exp(-t/\tau) \tag{8}$$

to the data in the early stages of the annealing process are shown in Fig. 4. N_0 is the dopant concentration after the initial annealing is complete; τ is the time constant for that annealing; and N_A is the concentration of the acceptor sites that can be removed by the annealing process. The constants from those fits are given in Table II. The lack of sufficient measurements for the warm detector allows us to place only an upper limit of 1.0 days on its time constant. For the cold devices the results are fairly consistent and the average value of τ is 4.3 days. That small value indicates that even for the cold devices, the large depletion voltage seen immediately after our run will anneal away very quickly in comparison to the long period projected for collection of similar fluences at the SSC.

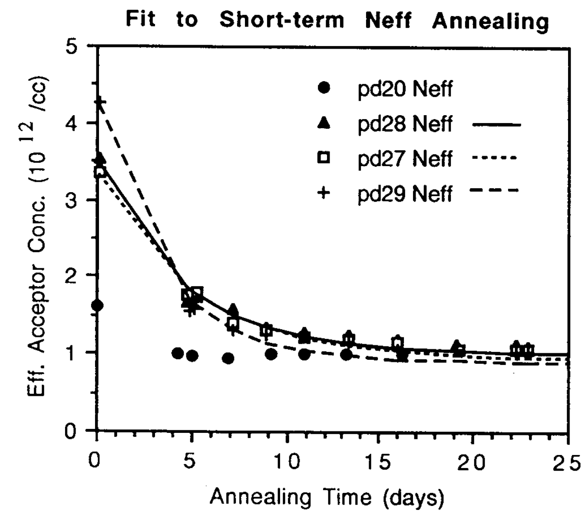

Fig. 4: Fits to the short-term annealing of the effective acceptor concentration. The formula fit was $N_{eff} = N_0 + N_A \exp(-t/\tau)$. For the sake of clarity we only show the first 25 days of data, whereas the fits extended to longer times.

Table II: Constant for the short-term annealing:

Device	N_A [10^{12}/cc]	N_0 [10^{12}/cc]	τ [days]
pd27 (cold)	2.4	1.0	5.0
pd28 (cold)	2.5	1.0	4.5
pd29 (cold)	3.4	1.0	3.4
pd20 (warm)	0.9	1.0	< 1.0

Fig. 5 shows the effective dopant concentration over longer time scales and for various warm-up conditions. Device pd20 was always kept at room temperature, pd28 was always kept at approximately 0°C, while pd27 and pd29 were initially cold, but then warmed to room temperature at different times. All the devices were allowed to anneal with no bias voltage being applied with the exception of pd29. An 80V bias was applied to pd29 starting when it was warmed back up to room temperature. Fig. 6 shows fits to the effective dopant concentration as a function of the relative annealing time. A time of zero was assigned to the point where the detectors were warmed back up to room temperature, or, in the case of pd20, the point where the depletion voltage began to increase again. The function fit to the data is

$$N_{eff} = N_0 + N_A\,(1 - \exp(-t/\tau)) \qquad (9)$$

where N_0 is the initial dopant concentration before the long-term annealing begins and is equal to N_0 in eq. (8). The time constant for the annealing is τ and N_A is the concentration of the potential acceptor sites that can become activated. The values for the constants found are given in Table III. The time constant for the detector that remained cold is infinity within the precision of our measurements. We will refer to the long-term variations as anti-annealing, since it is clearly detrimental to the operation of the detectors. The data show that operation at 0°C freezes out the anti-annealing process. However, as soon as a detector is warmed back up to room temperature, the anti-annealing begins and has essentially the same time constant as for the device that was never cooled. Furthermore, if the detector is biased during the anti-annealing period, the time constant is cut by almost a factor of two. The anti-annealing eventually moves the operating point of the detectors beyond the value that they had immediately after their removal from the beam.

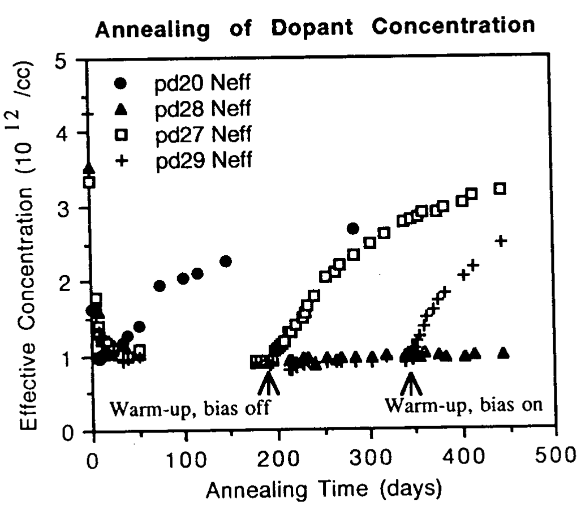

Fig.5: The effective acceptor concentration value as a function of annealing time. pd20 is warm, pd28 is cold, pd 27 was warmed-up with the bias voltage off, and pd29 was warmed-up with the bias voltage on.

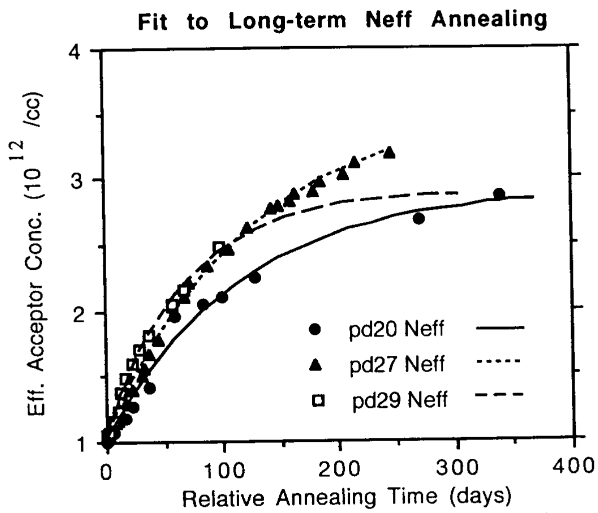

Fig.6: Fits to the effective acceptor concentration value as a function of time. The data were fit using the formula $N_{eff} = N_0 + N_A(1\text{-}\exp(-t/\tau))$.

Table III: Constants for the long-term annealing:

Device	N_A $[10^{12}/cm^3]$	N_0 $[10^{12}/cm^3]$	τ [days]
pd28 (cold)		1.0	>> 450
pd27 (warmed)	2.5	1.0	128
pd29 (warmed, Vb)	1.8	1.0	68
pd20 (warm)	1.9	1.0	115

IV. CONCLUSIONS

The operating temperature of silicon detectors is a critical parameter affecting their longevity. Operating the detectors at reduced temperatures lowers their leakage current by approximately a factor of two for every 7°C temperature reduction. That factor remains essentially unchanged when the devices are damaged by radiation. Past results [3,7] have shown that the leakage current value does improve with time. However, the reduction stops after the leakage current has dropped by a factor of two. Furthermore, the annealing has a very long time constant (~130 days), even at room temperature. A reduction in the operating temperature from 24°C to 0°C would lead to a factor of ten decrease in the leakage current. Even if one takes into account the potential lack of annealing for the cold detector, the reduction factor would still be about 5 [2]. Thus from a leakage current point of view, a lower operating temperature is clearly beneficial.

From the standpoint of the operating voltage the data presented in Fig. 2. also clearly show that operation at 0°C is much more desirable. For detectors that have received fluences of ~ 9 x 10^{13} p/cm^2, the anti-annealing would result in a final full depletion voltage of ~ 60V for a 300μm thick detector kept at 0°C compared to ~ 200V for a similar detector operated at room temperature. Furthermore, to ensure full and prompt collection of the signal on both sides of the double-sided silicon detectors that are planned for use in the SDC experiment, the detectors must be operated at voltages greater than the minimum needed to achieve full depletion. Prototypes of those detectors presently have a maximum operating voltage of 80V per side [8], and therefore have a maximum bias voltage of about 160V. That is well below the 200-plus volt value required for detectors kept at room temperature, but fully compatible with the value for detectors kept at 0°C.

In conclusion, detectors will have to be operated at 0°C, and, once damaged, be maintained at 0°C in order to keep their operating voltage at a reasonable value (<< 160V). Turning off the bias voltage when the detectors are not in use seems to provide an extra margin of safety.

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