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G. Lindström, E. Fretwurst, H. Herdan
M. Rollwagen, P. Thomsen, R. Wunstorf
I. Institut für Experimentalphysik, Universität Hamburg

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I. Institut für Experimentalphysik, Universität Hamburg, FRG *)

ABSTRACT

Radiation Damage in silicon detectors produced by monoenergetic 14 MeV neutrons, 25 MeV protons and 20 keV X-rays was investigated. The irradiation was performed up to fluences of 10^{12} particles per cm^2 resp. 5 kGy in short time exposures of less than 1 hour. The resulting increase of the leakage current (damage rate), change of the resistivity (impurity removal) and charge collection deficiency (decrease of trapping time constant) is discussed. Long term storage at room temperature and short term heat treatments showed appreciable annealing effects.

INTRODUCTION

The use of silicon detectors in high energy physics has gained increasing importance during the last years. Microstrip devices are a prime choice for vertex detectors but recently also large area pad detectors are foreseen for various applications (1), (2). In a number of experiments now under development, calorimeters for special purposes are instrumented with silicon detectors. An example is the H1-PLUG-calorimeter, for which our group is responsible (3). A full size hadronic test calorimeter is presently investigated by the SICAPO collaboration at CERN (4). During this conference a hermetic silicon instrumented hadronic calorimeter was proposed for the SSC (5). Survivability under the severe radiation conditions is a critical requirement for all these applications (6). For calorimeters the radiation damage is mainly produced by neutrons around 1 MeV. Radiation levels of up to several 10^{13} neutrons per cm^2 and year resp. 100 kGy for protons are expected in the forward region of a prospective SSC calorimeter (7). In comparison for the H1-PLUG-calorimeter 10^{11} neutrons per cm^2 and year are estimated. It is, therefore, very important to investigate the radiation hardness of silicon detectors in such radiation environments. The following effects are of main interest:

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- Radiation induced trapping centers lead to a charge collection deficiency. This is directly related to a degradation of the calorimetric response and, hence, influences the absolute energy calibration.

- The reverse current is strongly dependent on the dose. Very high values set a limit to the operability of the detectors.

- The change of the effective impurity concentration is also a consequence of radiation damage. This effect tends to increase the material resistivity and hence changes the depletion thickness as function of the detector bias voltage.

- All these effects can be partly annealed by various methods. This is of major importance since it will increase the possible "lifetime" for the detector operation.

In addition to the bulk defects the absorbed radiation may also cause some surface damage especially in the oxide passivated edge zones. However, this effect is only of importance for very high doses of charged particles or electromagnetic radiation.

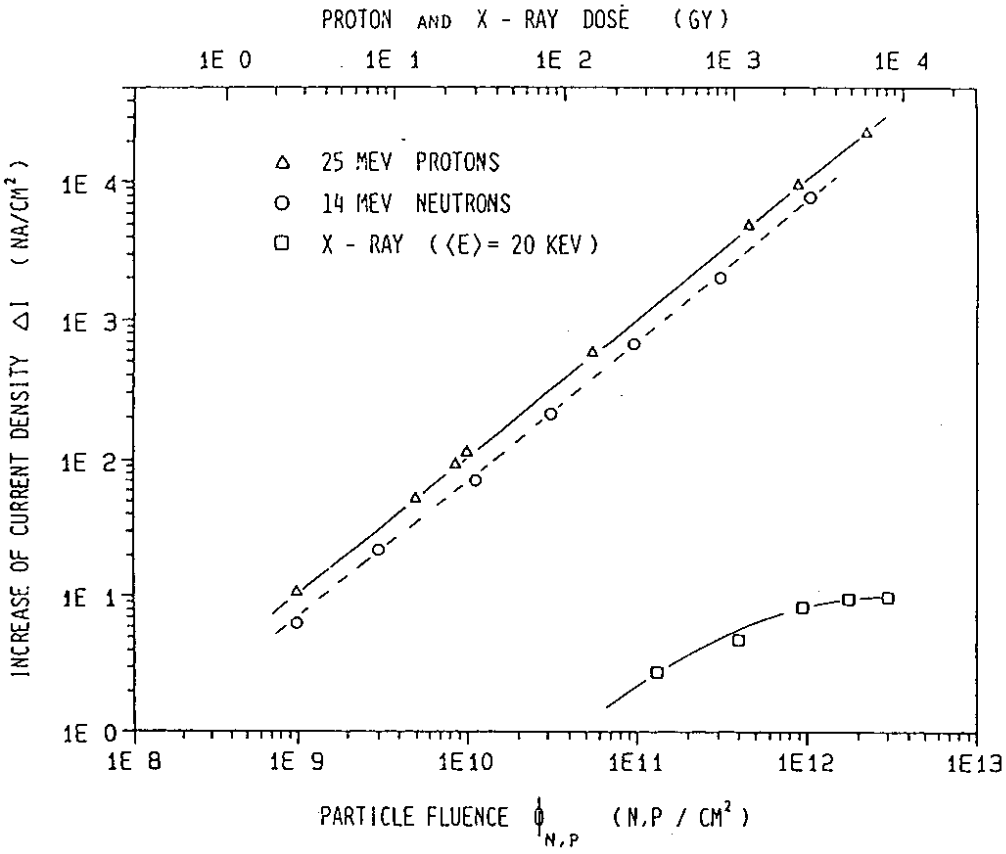

Fig.1 Increase of measured current density ΔI as function of particle fluence (neutrons and protons) and X-ray dose (upper scale). The upper scale represents also the equivalent absorbed proton dose in silicon.

INCREASE OF LEAKAGE CURRENT

Detectors manufactured from n-type silicon with a nominal resistivity of 3 resp. 5 kΩcm and an active area of 2 cm^2 and a thickness of 400 µm were used. The fabrication process combines planar and surface barrier techniques, described elsewhere (8). The detectors were irradiated with monoenergetic 14 MeV neutrons, 25 MeV protons and 20 keV X-rays in short time exposures of less than 1 hour for neutrons and protons resp. less than 4 hours for X-rays. Fig. 1 shows the increase of the current density in the range of up to $2 \cdot 10^{12}$ particles per cm^2 resp. 6 kGy. For neutrons and protons a linear dependence is obtained. For X-rays we observe a saturation above 4 kGy. As pointed out in (8), the linear increase of the current is due to bulk generation only and, therefore, we can extract from these data the current related "damage rate" α:

$$\left(I - I_0\right)/V = \alpha \cdot \Phi$$

where I_0 and I are the currents before and after irradiation, V is the depleted volume and Φ is the particle fluence measured in particles per cm^2. The damage rate is a quantity most useful for practical purposes and is given in A/cm. Table 1 contains the results together with relevant data from other authors. Comparing these experiments the following difficulties have to be kept in mind:

- The formation of generation centers responsible for the current increase depends on the particle type and energy. Protons will predominantly produce point defects whereas neutron irradiation leads also to damage clusters. For protons we expect a decrease with energy, for neutrons an increase (9).

- An appreciable self annealing effect is already visible at room temperature. This leads to some reduction during extended exposure. The same integrated dose may, therefore, result in different values for the damage rate, depending on the irradiation duration as well as on the time elapsed between irradiation and measurement.

- The bulk generation current is proportional to the intrinsic carrier density, which depends very much on the temperature. The extracted value of the damage rate is therefore sensitive to the detector temperature during the measurement.

In addition, the damage rate is expected to depend on the type and resistivity of the silicon and may also be different if the detectors are irradiated under bias or floating. On the other hand, a possible dose rate dependence was not observed (10).

Table 1

Radiation induced damage rate α of detector current increase per sensitive volume (experimental values normalized to T=20 °C) and damage constant k. α_{norm} and k_{norm} normalized to $E_n = 1$ MeV and corrected for self annealing, see text.

Particle Type	Energy (MeV)	ρ_{si} (kΩcm)	$\alpha(T=20\,^{\circ}C)$ (10^{-16}A/cm)	k (10^{-7}cm^2/s)	α_{norm}	k_{norm}	Reference
n	14	2.7	1.37±0.07	2.21	0.50	0.81	this work
n	14	6.6	1.68±0.08	2.71	0.61	0.98	this work
n	reactor	4	0.80±0.08	1.29	0.64	1.03	(10)
n	^{252}Cf	4 -6	0.511±0.034	0.82	1.04	1.67	(15)
n	Pu/Be	10.2	0.61	0.98	0.67	1.08	(16)
n	Pu/Be	14.4	0.48	0.77	0.61	0.98	(16)
p	25	2.7	2.26±0.19	3.65	—	—	this work
p	25	5.0	2.04±0.19	3.29	—	—	this work
p	$1.2 \cdot 10^4$	4	0.45	0.73	—	—	(11)
p	$8 \cdot 10^4$	5	0.16±0.2	0.26	—	—	(12)

For proton irradiation no comparable measurements in the MeV range exist. The values for 12 resp. 800 GeV are much lower than our result for 25 MeV. This may be expected from calculated displacement production rates as function of proton energy (see e.g. van Lint (9)). For neutrons we compare our data with those presented in this conference by Ohsugi et al. (10) and Vismara et al. (15) as well as those reported recently by Kraner et al. (16). As all four experiments were performed under different conditions the data can only be compared if normalized to a standard situation. As such we take a neutron energy of 1 MeV, correct for self annealing and normalize the extracted values to a standard temperature of 20 °C. For the normalization to a neutron energy of 1 MeV we followed the recipe given by Kraner (16), which yields a correction factor of 1 : 1.25 both for a ^{252}Cf neutron source and a reactor neutron spectrum, 1.70 : 1 for a PuBe neutron source and 2.75 : 1 for monoenergetic 14 MeV neutrons. The self annealing corrections are derived from our own measurements (see table 4 and 5, discussed below) and the temperature correction was carried out according to the well known equation for the intrinsic charge carrier density :

$$n_i(T) = 3.87 \cdot 10^{16} \cdot T^{3/2} \cdot \exp(-1.21/2kT)\ \text{cm}^{-3}$$

The damage rate α enables one to directly calculate the current increase caused by a given fluence and is therefore most useful for practical purposes. However from a more physical point of view the so called damage constant k is more interesting. It is related to the decrease of the minority carrier lifetime (see e.g. (8)) and connected with the damage rate by:

$$\alpha = \frac{e_0 \cdot n_i}{2} \cdot k$$

In contrast to α, the damage constant k is independent of the temperature. For comparison we have included the respective values of k also in table 1. It should be noted that Kraner used a different definition. Both values are however directly related to each other ($K_{Kraner} = k^{-1}$). In our comparison of available data we have disregarded the values reported by Kraner for such devices which have very small areas (in the order of 0.1 cm^2) since edge effects may play an important role here and could have led to the observed large values of the damage rate. Also we have only included those measurements, for which the experimental conditions were known so that the normalization to the standard situation could be performed. All data compiled in table 1 agree pretty well with each other after normalization, the value extracted from Vismara's work being only slightly larger than the average. For the value taken from Ohsugi we have assumed that the self annealing (which was measured in his own work) was already corrected for. Our comparison results therefore in an average damage rate value for 1 MeV neutrons, corrected for self annealing and normalized to 20 °C of:

$$\alpha = 0.68 \cdot 10^{-16}\ \mathrm{A/cm}$$

It should be emphasized here that within the limited range of the material resistivity, for which data are compared in table 1, in contrast to the results reported by Kraner no evident dependence on this parameter was found. However more experimental data are necessary to further clarify this point. Assuming that the neutron spectrum to be observed in a hadronic calorimeter results in about the same energy weighted damage rate as is given by fission neutrons with a relative yield of 1.25 with respect to 1 MeV we can expect the effective damage rate for silicon detectors in a calorimeter to be :

$$\alpha = 0.85 \cdot 10^{-16}\ \mathrm{A/cm}$$

DECREASE OF EFFECTIVE DONOR CONCENTRATION

Another interesting consequence of radiation damage is the change in the concentration of impurity centers. This influences the electric field distribution and is, therefore, also important for the charge collection process. The effective density of impurity centers can be taken from C-V characteristics. Measurements were carried out between fluences of 10^{10} and $2 \cdot 10^{12}$ particles per cm^2. The effect may be described by means of the removal rate β, which is given as

$$\beta = \frac{d\,N_{eff}(\Phi)}{d\,\Phi}$$

Our results for β are contained in table 2 together with some relevant data from the literature. Concentrating again on the more interesting case of

Table 2
Removal rate β of effective donor concentration (see text) for neutron and proton irradiation.

Particle Type	Energy (MeV)	ρ_{Si} (kΩcm)	N_{eff} ($10^{12} cm^{-13}$)	Operation type	β (cm^{-1})	Reference
n	14	2.73	1.60	floating	0.24 ± 0.06	this work
n	14	6.63	0.66	floating	0.31 ± 0.07	this work
n	^{252}Cf	4-6	1.1-0.73	—	0.15 *	(15)
p	25	2.56	1.71	floating	0.60 ± 0.09	this work
p	25	4.61	0.95	floating	0.41 ± 0.13	this work
p	25	4.65	0.94	biased	0.59 ± 0.08	this work
hadrons	$2 \cdot 10^5$	3	1.6	biased	0.050	(17)
p	$8 \cdot 10^5$	5	0.87	floating	0.029	(12)

* mean value for fluence range $0.2\text{-}1.9 \cdot 10^{11}$ n/cm^2

irradiation by neutrons the available data suggest no evident dependence on the material resistivity. This may be understood if the formation of V-P centers is not the predominant effect, but the main contribution is given by the generation of the negatively charged V-O and V-V centers (see also (15)). The V-P formation would give an effect, which is proportional to N_{eff}. On the other hand, the generation of V-O and V-V centers is independent of N_{eff} and hence in this case β would remain constant. It should, however, be stated that a more elaborate study is necessary on a wider range of resistivities to further clarify this effect. With the inclusion of the recent result reported by Vismara (15) we get an average value of:

$$\beta = 0.23 \text{ cm}^{-1}$$

As an example a neutron fluence of 10^{12} particles per cm^2 would result in an increase of the resistivity from an original value of 6.6 kΩcm by 35% to 8.9 kΩcm. This effect can be regarded to be small but may become quite large combined with a heat treatment necessary for annealing (see below). For 25 MeV protons β is slightly higher than for 14 MeV neutrons and seems to depend on whether the detector is under bias during irradiation or not. According to van Lint (9), β is expected to increase with decreasing free carrier concentration and, therefore, a detector under bias would be more susceptible than that without bias during irradiation. This is in agreement with our results. Finally, the β-values for higher proton energies, which are given here for comparison, are much lower than that obtained at 25 MeV. Also this tendency is in agreement with the general expectation (9) .

CHARGE COLLECTION DEFICIENCY

Especially for application in calorimetry a stable energy calibration during long operating periods is essential. For the H1 experiment a long term stability of 1 % should be maintained. In semiconductor detectors the damage enhanced trapping leads to an additional degradation of the detector performance, which has to be taken into account. The charge collection deficiency was measured after irradiation with 10^{12} particles per cm^2 (both for proton and neutron irradiation). With 5.8 MeV alpha particles incident on the front and rear side of the detector, electron and hole trapping could be studied separately, because the range of these particles (R = 30 µm) is very small compared to the depletion thickness of 400 µm. The effect was measured for different bias voltages, but always above total depletion. In each case the effective transit time t_c was calculated, taking the actual electric field distribution and the field depending carrier velocities (18) into account. The results for proton irradiation of a 5 kΩcm detector are plotted

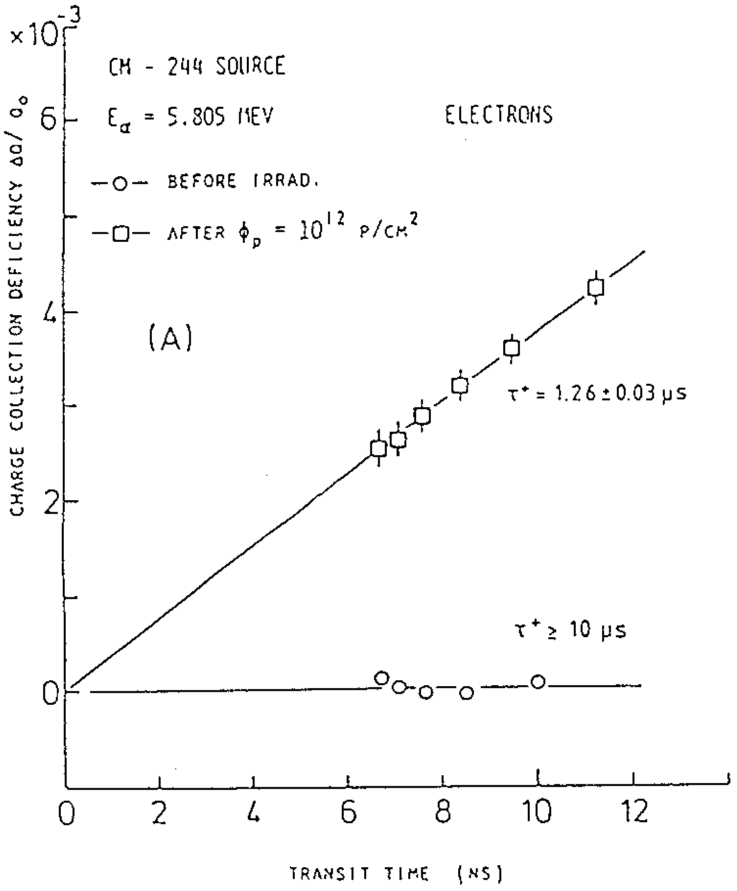

Fig.2 Charge collection deficiency versus transit time before and after proton damage (Φ_p= 10^{12} p/cm²) for 5,805 MeV α-particles. As an example the effect on electrons (front side entry) only is given.

in fig. 2. For small values of the charge collection deficiency this quantity is given by

$$1-\eta = \Delta Q/Q_0 = \tfrac{1}{2}\cdot\alpha\cdot t_c/\tau^+$$

where $\alpha = (w-x_0)/w$ (x_0 = center of charge distribution generated by the alpha particles and w = detector thickness) and τ^+ is the trapping time constant. this way τ^+ was derived both for electrons and holes before and after irradiation. While the effect is very small for electrons (τ^+= 1.25 µs, $\Delta Q/Q_0$=0.25% for an operating voltage of 190 V), we get an appreciably larger value for holes (τ^+=0.68 µs, $\Delta Q/Q_0$=1.2%; see (8)).

In the case of a nearly homgeneous electric field distribution (at overbias voltages) and particles traversing the detector with constant ionization density (e.g. mip's), the resulting charge collection deficiency is given by

$$\Delta Q/Q_0 = 1/6\cdot\{ t_{c,e}/\tau_e^+ + t_{c,h}/\tau_h^+ \}$$

This leads in our case of $\Phi = 10^{12}$ p/cm^2 to $\Delta Q/Q_0$=0.6%, a value well below 1%! For neutron irradiation of a 2 kΩcm detector we get very similar results. Plots like that of fig. 2 resulted in electron trapping with τ^+=2.33 µs and $\Delta Q/Q_0$= 0.13% for an operating voltage of 215 V and for hole trapping we obtained τ^+= 0.71 µs and $\Delta Q/Q_0$= 1.6%.

ANNEALING EFFECTS

As was mentioned above annual neutron fluences of up to several 10^{13} particles per cm^2 have to be envisioned for applications in future HEP-experiments. For this radiation level the operation of large area silicon detectors will, however, become practically impossible, as the bulk generation current would by far exceed a tolerable level. The possibility of annealing is, therefore, of utmost importance.

We studied this effect for extended storage times at room temperature as well as for different short heat cycles. The results for self annealing after irradiation with 10^{12} particles per cm^2 are displayed in fig. 3. Here we have plotted the unannealed fraction of the detector current as function of time. The curves could be analysed with the superposition of several exponentials:

$$\Delta I/\Delta I_0 = \sum_i A_i \exp(-t/\tau_i)$$

The extracted parameters are given in table 3. Other authors have used a different ansatz (11). Therefore, it should be useful to directly compare the unannealed fraction of the leakage current as function of time. As an example such a comparison is contained in table 4 for neutron damage. As can be seen, our data are in very good agreement with those of Ohsugi (10).

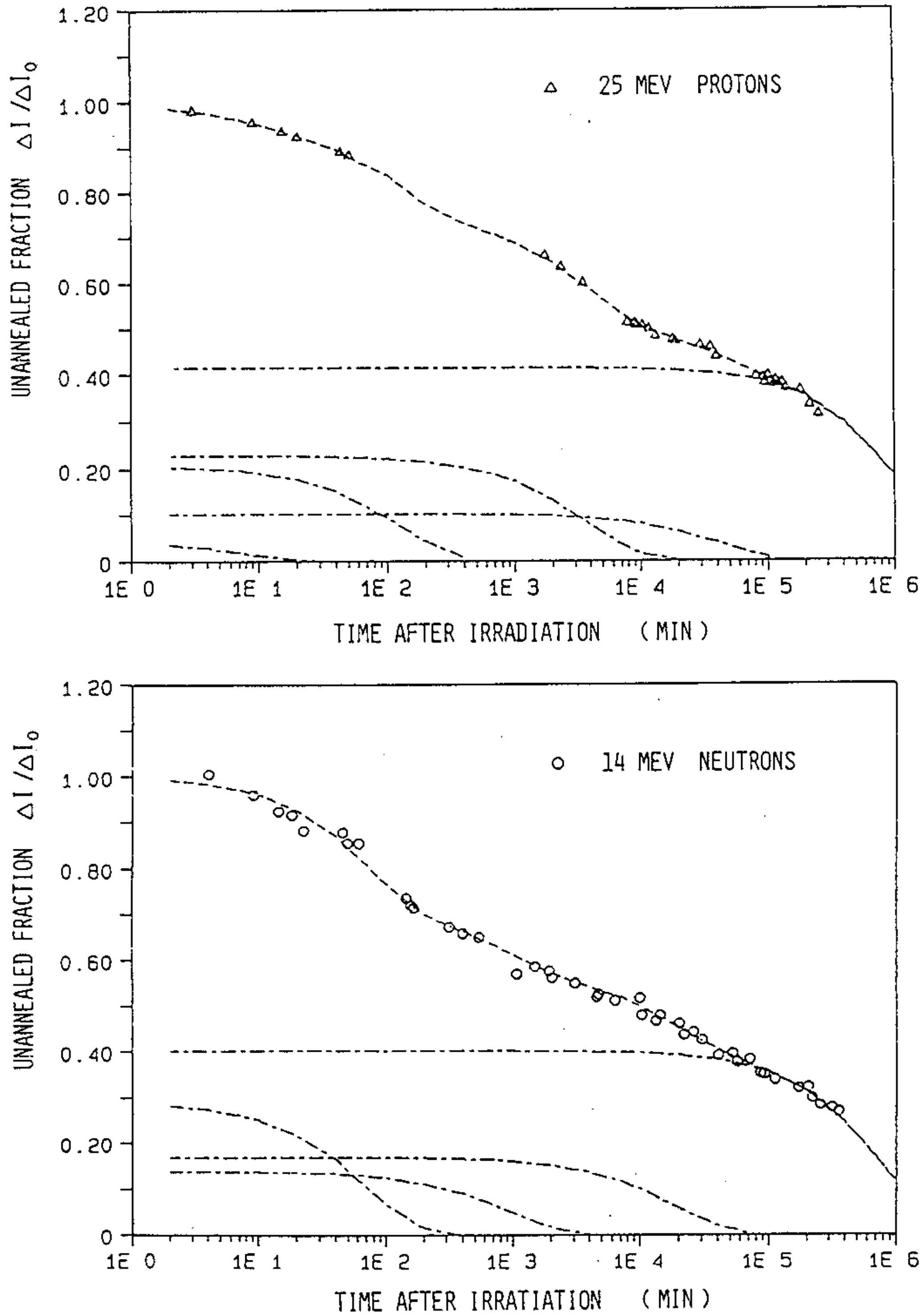

Fig.3 Room temperature annealing of proton and neutron induced damage: Ratio of detector leakage current $\Delta I/\Delta I_0$ as function of time after irradiation ($\Phi_p = 2.23 \cdot 10^{12}$ p/cm², $\Phi_n = 1.1 \cdot 10^{12}$ n/cm²).

Table 3
Time constants τ_i and relative amplitudes A_i (see text) obtained from fitting the self annealing curves given in fig.3.

	25 MeV PROTONS		14 MeV NEUTRONS	
i	time constant τ_i (min)	rel. amplitude A_i	time constant τ_i (min)	rel. ampliltude A_i
1	$(1.2 \pm 0.2) \cdot 10^6$	0.42 ± 0.01	$(8.1 \pm 0.5) \cdot 10^5$	0.40 ± 0.01
2	$(4.1 \pm 0.6) \cdot 10^4$	0.10 ± 0.01	$(1.9 \pm 0.1) \cdot 10^4$	0.17 ± 0.01
3	$(3.7 \pm 0.3) \cdot 10^3$	0.23 ± 0.02	$(9.7 \pm 2.8) \cdot 10^2$	0.14 ± 0.02
4	124 ± 25	0.21 ± 0.02	70 ± 4	0.29 ± 0.02
5	8 ± 5	0.04 ± 0.03		

The self annealing during irradiation with a constant flux can be calculated from

$$\Delta I_{an}/\Delta I_{na} = \sum A_i \cdot \frac{\tau_i}{T} \cdot \left(1 - \exp(-T/\tau_i)\right)$$

ΔI_{an} is the current increase including self annealing whereas ΔI_{na} is the value, which would be reached if no annealing would take place. T is the irradiation exposure time. The resulting ratios are plotted directly as function of the exposure time T in table 5. Tables 4 and 5 may be used to correct for both self annealing during the time elapsed between irradiation and measurement (table 4) and during an extended exposure itself (table 5). E.g. for the 206 resp. 660 h exposures reported in Kraner's work we get $\Delta I_{na}/\Delta I_{an} = 1.87$ and 2.15, for the 3 months irradiation by Vismara the corresponding factor is 2.55. These corrections have been carried out for the compilation of the data in table 1.

Table 4
Room temperature annealing of neutron induced damage: ratio of leakage current at time t to that 1 hour after end of irradiation.

Time t after irradiation	I(t)/I(1h) Ohsugi et al. (10)	I(t)/I(1h) this work
2 h	0.94	0.90
10 h	0.82	0.78
24 h	0.75	0.71
6 d	0.59	0.61
30 d	0.43	0.48
100 d	0.36	0.41

Table 5
Self annealing effect during neutron irradiation at room temperature. ΔI_{an} is the current increase during irradiation time T, ΔI_{na} is that which would be obtained without annealing.

Irradiation time T	$\Delta I_{an}/\Delta I_{na}$
6 h	0.741
1 d	0.651
6 d	0.553
30 d	0.461
100 d	0.389
365 d	0.300

It may be interesting to estimate the self annealing effect during long periods of operation as e.g. in the SSC calorimeter. If the detector accumulates a dose of 10^{13} neutrons per cm^2 in one year, the current increase would be only a factor of 3 less than obtained if the same fluence would be reached in one hour. Hence it is clear that self annealing is by far not enough to ensure the operability of such detectors over an extended period of time.

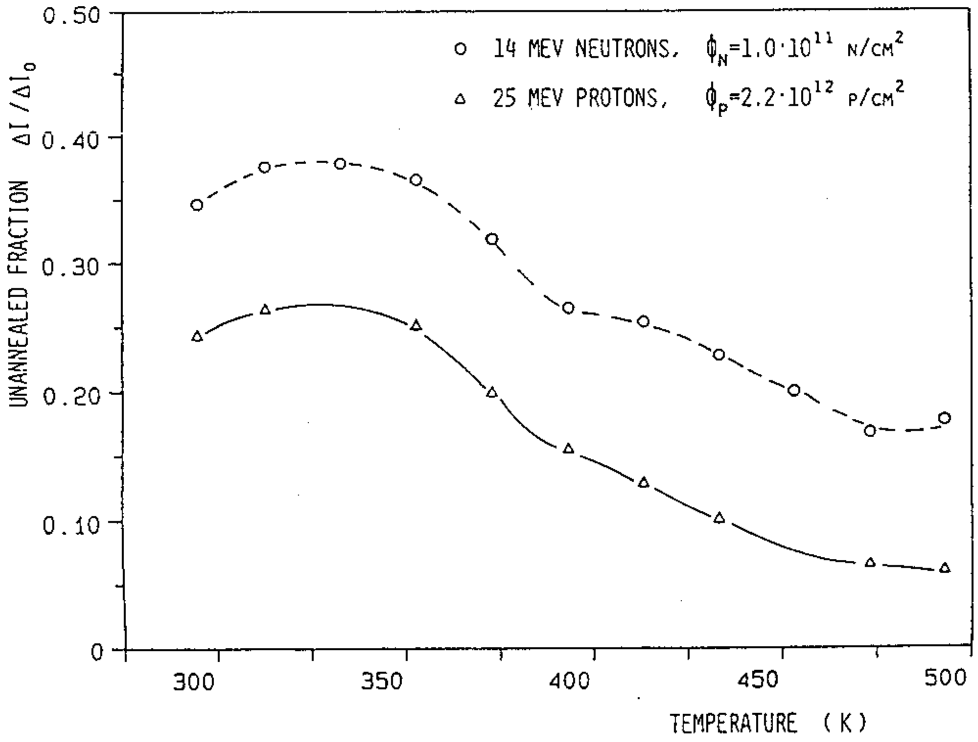

Fig.4 Unannealed fraction of neutron and proton damage of silicon detectors: Ratio of leakage current $\Delta I/\Delta I_0$ versus annealing temperature, annealing time t_a= 60 min.

Therefore, in addition, a temperature enhanced annealing was investigated. We concentrated on the isochronal method only, using heat cycles of 1 hour each and temperature steps of 20 °C between room temperature and 220 °C. The results are shown in fig. 4. As these experiments were performed after extended storage periods of up to 6 months, the damage was already reduced by an appreciable self annealing. The total recovery amounts to 94% in the case of protons and 83% for neutrons. The curves are quite similar for proton and neutron induced damage and their particular shape indicates two different annealing stages at about 370K and 440K. For low resistivity material and 14 MeV neutrons similar effects at 350K and 425K have been reported by Stein (19). According to Frank (20) and Corbett (21) these stages may be attributed to the annealing of the V-V and the V-P center respectively (see also (15)).

For very high neutron fluences of several 10^{13} n/cm^2 and year, to be foreseen in the SSC calorimeter at very forward angles, the detectors may have to be replaced in rather short intervals like every few months. In this case annealing would be only a solution if - even after several damage/annealing cycles - the damage rate is not increased appreciably. Only in this case we can hope to maintain a certain acceptable average detector

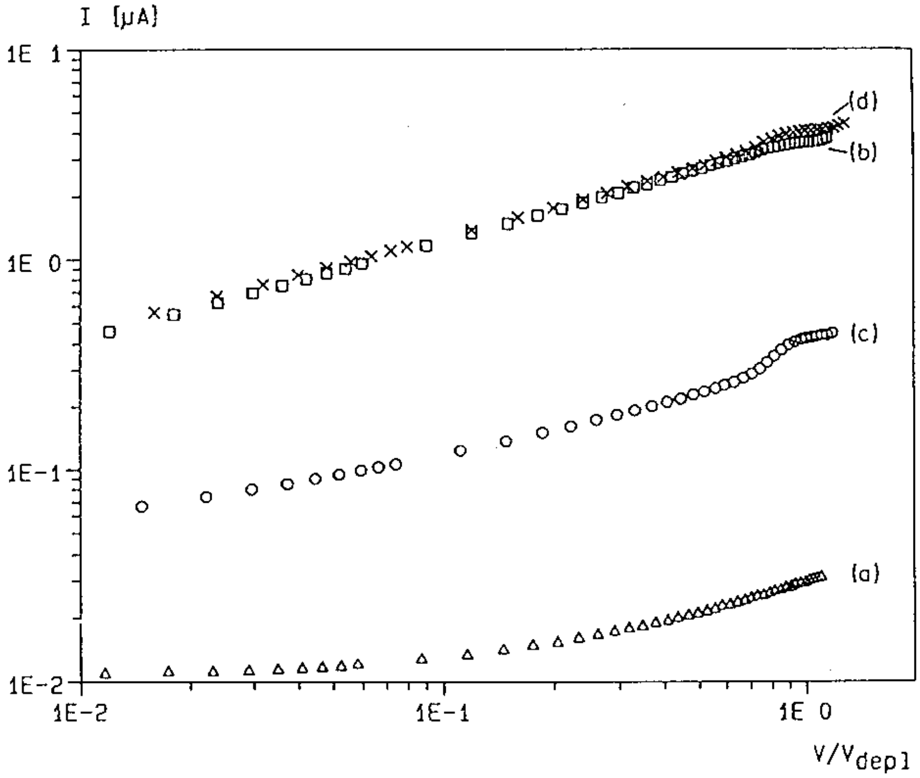

Fig.5 Current-voltage characteristics measured after different steps: (a) before irradiation, (b) after first irradiation with $3 \cdot 10^{11}$ n/cm^2, (c) after 6 months room temperature annealing, (d) after annealing for 1 hour at 200 °C and (e) after second irradiation with $2.7 \cdot 10^{11}$ n/cm^2.

current level over a period of years. Neutron damage is of a complex structure and results not only in point defects but also in clusters or voids. Annealing can be expected to heal primarily the point defects and change the effectiveness of clusters as charge generation centers. In addition some secondary defects may be produced which would in turn affect a subsequent damage. Therfore it is necessary to ensure that the damage rate does not depend on the history of former damage/annealing cycles. A preliminary experiment was undertaken in this respect. A detector produced from 3 kΩcm material was first irradiated with a fluence of $3 \cdot 10^{11}$ n/cm^2. The current voltage characteristic immediately after damage is shown in fig. 5 (curve (b)). The detector was then stored in normal ambients and underwent a self annealing for about 6 months. An additional heat treatment at 200° C for one hour resulted in an annealing of 90% of the original damage (curve (c)). A subsequent damage with $2.7 \cdot 10^{11}$ n/cm^2 led again to a current increase (curve (d)), which is approximately identical to that suffered by the first damage. Both curves are measured after the same elapsed time after irradiation (10 minutes). The corresponding damage rates, taking the observed shift of the depletion voltage into account, are $1.40 \cdot 10^{-16}$ A/cm for the first irradiation and $1.60 \cdot 10^{-16}$ A/cm for the second. The difference of about 13% is not significant since the exposure times were not the same and therefore a different amount of self annealing can be expected. The irregular behaviour of the I/V characteristic near depletion voltage, especially seen after annealing, may be attributed to some temperature enhanced migration of defects to the rear electrode. In conclusion there seems to be an evidence that the damage rate due to bulk defects does not depend on a previous damage/annealing cycle. This has to be substantiated by further experiments. On the other hand the surface effects have to be studied more carefully.

Finally it should be mentioned that the heat treatment which resulted in such a nice recovery as far as the current related damage is concerned gives also rise to a further appreciable increase in resistivity. Though this effect may be regarded to be profitable (e.g. lower depletion voltage) it could eventually lead to an inversion from n to p type material and hence to a complete breakdown of the detector operation. The development of a more refined annealing procedure avoiding this effect is under further study.

CONCLUSIONS

Radiation damage experiments performed with 14 MeV neutrons, 25 MeV protons and 20 keV X-rays have shown that the major degradation in detector performance is due to the damage induced bulk generation current. For neutrons and protons up to 10^{12} particles per cm^2 the observed damage rates are $1.4 \cdot 10^{-16}$ A/cm for 14 MeV neutrons and $2.3 \cdot 10^{-16}$ A/cm for 25 MeV protons . For X-ray doses up to 8 kGy the effect is small reaching a saturation value in the current increase of about 10 nA/cm^2. Taking the energy dependence and self annealing into account, the damage rate for 14 MeV neutrons reported here is in good agreement with that obtained for other neutron sources. No dependence of α on the material resistivity was observed. The normalized value (1 MeV neutrons, corrected for self annealing, T=20 °C) is $\alpha=0.68\cdot10^{-16}$ A/cm. For the neutron spectrum in a hadronic calorimeter a damage rate of $\alpha=0.85\cdot10^{-16}$ A/cm is to be expected. For the 5 cm^2 x 400 µm silicon detectors envisioned for a possible SSC calorimeter (5) a neutron fluence of 10^{12} particles per cm^2 and year would therefore lead to a current increase of 6 µA including already the dampening effect of self annealing during that period. A fluence of 10^{13} per cm^2 and year as to be envisioned for future calorimetric applications would therefore only be tolerable using an effective annealing by an additional heat treatment (see below). The observed decrease of the effective impurity concentration as given by the removal rate β is in the order of 0.23 cm^{-1} for neutrons, leading to a moderate increase of the resistivity from e.g. 6.6 kΩcm to 8.9 kΩcm if irradiated by 10^{12} n/cm^2. For 25 MeV protons we get $\beta=0.53$ cm^{-1}. The charge collection deficiency after exposure to a fluence of 10^{12} particles per cm^2 is not larger than about 1%, which is well within the required stability for calorimeter applications. All detectors show an appreciable self annealing effect. An additional isochronal annealing at temperatures up to 220° C has resulted in an 83% damage recovery for neutron and 94% for proton irradiation, thus giving a handle to extend the usable life time and, therefore, improve the cost effectiveness considerably. This is even more important since a successive damage after annealing does not result in an increased damage rate. The annealing procedure has to be further refined in order to avoid an excessive increase of the material resistivity and hence a possible inversion after high fluences and successive annealing. More detailed studies are under way.

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