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STUDY OF OPERATING CONDITION OF SEMICONDUCTORS FOR CALORIMETRY IN LHC/SSC RADIATION ENVIRONMENT

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Abstract

For experiments with future hadron colliders involving multi-TeV proton beams, such as the LHC and SSC, sampling calorimeters with silicon as active medium satisfy the special experimental conditions. Defect formation processes and electrical behavior of neutron irradiated p⁺-n ion implanted silicon detectors were studied. A fast monolithic preamplifier to be employed at hadron calorimeters was investigated for noise as a function of the expected leakage current in an SSC/LHC silicon calorimeter.

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1. INTRODUCTION

In the future hadron colliders, experimental conditions are defined by the very high luminosity (of about $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for LHC and about $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ for SSC) and high multiplicities, which require special features of the detectors. A sampling calorimeter with silicon as active medium can satisfy requirements of compactness, granularity, fast charge collection, easy calibration, good energy resolution, and compensation condition necessary to match with the experimental conditions.

In view of the very high neutron fluences (several 10^{13} n/cm^2 per year are foreseen in the SSC calorimeter at very forward angles), the use of silicon detectors in such an environment requires detailed studies in order to understand the defect formation processes and the electrical behavior of irradiated silicon detectors. In a hadronic cascade inside a calorimeter the generated fast neutrons have a calculated energy spectrum with a maximum around 1 MeV [1]. Fast neutrons interact by elastic scattering with silicon atoms, inducing deep defect levels in the silicon band gap under the form of vacancies, multivacancies, vacancy-impurity pairs, and clusters of defects. It is, therefore, important to perform measurements on silicon samples in order to correlate the damages caused by neutrons with the degradation of detectors.

Information about many of the properties of the radiation induced deep defects has been obtained in recent years, mainly by means of Thermally Stimulated Currents (TSC) and Deep Level Transient Spectroscopy (DLTS) methods. The leakage current and its increase appear as a direct sign of the effects of radiation damage on the silicon detector performances. The leakage current depends on the accumulated dose. High values of the current and the related electronic noise impose a limit on the operation of the detectors and, hence, on the lifetime of the calorimeter. Therefore, the study of the possibility of damage annealing becomes of primary importance. Room temperature self annealing and short term heat treatment on irradiated detectors have been carefully investigated, together with the effect of the leakage current increase, on the equivalent noise charge (ENC).

In this paper the defect formation processes and electrical behavior of irradiated silicon detectors, as expected in the above mentioned experiments, have been studied.

In the second section, leakage current measurements results of neutron-irradiated p^+-n ion implanted silicon detectors are presented and results from annealing of those detectors, both at room temperature and up to 250°C , are also shown. DLTS and TSC measurements are presented in this section, as different peaks, corresponding to different point defects.

In section 3 a fast monolithic preamplifier, to be employed at hadron calorimeters, is described and its noise measurements are given as function of the leakage current.

2. INVESTIGATION OF IRRADIATED DETECTORS

Irradiation of p^+-n silicon detectors was performed at room temperature, with no bias applied, using a ^{252}Cf isotopic neutron source. The nominal areas of the detectors was $5 \times 5 \text{ mm}^2$ and $10 \times 10 \text{ mm}^2$, their thickness $400 \mu\text{m}$ and their resistivities between 4 and $6 \text{ k}\Omega\text{-cm}$.

The flux measured by activation of indium foils, was between 3.4×10^3 and 9.9×10^4 neutrons $\text{cm}^{-2}\text{s}^{-1}$. The irradiation periods were between 10^6 and 10^7 s and the fluences between 10^{11} and $10^{12} \text{ neutrons cm}^{-2}$.

The increase of the leakage current after irradiation is a linear function of fluence (ϕ).

$$\Delta I = \alpha \cdot \phi \cdot V$$

where α is the leakage current constant,
V-the detector volume

$$\text{and } \Delta I = I_i - I_0 \begin{cases} I_i - \text{leakage current after irradiation} \\ I_0 - \text{leakage current before irradiation} \end{cases}$$

The leakage current was measured at 20°C, the neutron emission energy of the ^{252}Cf source is about 1 MeV and the irradiation duration was 10^7s , simulating the one year operation in LHC/SSC apparatus.

The experimentally found value of α is:

$$\alpha = (4.8 \pm 0.9) \times 10^{-17} \text{ A / cm}$$

The error of the α value is due mainly to the error of the flux measurements.

2.1 ANNEALING PROCEDURES

Immediately after storing irradiated detectors at room temperature, a decrease of leakage current is observed. Therefore, for a source employed during a long irradiation time period, like ^{252}Cf used in this investigation, self-annealing takes place during the irradiation itself. Thus, the final value of leakage current after irradiation is lower than the expected one from a source reaching the same dose, but during short irradiation time.

With heat treatment at 100°C, the leakage current decreases by 50% and at 150°C, by 80%.

As already mentioned the leakage current of the detectors increases when irradiated with the ^{252}Cf neutron source and when annealed by heat treatment, they recover. When irradiated a second time, with the same neutron source, the leakage current increases at a very similar rate and also the recovery behavior pattern is similar for the same heat treatment annealing.

2.2 DETERMINATION OF DEFECTS BY DLTS AND TSC TECHNIQUES

The DLTS (Deep Level Transient Spectroscopy) and TSC (Thermally Stimulated Currents) techniques enable the detection of deep defects produced in the bulk of the detectors by the absorbed radiation. DLTS uses the measure of the capacitance transient variation (due to the slow emission of the carriers captured in traps) as a function of temperature. TSC uses the measure of the detector leakage current during a thermal scan and after the traps present in the band gap of the silicon are being filled.

By analyzing irradiated silicon detectors with DLTS, three peaks corresponding to three different point defects, were found (fig. 1, see Ref. 2). The activation energies E_1 , E_2 , and E_3 were 0.16 ± 0.01 , 0.25 ± 0.02 , and (0.40 ± 0.02) eV respectively, below the conduction band energy E_C . The first peak is the activation energy reported for the A center [3], the second one can be associated with the double-minus charge state of the divacancy and the third is a complex of two defects, the E center [2] and the single-minus charge state of divacancy.

By using the TSC technique, the E_3 component was resolved. The two obtained values were (0.39 ± 0.01) eV for the single charge state of divacancy and (0.42 ± 0.02) eV for a vacancy-phosphorous-complex.

Electron capture cross-sections were also measured [4].

Heat treatment annealing performed at 200°C , caused a 80% decrease in trap concentration of the E_3 defect.

Six silicon detectors with nominal area of $5 \times 5 \text{ mm}^2$ were placed in an iron calorimeter at different positions of the shower. The Fe-calorimeter was irradiated with the primary 24 GeV proton beam at CERN, during three hours. The detectors were inserted in different positions, with Al-plates. Next to the detectors, targets of indium were placed in order to obtain the correct values of neutron fluxes irradiating the respective detectors. The iron plates area were $30 \times 30 \text{ cm}^2$ and 5 cm thick. The fluences of neutrons, measured with the indium targets, were from 8×10^{11} to $7 \times 10^{12} \text{ n/cm}^2$.

The obtained DLTS and TSC spectra were the same as that for detectors irradiated with the ^{252}Cf source.

The values of the leakage current of the silicon detectors placed in the Fe-calorimeter are in good agreement with the expected ones from neutron fluences. This indicates that the damages in silicon detectors are mainly due to the neutrons generated in hadronic showers.

3. EFFECT OF LEAKAGE CURRENT INCREASE ON THE EQUIVALENT NOISE CHARGE (ENC)

A fast VLSI preamplifier, to be used in silicon calorimetry applications at the next generation hadron colliders experiments, was used to measure the ENC value as a function of the detector leakage current. The preamplifier [5] employs a mixed bipolar CMOS technology developed by SGS Thomson Microelectronics. The rise-time of the preamplifier is about 7ns for a 5 V output swing with 150 pF input capacitance and is linear above 1 GeV, with $C_f = 10 \text{ pF}$.

The equivalent noise charge (fig. 1) is

$$\text{ENC}(e) = \frac{\exp(1)}{2q} \left\{ \frac{1}{2\tau_m} \left[(C_D + C_f + C_B)^2 \bar{e}_{eT}^2 + (C_D + C_f)^2 \bar{e}_{BB'}^2 \right] + \frac{\tau_M}{2} (\bar{i}_B^2 + \bar{i}_f^2) \right\}^{1/2} \quad (1)$$

where τ_M is the RC-CR shaping time.

C_D – input capacitance,

C_f – feedback capacitance,

C_b – transistor input capacitance,

$\bar{e}_T^2 = \frac{4kT0.5}{g_m}$ – collector shot noise referred to the input,

$\bar{e}_{BB'}^2 = 4kTR_{BB'}$ – input base spreading resistance thermal noise,

$\bar{i}_B^2 = 2qI_B$ – input current shot noise, and

$\bar{i}_f^2 = \frac{4kT}{R_f}$ – thermal feedback resistance noise.

Fig. 1

The main noise sources of the signal acquisition channel.

From eq.(1) it can be seen that the series noise is proportional to the input capacitance and to the inverse of τ_M , while the parallel noise is proportional to τ_M . In this respect, at low τ_M values and high input capacitance, the parallel noise contribution to ENC may become negligible. This is the case for the detector leakage current which can be expressed by adding $i_d^2 = 2qI_D$ in the parallel noise term of eq.(1), where I_D is the leakage current of the detector.

Fig. 2

The noise, expressed in dimension of energy, as a function of detector leakage current.

In figure 2, $\sigma_n [= 3.6 \text{ ENC}(e)]$ is presented as a function of I_D , where σ_n is noise expressed in dimension of energy. The factor 3.6 is the energy in eV, necessary to generate an electron-hole pair in silicon.

The calculation of the noise was performed by using the following parameter values:

$$\tau_M = 20\text{ns},$$

$$C_D = 150 \text{ pF} \quad R_{BB'} = 370 \Omega$$

$$C_f = 10 \text{ pF} \quad R_f = 100 \text{ k}\Omega$$

It can be seen that σ_n increases by 9% for an increase of the detector leakage current from a few nA to 200 μA . The measured points were in good agreement with the calculated ones.

4. CONCLUSIONS

Silicon detectors, irradiated with fluences of up to about 10^{12}n/cm^2 , showed a linear increase of leakage current versus the fluence of irradiation with a proportionality constant (α) of $(4.8 \pm 0.9) \cdot 10^{-17} \text{ A/cm}$ for an irradiation duration of up to about 120 days, at 20°C .

The increased leakage current leads towards a gradual deterioration of the silicon detectors. However, the appreciable decrease of the leakage current caused by annealing, already at room temperature, extends considerably the detector life expectancy.

The leakage current increase caused by neutron irradiation of the order of magnitude expected at future colliders is considerably ameliorated by the above described preamplifier. The fast VLSI preamplifier, which was especially developed to be employed with silicon sampling calorimeters, has a noise performance which is almost independent on the leakage current values.

REFERENCES

- [1] D.E. Groom, Nucl. Inst. Meth. Phys. Res., A279 (1989) 4.
- [2] E. Borchini et al., Nucl. Inst. Meth. Phys. Res., A279 (1989) 277.
- [3] Y. Tokuda, A. Usami, IEEE Trans. Nucl. Sci., NS-28 (1981) 3564.
- [4] E. Borchini et al., Leakage current, annealing, and deep defect production studies in neutron irradiated n-type Si-detectors. Submitted for publication.
- [5] A. Gola, G. Pessina, P.G. Rancoita, Nucl. Inst. Meth. Phys., Res. A292 (1990) 648.