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Hall Effect Analysis on Neutron Irradiated High Resistivity Silicon

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Abstract

Electrical conductivity and Hall coefficient modifications produced by high fluences of fast neutrons have been measured in high resistivity n-type silicon, using the four-point technique. A model based on dopant removal by neutron irradiation is proposed to describe the changes in the resistivity of homogeneous samples. From the fit of the experimental data, the initial dopant concentrations and the parameters describing donor and acceptor removal have been determined. Differences between the calculated values of Hall coefficient on the basis of this model and the measured ones, at fluences higher than 10^{19} n/cm², are explained in terms of the degradation of the Hall mobility.

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HALL EFFECT ANALYSIS ON NEUTRON IRRADIATED HIGH RESISTIVITY SILICON

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ABSTRACT

Electrical conductivity and Hall coefficient modifications produced by high fluences of fast neutrons have been measured in high resistivity n-type silicon, using the four-point technique. A model based on dopant removal by neutron irradiation is proposed to describe the changes in the resistivity of homogeneous samples. From the fit of the experimental data, the initial dopant concentrations and the parameters describing donor and acceptor removal have been determined. Differences between the calculated values of Hall coefficient on the basis of this model and the measured ones, at fluences higher than 10^{11} n/cm², are explained in terms of the degradation of the Hall mobility.

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1 Introduction

The answer to the questions arising from the study of fast neutron degradation effects in silicon detectors are conditioning their large scale utilization in the next generation of colliders.

The increase of the leakage current with neutron fluence was by the first problems studied [1-4]. It is not regarded now to conduce to a limitation of silicon detector utilization due to the possibility of cooling. The charge collection deficiency seems to be another solved question for the fluences expected to LHC ($F_s \sim 10^{14}$ n/cm²) [5]. The opened problems are now the increase of the effective carrier concentration in the space charge region of the detector at high neutron fluences, its reverse annealing at room temperature, which could make full depletion nearly impossible [6-7], and the increase of the resistivity in the neutral bulk region of the undepleted detector.

In this respect, the study of bulk silicon samples is done not only to clarify the fundamental interactions and processes in high resistivity neutron irradiated silicon, but to separately study the phenomena occurring in the neutral region of an undepleted detector. The main difference is that in the neutral region of a p-n junction, as well as in an homogeneous sample, there is no Fermi level crossing of radiation induced energy levels, and correspondingly, no change of their charge state.

In this paper, a model for the dependence of the resistivity of homogeneous samples on the neutron fluence is developed, starting from the fundamental interactions of neutrons with the silicon lattice. It

describes the measured effects in samples of n-type silicon, of initial resistivity 2 K Ω cm, in the range of fluences 10^{12} - 10^{14} n/cm².

The results of Hall coefficient measurements on the same samples are interpreted in terms of the degradation of Hall mobilities.

II. Experimental setup and procedure

The materials investigated in this study were high resistivity, n-type, float zone silicon, with initial resistivity 2-6 K Ω cm, from Wacker. Square shaped samples of 10x10 mm² area and 1mm thickness have been utilized. The four aluminium ohmic contacts in the corners have been deposited in vacuum on the scratched silicon surface [8]. Samples have been made at the Brookhaven National Laboratory, USA.

Fast neutrons, of average energy close to 1 MeV, have been obtained from 4 MeV Van der Graaff accelerated protons, incident on a lithium target, by means of the ⁷Li(p,n) reaction [9], at the irradiation facility of the University of Lowell. The neutron fluence varied from 10^{12} to 10^{14} n/cm². The changes in the resistivity and Hall coefficient induced by the neutron irradiation have been studied using d.c. four point probe measurements, at room temperature, at the Department of Energetics laboratories, Florence (DEF). The experimental set-up [10] consists of a Keithley measurement chain, that provides injection current to the sample, and allows the measurement of the Van der Pauw and Hall voltages. A magnetic field up to 10 KGs, with a 5 cm diameter homogeneous field region, is applied in Hall measurements.

III. Experimental results and discussion

The dependencies of the resistivity and Hall coefficient on the neutron fluence measured for the samples are presented in figures 1 (a) and (b) respectively approximately four months and 1 year after irradiation. One year of selfannealing at room temperature does not change significantly the shape of the resistivity and of the Hall coefficient curves. It could be

nevertheless observed after selfannealing a slight displacement toward lower fluences of the point corresponding to the maximum of the resistivity, to the minimum and to the point of sign inversion of the Hall coefficient. The resistivity increased with the irradiation fluence, near the value corresponding to intrinsic resistivity in silicon, in agreement with the results reported by other groups [11-12]. The Hall coefficient starts from low negative values, at low fluences, decreases with the increase of the fluence up to a minimum, and after that increases sharply and changes sign. This behaviour corresponds to the decrease of the electron concentration in the sample, with the corresponding increase of hole concentration, to satisfy the mass action law.

Fast neutron irradiation at room temperature leads, in silicon, to the introduction of deep energy levels, which act as generation-recombination or trapping centers [13-15], to the decrease of the net impurity concentration [16], and to the degradation of the mobility of charged carriers [17-18].

Bulk silicon degradation is understood today in terms of interaction of fast neutrons with the silicon atoms, with the formation of Si-V pairs, unstable, and which, in their turn, recombine and form stable defect complexes with some impurities or other defects they found in their way in the lattice. If the impurities that are participating to the formation of defects are dopants, as in the case of phosphorus (P) and boron (B), with the formation of P-V and B-V defects, a decrease of the dopant concentration results. The defects generated by irradiation correspond to different energy levels in the band gap, which charge states depend on the relative position of the Fermi level. The defect structures produced by moderate irradiation fluences, in the order of 10^{12} n/cm², had been studied by different physical methods, and the correspondence between the lattice defect and the energy level done [13]. The most important contributions to the change of resistivity with the irradiation fluence in homogeneous samples could come from the modifications of dopant concentrations. The presence of levels induced by irradiation is not important in the measurement of resistivity, as they are neutral and are not changing the charge state. The P (phosphorous) and B (boron) concentrations are modifying at irradiation due to their interactions

with the silicon interstitials and vacancies, according to the following reactions:

As was already pointed out, the up-mentioned reactions are neither the only ones where Si_i and vacancies V are participating, nor the most important: the main mechanism of their disappearance is their mutual annihilation, and by the most important impurities with which they are forming stable defects is oxygen. Other sinks for them could be other substitutional impurities, defect clusters, dislocations and crystal surfaces. In the present model it will be assumed that the reactions (1)-(4) are important only for the decrease of P and B doping concentrations, and that other reactions will not modify the carrier concentrations. While the $P-V$ defect is stable at room temperature, the B_i-V complex self anneals before room temperature, and restores this way B . The difference in the reactions of formation of $P-V$ and $B-V$ reflects in the dependence on fluence of P and B dopant concentrations:

$$N_p = N_p^0 \exp[-b_p \cdot F] \quad (5)$$

$$N_b = N_b^0 (b_1 + b_2 \exp(-b \cdot F)) / b \quad (6)$$

where N_p^0 and N_b^0 represent the P and B concentrations before

irradiation, and parameters b_p , b_1 and b_2 with $b_p = b_1 + b_2$ are related to the probabilities of formation of the defects.

Starting from the neutrality equation in the silicon bulk, from the mass action law and from the expression of resistivity in a near intrinsic semiconductor, the parameters N_p^0 , N_b^0 , b_p , b_1 and b_2 where determined by fit: results are shown in figure 2. Used fit parameters are the following:

$$N_p^0 = 0.526 \times 10^{12} \text{ cm}^{-3}$$

$$N_b^0 = 0.156 \times 10^{12} \text{ cm}^{-3}$$

$$b_p = 1.92 \times 10^{-13} \text{ cm}^2/\text{n}$$

$$b_1 = 34.5 \times 10^{-13} \text{ cm}^2/\text{n}$$

$$b_2 = 9.27 \times 10^{-13} \text{ cm}^2/\text{n}$$

It was assumed that the conduction mobility does not vary with the neutron fluence. Equations (5) and (6) has a consequence: the evolution toward p type of the sample at high fluences as may be observed in figure 3, where the calculated electron and hole concentrations are shown toward the fluence of irradiation. Figure 4 describes the corresponding change in the Fermi level position inside the band gap versus the neutron fluence.

Taking into account a decrease of the conduction mobility with the irradiation fluence, in agreement with the results reported in [17], the quality and the parameters of the fit do not change significantly.

The Hall coefficient was calculated, from the electron and hole concentrations obtained from resistivity measurements, supposing that the predominant scattering mechanism of charge carriers is on ionized impurities, and taking into account the correction for non spherical energy surfaces of silicon [20]. A good concordance with the measurements has been obtained, up to fluences in the order of 10^{11} n/cm^2 . To keep the same concordance, special assumptions are to be made on the Hall mobility, both for electrons and holes. Again, the introduction of a variation of the conduction mobility as a function of the neutron fluence has no so much influence on the Hall coefficient.

The degradation of both hole and electron mobilities, pronounced after fluences in the order of 10^{13} n/cm² is the determining factor which could explain this nonconcordance. The degradation of electron and hole Hall mobilities has to be correlated with the high concentration of radiation induced point defects and clusters, which are introducing supplementary scattering mechanisms and are changing their relative importance.

IV. Conclusions

The proposed model for the dependence of resistivity on the neutron fluence describes well quantitatively the behaviour of n-type, high resistivity silicon samples. From the fit to the experimental data, the initial dopant concentrations and the parameters describing donor and acceptor removal have been determined. The importance of the initial compensation of the starting material has been pointed out. A degradation of the Hall mobilities, both for electrons and holes, at fluences higher than 10^{13} n/cm², has been found. This information has to be utilized in detector degradation understanding, directly for the undepleted region of the p-n junction, and indirectly for the space charge region of pn junctions.

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Figure 1.

(a) resistivity and (b) Hall coefficient vs. neutron fluence four months (1993) and one year (1994) after irradiation.

Figure 2.

Fit of the sample resistivity after four months selfannealing using equations (5) and (6).

Figure 3.

calculated (o) electron and (+) hole concentrations after four months selfannealing.

Figure 4.

Fermi level position inside the forbidden gap versus the fluence of irradiation: (x) measured and (-) fitted values.