Experimental Studies of Radiation Damage of Silicon Detectors*

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1 INTRODUCTION

New particle physics experiments are correlated with high luminosity and/or high energy [1]. The new generation of colliding beam machines which will be constructed will make an extrapolation of a factor of 100 in the center of mass energy and of 1000 in luminosity beyond present accelerators. The scientific community hopes that very exciting physics results could be achieved this way, from the solution to the problem of electroweak symmetry breaking to the possible discovery of new, unpredicted phenomena.

The characteristics of the radiation field the detectors must cope with is a complex function on the particles which collide, on their center of mass energy, on the machine luminosity, as well as on the details concerning the geometry and composition of the whole detection system. The radiation level depends substantially on the type of interactions (electromagnetic or strong), between the particles in the colliding beams. Specific problems appear in the calculations of composition and intensity of the radiation field for the proposed hadron colliders. Studies were developed to model the radiation field at colliders (see [2-4] and references cited therein). Both the increase of the center of mass energy and the increase of luminosity act in the same direction, increasing the fluences of particles which are traversing the detectors.

The particles which compose the radiation field are: electrons, pions, neutrons, protons and photons.

It has become evident that the problem of the radiation resistance of detectors in this severe environment is a crucial one.

This situation is complicated more by the fact that detectors must work all the run time of the machine, and better all the time of the experiment, without replacement (part or whole). So, studies related to the investigation of the radiation hardness of all detector parts, are developing (see, e.g. the CERN RAD program). These studies are in part material and device characterization after irradiation, and in part technological developments, made in order to find harder, cheaper technologies, for larger surfaces.

Semiconductor detectors have proven to be a good choice for vertex and calorimetry [5]. Both fixed target machines and colliders had utilized in the past silicon junction detectors as the whole or part of the detection system (see in [6] a list of present and future experiments which utilize semiconductor detectors). Precision beam hodoscopes and sophisticated trigger devices with silicon are equally used. The associated electronics is located near the detectors, and is subjected to the same radiation fields. Studies of material and device radiation hardness are developing in parallel.

2. NEUTRON INDUCED DAMAGE IN SILICON BULK AND IN SILICON DETECTORS

Neutrons have been recognized to produce significant lattice defects in silicon [7-8]. For the new machines, the major sources of all types of radiation are the primary pp collision and the subsequent interactions of the secondaries in the detector element, and in machine equipment. Secondary interactions are producing

lot of particles at lower energies than the primaries; their energies are in the region where defect production is more probable. There exists detailed simulations on the sequence of particle generation in hadronic interactions at high energies, first in a primary collision, then via nuclear spallation and evaporation processes plus electromagnetic interactions.

Regarding neutrons, it was obtained, as a conclusion of these simulations, that their energy spectrum is centered around 1 MeV. High neutron fluences were estimated, especially for the calorimeter region, for the future colliders [5]. So, the necessity of the study of the interaction of neutrons with the silicon bulk, as well as to the study of changes induced by neutrons in the characteristics of silicon junction devices is imposing by itself.

The primary interaction of neutrons with silicon produces primary knock-on atoms (PKA) and vacancies; in their turn, the PKA has sufficient kinetic energy to displace other Si atoms in the same lattice, generating a cascade of collision processes. The size of the displacement effects is proportional to the non-ionizing nuclear energy available [9]. The resultant vacancies are not stable at room temperature, and move in the lattice, which leads to the formation of stable defects, as divacancies and vacancy-impurity complexes. Lattice defects correspond to energy levels in the semiconductor band-gap.

The main methods of detection and characterization of energy levels in the silicon band-gap are thermostimulated current spectroscopy (TSC) and deep level transient spectroscopy (DLTS), which permit the determination of the defect energy level, the concentration and the capture cross section.

The modifications induced by irradiation in the lattice and in the energy diagram, mentioned before, are producing, in their turn, changes in the physical parameters of the material. Acting as generation-recombination centers, the defects produce the decrease of the minority carrier lifetime. Defects are also modifying carrier concentrations and their mobility. These defects result in long-lived modifications of the electrical properties of the silicon detectors upon which their good operation may depend.

The main detector characteristics which are modifying after neutron irradiation are:

- the leakage current,
- the C-V characteristic (slope and frequency dependence),
- the charge collection efficiency,
- the effective doping concentration or full depletion voltage.

tage.

Neutron irradiation produces the increase of the leakage current, the decrease of the charge collection efficiency, and, if the neutron fluence is higher than a specified threshold, in the order of 10^{13} n/cm^2 , the inversion of the conductivity type in the space charge region of the p⁺-n junction, from high resistivity n to p.

It is important to understand and to characterize quantitatively the changes induced by irradiation in the parameters of semiconductor detectors, in order to make the necessary corrections when their response is read-out.

This paper presents the common activity of groups from the Joint Institute for Nuclear Research (JINR), Dubna (Laboratory of Superhigh Energy Physics), the University of Florence & INFN Florence, Italy, the Brookhaven National Laboratory, USA, and the

University of Bucharest & Institute of Atomic Physics, Bucharest, Romania, directed toward the elucidation of different problems related to radiation damage in semiconductors and semiconductor devices.

Some results obtained in the characterization of degradation phenomena in neutron irradiated silicon and silicon detectors, as well as the influence of different technological conditions on their radiation hardness are reviewed:

- The modifications of the leakage current and of the depletion voltage of the p-n junction with the neutron irradiation fluence have been measured, at different time intervals after irradiation. The influence of the energy spectrum of the neutrons has been investigated, making irradiations at different facilities.

- Starting from the importance to have a microscopical understanding of the exchanges produced in the silicon lattice and in its band gap by irradiation, spectroscopical measurements (thermostimulated currents) were performed. Some information on the relation between the radiation induced energy levels in the silicon band gap, the neutron fluence, and the processing conditions could be drawn.

As some measurements in the space-charge region of semiconductor detectors (capacitance-voltage, charge collection efficiency after irradiation with short range particles) have indicated an inversion of the conductivity type, irradiated silicon bulk has been characterized by conductivity and Hall measurements. Preliminary results on the behavior of electron and hole concentrations in highly neutron irradiated silicon samples could be extracted.

3 SAMPLE PREPARATION

The study of radiation damage in neutron fields implies the understanding of defect formation, migration, and interaction with impurities in the silicon lattice. This could be done partially studying the role of ambient and processing conditions on the defects produced by irradiation. In this idea were prepared the samples.

The samples studied were either in the form of p-n junctions, or four point contacts bulk silicon, for Hall measurements, all from high resistivity silicon (4-7 k Ω cm).

The samples were made by SGS-Thomson after the project of INFN, by the Russian industry after the project of JINR-Dubna, and at BNL, after its own project, as follows.

P-n silicon junctions were prepared by SGS-Thomson, Italy, in the form of 2x2 mm² and 5x5 mm² detectors, one or four on the same wafer, using Wacker <111> silicon, and a "standard" technology: thermal oxidation, photolithography, ion (B and P) implantation, thermal evaporation of metallic contacts.

Detectors, made on JINR-Dubna project by the ELMA Association, Russia, in the form of p-n junctions, 20x20 mm² [10], were also measured. The p⁺ side of the junction is realized by B implantation, but the possibility to make it by a cheaper process, diffusion, is

in study. Aluminium ohmic contacts 1 μm thick have been deposited.

Special technologies have been developed at the BNL's Silicon Detector and Development Processing Laboratory, to do "impurity engineering". Different oxidation conditions have been utilized, to investigate their influence on the radiation hardness [11]. These five oxidations differ in the maximum temperature, the composition of the oxidation ambient and the oxidation time (see Table 1).

A special technology to do ohmic contacts has also been developed at BNL, by Al deposition on "sand papered" high resistivity silicon [12]. This method has been utilized for the four contact bulk silicon samples, where a possible inversion of the conductivity type could appear. Ohmic contacts are usually realized on high resistivity silicon by a previous shallow impurification of the semiconductor in the region adjacent to the contact. These four contacts square shaped samples, 10x10 mm², of 400 and respectively 1000 μm were made specially for Van der Pauw and Hall measurements.

4. NEUTRON IRRADIATION

As it has been mentioned before, neutrons are a major component of the radiation field of a collider [2], so hardness testing in neutron fields is nowadays an essential stage in detector construction, technological research and development studies.

It is recommendable to do such tests of radiation resistance of detector components in neutron fields in conditions similar to

that in which they will work in the colliders. The most important characteristics of neutrons from this point of view are the energy spectrum, the fluence and the flux. In order to have a separate characterization of the damages induced by neutrons and photons, it is recommendable that the neutron irradiation facility have a γ component as low as possible. As semiconductor parameters have a strong temperature dependence, an equally important qualifier of the irradiation facility is the temperature during irradiation.

Irradiations of silicon p-n junction detectors, of silicon fast amplifiers, of bulk silicon samples with and without metallic contacts have been made at the IBR-2 pulsed reactor of JINR-Dubna, at the irradiation facility of the Lowell University (USA), and at the Sigma-Sigma ($\Sigma\Sigma$) facility of the Institute of Atomic Physics in Bucharest.

All of them have average neutron energies around 1 MeV, being in the region of interest from the point of view of the simulated energy spectrum of colliders, but in the same time of significant displacement damage in silicon [13].

Neutron irradiations in this spectral region (~1 MeV) have been performed at the Sigma-Sigma ($\Sigma\Sigma$) facility in Bucharest [14]. It has been constructed to be an intermediate energy neutron source for reactor dosimetry [15]. So, it has a high precision of the evaluation of the fluence, as well as a complete description of the neutron energetic spectrum; these two qualities are very important for the studies of radiation damage.

The facility is a coupled spherical source located inside the graphite thermal column of the VVR-S Bucharest reactor. The fission source is a metallic uranium multishell sphere, with central

cavity of a diameter of 110 mm, used for irradiation. It is contained inside a screen which absorbs thermal and epithermal neutrons.

The neutron spectrum has been measured using proton recoil spectrometers; the differential flux-spectrum has also been computed using the unfolding code SAND II and the fission and activation reactions rates. The good concordance found between measurements and computation gives an idea about the quality of the calibration.

As was mentioned before, the most important characteristics of an irradiation facility for damage studies are the energy spectrum and the flux.

In Fig. 1, the differential spectrum of neutrons in Σ is represented. At the nominal power of the reactor (2 MW) the averaged energy in the range 10 KeV - 18 MeV is [15]:

$$\langle E_n \rangle = 0.827 \text{ MeV}$$

The calculated spectral index corresponding to the spectral shape is 17.2 ± 0.7 . The hardness parameter, which characterizes the displacement damage, was found to be 0.704 ± 0.07 .

The integral flux density in the range 10 KeV - 18 MeV is:

$$\langle \Phi_n \rangle = 3.385 \cdot 10^9 \text{ n/cm}^2 \text{ s.}$$

The measurement of the fluence is realized with two fission chambers, placed in the thermal column before and after the Σ sphere. An absolute calibration is done before the irradiation. The total error in the evaluation of the fluence is about 4 % (the statistical error being less than 0.5 %).

The ratio between gamma dose rate and neutron flux density, measured with thermoluminescent detectors at neutron fluences up to

$3 \cdot 10^{12} \text{ n/cm}^2$ is $6.84 \cdot 10^{-7} \text{ (rad/h)/(n/cm}^2 \text{ s)}$. The dose measurements are reproducible within 10%. A comparison between the gamma dose inside the ITN- Σ facility and that evaluated in the central tracking region of the LHC (see [10] and ref. cited therein) gives a factor of 14 smaller gamma dose rate in the studied irradiation facility, so that the supplementary effect due to gamma photons is believed to be small.

Temperature measurement during irradiation showed that up to 10^{12} n/cm^2 fluence, the temperature is 23°C , and increases up to 33°C at 10^{14} n/cm^2 .

At the irradiation facility of the University of Lowell, neutrons are obtained from Van der Graaff accelerated protons, of MeV energy, incident on a Li target, by means of the ${}^7\text{Li}(p,n)$ reaction [16]. This facility has been specially designed to have a very low ratio between gamma dose and neutron fluence, to make possible to separately study the influence of neutrons and of γ rays.

In the irradiations at the IBR-2 pulsed reactor, of JINR Dubna, the detectors were placed in the horizontal column, at a distance of 720 cm from the reactor core. The diameter of the neutron beam is 100 mm. A screen of 2 cm Pb and 1 cm B_4C absorbs thermal and epithermal neutrons. The energy spectrum of this facility (see, e.g. [5]) is similar in shape with the prompt fission spectrum of ${}^{235}\text{U}$.

The integral flux density in the interval 0.5 - 17 MeV is:

$$\langle \Phi_n \rangle = 3.2 \cdot 10^9 \text{ n/cm}^2 \text{ s.}$$

5 EXPERIMENTAL SET-UPS FOR THE CHARACTERIZATION OF RADIATION DAMAGE

a) MEASUREMENT OF CURRENT-VOLTAGE AND CAPACITANCE-VOLTAGE CHARACTERISTICS OF JUNCTION DETECTORS

It has been proven of interest to quantitatively characterize the neutron induced damage in p-n junction detectors from the study of I-V and C-V characteristics before and after irradiation. A Hewlett-Packard set-up, at the Microelectronica factory in Bucharest was utilized. The contacts in the measurement system are realized with low vacuum (back contact), and with a touch needle coupled to a microscope table for the rear one.

In the measurement of the I-V characteristic, the Keithley 616 applies and stores the current in the sample. The 3455A Hewlett-Packard (HP) digital voltmeter read-out the voltage. The HP-3052A is the data acquisition system, coupled to the HP-9845A calculator. A light screen was necessary due to the sensitivity of the silicon to light. The range of voltage variation was 0 - 50 V.

For the measurement of the C-V characteristic, the 410 Princeton Applied Research C-V plotter was utilized too. The voltage varied in the range 0 - 100 V.

The I-V and C-V characteristics of all p-n junction type detectors irradiated at the Σ facility have been measured utilizing the described set-up, both before and after irradiation, at several

time intervals after the neutron exposure, in order to understand the selfannealing mechanisms. The temperature during the measurement was taken.

b) TSC SET-UP AND DATA PROCESSING

Thermally stimulated current spectroscopy (TSC) permits determination of the main parameters of the neutron induced defect levels in the semiconductor band-gap [17-20].

In this technique, a semiconductor detector is first cooled to a low temperature with a reverse voltage applied to it. Then the energy levels associated with the defects are filled by applying forward bias, and, after returning to the reverse bias, the detector is heated with a constant rate. Measurements of the reverse current during the heating process show peaks due to the detrapping of carriers from the defect levels. The temperature at which the peaks occur is related to the energy level of the defect E_t [21].

Each deep trap is characterized by the energy level in the band gap associated with the defect, E_t , by its capture cross section, σ , and by the bulk concentration N_t . To obtain these parameters from TSC spectra, two different procedures can be used: the variation of the heating rate method [16] & [20], and the delay heating one [18-19].

The TSC experimental set-up [21] was entirely designed & built at the Energy Engineering Department Physics Laboratory

the University of Florence. It mainly consists in a liquid helium dewar in which a descending sample holder is inserted. The sample is maintained in the liquid helium vapors and thermal scans are obtained by simply pulling the sample holder up and down inside the dewar. A temperature controller (Lake Shore DC-91) is connected to a silicon sensor, placed inside the sample holder, close to the device under examination, to read the temperature during the thermal scan. A Keithley 617 electrometer ensures that the sample current is stored during the measurement. The entire system is computer interfaced by IEEE 488 modules. The data acquisition apparatus allows one to change the deexcitation time, the reverse voltage applied during the thermal scan, and the value and sign of the filling voltage.

For samples irradiated with neutron fluences in the order of 10^{13} n/cm² and higher, due to the presence of a multiplicity of defects inside the semiconductor bulk, a compound TSC spectrum results. The obtained TSC peaks are no more isolated, so the two methods cited above (the variation of the heating rate and the delayed heating) cannot be applied.

A deconvolution program which takes into account carrier emission from traps during the thermal scan [22] has been developed. Its main starting hypothesis are that during the thermal scan the carrier capture process by traps is negligible and that the depletion thickness is a constant. The performances of this code have been tested by directly comparing the experimental and numerical shapes of the isolated TSC peak, related to the A center. A very good concordance has been found, including the asymmetrical shape in temperature of the thermal emission peak.

TSC measurements have been utilized to study the characteristics of the radiation induced energy levels in the silicon band gap: at a high fluence of radiation (in the order of 10^{14} n/cm²), for samples processed in different conditions, and as a function of the irradiation fluence, for given processing conditions.

C) HALL AND VAN DER PAUW MEASUREMENTS AND SET UP

From the study of the capacitance-voltage characteristic of irradiated silicon detectors it has been found that irradiation induces resistivity variations in the bulk of p-n junction detectors [23-25], some possible explanations being donor removal and acceptor creation as a result of neutron irradiation (see the model of J. Walter [26] and the experimental results of the Hamburg group in [27]). So, in high resistivity silicon, the problem of the inversion of the conductivity type appears after a high level of irradiation (order of 10^{12} n/cm²). Different techniques were utilized to put in evidence the phenomenon, by different groups [28-30].

The Van der Pauw (resistivity) and Hall (Hall coefficient) measurements could give an understanding of the phenomena which occur in high resistivity silicon under neutron irradiation. Starting from the measured parameters, resistivity and Hall coefficient, the electron and hole concentrations could be found and some suppositions on the scattering mechanism are done [31].

Four contacts samples are required both for van der Pauw and

Hall measurements. In the first case, a current is applied between two adjacent terminals, while the voltage is measured between the two opposite ones. In the second, current is applied and voltage measured across the diagonal of the sample. For both, a total of eight voltages are taken for each measurement, doing cyclic permutations of the contacts, and for Hall, also the inversion of the sign of the magnetic field. From these voltages, the resistivity and the Hall coefficient of each sample can be deduced [32-33], and from their ratio the Hall mobility can be derived.

A Keithley chain, at the Energy Engineering Department Physics Laboratory of the University of Florence has been utilized for both types of measurements: a Keithley 199 DMM to measure the voltages across the sample under test, a Keithley 220 Current Source to apply the current, a Keithley 617 Electrometer to monitor the applied current, and a Keithley 705 Scanner + 7065 Hall Effect Card to do the necessary connections for these measurements. All this system is controlled by an IBM compatible computer, with the IEEE 488 interface. The data acquisition program has been done in Quick Basic. The magnetic field is applied utilizing the Varian V-4005 Electromagnet, with a Varian V-2900 source. From the magnetic field calibration with a Bell gaussmeter, an homogeneous field zone of 5 cm diameter was found.

6. RESULTS AND DISCUSSION

The main directions in the study of degradation induced by

neutron irradiation are the understanding of fundamental interactions of neutrons with the silicon lattice (comprising also interactions with impurities present there, and this way of influence of technology), and the passage from the microscopical level (crystal lattice, band gap), to the macroscopical one (parameters modified in radiation field).

The role of processing conditions on the radiation hardness of silicon detectors has been investigated in parallel with the influence of the neutron fluence on the characteristics of deep energy levels produced by irradiation. TSC measurements have been realized in both cases.

The degradation of the electrical characteristics of silicon bulk after neutron irradiation have been studied utilizing conductivity and Hall measurements. The free carrier concentrations have been derived. To note that, in comparison with the previously cited analysis, related to the space-charge region of the junction, these measurements have been performed in conditions of low electrical field. So, there is no a direct relation between carrier concentrations computed from Van der Pauw and measurements in bulk silicon and the same concentrations could be computed applying carrier statistics on the results of measurements, supposing the same starting material, the same spectrum and fluence for the irradiation neutrons. However, correlation between the results obtained from the two types of measurements is of interest.

In the first case, the TSC spectra of samples with five different oxidations (see Table 1) and which received the same high radiation fluence of $1.06 \times 10^{16} \text{ n/cm}^2$ were compared (see [34]).

draw conclusions on the influence of processing conditions on the radiation hardness.

The deconvolution method [22] has been applied to all TSC spectra, which, due to the high radiation fluence, are characterized by the overlapping of peaks corresponding to different defects. In fig. 2, a TSC spectrum is presented, for the sample with oxide A, in the temperature range 52-190 K, together with the performed deconvolution. In this restricted temperature interval 13 peaks have been found, corresponding to many energy levels in the band gap.

The results obtained from the application of the deconvolution method to the TSC spectra measured for all five samples, each corresponding to one type of oxidation, are summarized in table 2.

The corresponding peak temperature, and in the case it has been known from literature, the correspondence with the lattice defect, can be found in the same table. It can be seen that the lowest number of levels is obtained for the lower oxidation temperature, in the process without trichloroethane (TCA), and the highest number for the higher oxidation temperature, with TCA. An arrangement of the energy levels from table 2 in the silicon band gap, corresponding to all oxidations analyzed, is presented in fig. 3.

The previously known energy levels are put in their right positions in the band gap, donor or acceptor, while all others are placed in the upper middle of the gap, because TSC measurements could not, in fact, clarify the minority or majority character of traps.

From this study, we found that: the oxidation temperature is not the direct determining factor, neither in the number of energy levels, nor in the concentration of known defects, although a few levels were observed in the case of high temperature, with TCA oxidation. From the point of view of radiation hardness, it seems that the processing with TCA may induce more levels. However, extra levels introduced in the TCA processed samples may also serve as sinks for vacancies, which may decrease the concentrations of dominant defect levels that are contributing to the more serious problems such as the reverse annealing of the effective impurity concentration.

Samples with the highest temperature oxidation and without (oxidation A mentioned before), which seem more hard to radiate, were irradiated with neutrons of average energy 1 MeV, with fluences ranging from 2×10^{12} to 1×10^{14} n/cm², and then were analyzed by TSC, to study the characteristics of deep levels induced by high fluence neutron irradiation. Unirradiated samples were also in the composition of the set to be characterized. The original results of this study were reported in [35].

Fig. 4 presents a general overview of the TSC total-spectrum observed for fluences 0, 4.8×10^{12} , 1.1×10^{13} and 5.8×10^{13} n/cm², respectively. Only two peaks have been found for the undamaged detector, with temperatures close to 16 and 19K (fig 4a). These peaks are present in the spectra of irradiated samples also, but at different heights. Many new peaks between 20K and 160K appear when the fluence is of the order of 1.1×10^{13} n/cm² (fig 4c). With further irradiation, some of these new peaks simply become higher, others overlap and become broad peaks (peak temperatures: 26,

41, 47, 90, 110 and 155K respectively). There are some other peaks which appear already at the lowest irradiation fluence, of 1.5×10^{12} n/cm² (peak temperatures: 70, 120, 135, 142 and 147K respectively). Energy levels and trap concentrations related to each of the detected peaks for the fluences examined are reported in tables 3 and 4. The two peaks, present in all analyzed samples, unirradiated and irradiated, have been identified as phosphorus and boron dopant levels. In addition to the A and E centers, carbon related defect and divacancy complex in different charge states, nine new defect levels have been observed for fluences over 10^{13} n/cm². All peaks are strongly dependent on the filling forward voltage or injection current, especially for high fluences of irradiation. The dependence on the filling voltage of the total TSC spectrum related to 3.6×10^{13} n/cm² fluence is shown in fig. 5, for 10 and 50 Volts filling voltage.

Experimental investigations at high fluences have shown that almost all trap concentrations are of the same order of magnitude as the initial doping concentrations (see table 4), so that no defect should be neglected when radiation induced lattice disorder effects are examined.

The study of high resistivity irradiated silicon by Van der Pauw and Hall measurements has also been initiated. Fast neutron irradiation fluences ranged between 0 and 9×10^{13} n/cm². Electron and hole concentrations have been derived, supposing that radiation induced clusters in the silicon bulk do not change the scattering mechanism for different irradiation fluences. The preliminary results obtained from this study have been reported in [36].

We found that the resistivity increases with the irradiation fluence (this means the silicon becomes more intrinsic), and, at a given fluence begins to decrease a little, but mainly remains high resistivity, close to the intrinsic value, in agreement with ref [12] - see fig. 6. For the same set of samples, the Seebeck coefficient starts from low negative values, increases in absolute value and then passes to positive values - see fig. 7.

From these results, the dependencies of electron and hole concentrations on the irradiation fluence could be derived - see fig. 8.

The most important observation resulting from these graphs is that, in the bulk of the irradiated silicon, both the electron and hole concentrations evolve toward the corresponding intrinsic value in the material. To note that at the low free carrier concentrations present at high fluences, an inversion between n and p type may occur also in the electrical neutral bulk.

We note here that, the Hall measurement was performed at condition of no or low electric field, where there is no band bending and no Fermi level crossing by deep levels. On the other hand, the C-V measurements were carried out in full depletion or high electrical field, with band bending and Fermi level crossing [37]. In the Hall case, one measures the free carrier concentrations, n and p. In the C-V case, one measures the net concentration of all ionized impurities and deep levels, N_{eff} , which is equal to n or p for neutron irradiated silicon detectors.

Taking into account the interest presented by this field,

for high energy and high intensity physics experiments, the continuation of this research activity is intended, by multiplying the irradiation types. The range of neutron fluences will be increased, and in the same time the particle type will be diversified, passing from neutrons to charged particles, like electrons, protons and heavy ions.

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TABLES

Table 1: Processing conditions for the samples analyzed at a).

Table 2: Characterization by TSC of energy levels induced by irradiation in all type of processed samples.

Table 3: Energy levels present in samples irradiated with different neutron fluences.

Table 4: Concentrations of traps in samples irradiated with different neutron fluences.

FIGURE CAPTIONS

Fig. 1. Neutron flux density in the ITN - $\Sigma\Sigma$ facility (normalized to 9.305×10^9 n/cm²s)

Fig. 2. TSC spectrum for sample with oxide A, in the temperature interval 52-190 K, together with the performed deconvolution.

Fig. 3. Graphical representation of the energy levels in the band gap of silicon for oxidations analyzed in [34].

Fig. 4. TSC total spectra observed for fluences of a) 0, b) 4.8×10^{12} c) 1.1×10^{13} , and d) 5.8×10^{13} n/cm² respectively, obtained in conditions of high positive filling voltage.

Fig. 5. Total spectra for: a) 10 and b) 50 Volts obtained after 3.6×10^{13} n/cm² fluence.

Fig. 6. Dependence of van der Pauw resistivity on the neutron fluence.

Fig. 7. Dependence of Hall coefficient on fluence.

Fig. 8. Electron and hole concentration dependence on irradiation fluence derived from Hall and van der Pauw measurements.

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TABLE 1

Oxide Name	Oxide C	Oxide A'	Oxide A	Oxide A	Oxide A'
Thermal Conditions	6 hr, 1100 C, TCAO ₂ 18 hr, 700 C, TCAO ₂ 4 hr, 1000 C, TCAO ₂ 2 hr, 1000 C, N ₂	18 hr, 975 C, TCAO ₂ 2 hr, 975 C, N ₂	18 hr, 1200 C, O ₂ 2 hr, 1000 C, N ₂	20 hr, 1200 C, TCAO ₂ 2 hr, 1000 C, N ₂	20 hr, 1200 C, TCAO ₂ 2 hr, 1000 C, TCAO ₂
Oxide thickness	4500 Å	2800 Å	2800 Å	9000 Å	Bad Oxide, MOS impossible

TABLE 2

E _t [eV]	OXIDES					T [K]	Defects
	A 975 C	A' 1200 C	C 1100C TCA	A' 975 C TCA	A' 1200 C TCA		
.00-.04	.031 .034 .038	.031 .038	.031 .034 .038	.031 .034 .036	.031 .036 .040	16 19 20	B ⁻ ? P ⁺ ?
.04-.08	.053 .069	.052 .069	.045 .052 .069 .074	.052	.052	27 34 47	V ⁺ ?
.08-.12	.098	.086 100	.080 .102	.089 .098 .103 .108	.082 .092 .102	41 46 48	V ⁻ ?
.12-.16		.130	.130			63	V ⁺⁺ ?
.16-.20	.163 .177 .194	.167 .171 .187 .203	.167 .171 .175 .195	.165 .169 .183 .202	.165 .170 .185 .202	70 81 88 98	V-O ⁰
.20-.24	.215 .229		.215 .240	.233	.240	102 109	V-V ⁰
.24-.28	.253	.261	.255	.253	.251	120	V-V ⁼
.28-.34			.300	.300	.280	138	C _i -C _s ⁺
.34-.38	.340 .361	.341 •	.340 •	.347 .375	.350 .375	148 155	
.38-.41	.392	•	•	.40	•	165	V-V ⁻
.41-.43	.42	•	•	.42	•	173	P-V
.43-.46	.45	•	•	.45	•	182	B-V

TABLE 3

E_t [eV]	Trap Energy Levels E_t [eV]										T [K]	Defect
	Fluences (10^{13} n/cm ²)											
	0	1.55	1.97	2.55	4.79	7.50	11.4	19.9	35.9	56.7		
.00-.04	.031 .034 .039	.031 .032	.031 .034	.031 .034	.031 .036	.031 .035	.031 .035	.029 .033	.031 .035	.031 .035	16 19 22	B ⁻ ? P ⁺ ?
.04-.08	.053		.053	.052	.052	.060 .068	.054 .070	.050 .066	.054 .068	.051 .056	26 34	V ⁺ ?
.08-.12						.087 .092	.091 .100	.086 .098	.087 .100	.087 .099	41 47	V ⁻ ?
.12-.16												V ⁺⁺
.16-.20		.165	.162	.162	.160	.165	.163 .198	.163 .194	.162 .197	.163 .195	70 90	V-O ⁻
.20-.24									.230	.225	100 110	V-V ⁻
.24-.28		.270	.245	.255	.270	.250	.250	.250	.260	.250	120	V-V
.28-.34		.310	.295 .320	.324	.310	.330		.305 .327	.305	.308 .321	135 142	C _i -C _s
.34-.37		.345	.340	.356	.345	.342	.343	.342 .360	.348 .366	.341 .363	147 155	
.37-.41				.387	.370	.380	.380	.390	•	.395	163	V-V
.41-.45				.425	•	.422	.420	.425	•	.438	175	P-V

TABLE 4

E_t [eV]	Trap Concentration N_t [cm ⁻³]												T [K]	Defects
	Fluences [10 ²¹ w/cm ²]													
	0	1.55	1.97	2.55	4.79	7.50	11.4	19.9	35.9	56.7				
.00-.04	27	8.0	19	15	8	12	14	12	18	27			16	B-?
	17	1.0	1.3	1.4	1.2	1.4	.64	1.2	2.3	2.2			19	P+?
	3.6												22	
.04-.08	1.9		.40	.35	.17	.03	.76	.54	1.4	.76			26	V+?
.08-.12						.30	1.0	.90	2.3	5.0			34	
						.15	1.0	.50	1.3	6.3			41	V-?
.12-.16						.10	.60	.80	1.7	5.2			47	V++?
.16-.20		2.0	1.5	2.2	3.0	4.0	3.3	2.1	20	30			70	V-Oo
.20-.24							.15	.36	2.0	90			90	
										1.0	100		V-Vo	
.24-.28									6.2	2.2	110			
	1.0	2.3	16	23	.25	.39	1.6	2.7	1.7	120			V-V=	
.28-.34	17	6.8	19				3.4	7.0	28	135			135	
		8.0	3.0		1.2		3.4		10	142			C _t -C _s ⁺	
.34-.37	12	11	12	15	31	34	12	60	~100	147				
							8.0	10	16	155				
.37-.41				90	8.0	6.0	12	*	12	163			V-V-	
.41-.45				1.2	*	8.5	~10	~10	*	~100			P-V

Figure 1

Figure 3

Figure 2

Figure 4c

Figure 4d

Figure 4a

Figure 4b

Figure 5

Figure 6

Figure 7

Figure 8

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