Comparing radiation tolerant materials for ultra rad-hard tracking detectors

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Abstract – The need of ultra-radiation hard semiconductor detectors for the inner tracker regions in high energy physics experiments of the future generation has led the scientific community to deeply investigate the radiation hardness of different kind of materials. This report wish to directly compare state-of-art data on three materials studied in recent past and still under investigation: epitaxial Si, epitaxial SiC and diamond grown by chemical vapour deposition. Leakage current and full depletion voltage evolution with the accumulated fluence of irradiation due to fast hadrons as well as collected charge are discussed and compared.

1. Introduction

The possible increase of the luminosity of the Large Hadron Collider to 10^{35}cm^{-2}s^{-1} will increase the total fluence at which position sensitive silicon detectors would be exposed during a 5- to 10-year operation up to 1.5-3x10^{16}cm^{-2} in the innermost tracker layers [1]. An intense research program is under way to increase the radiation hardness of present semiconductor detectors and make them survive at such an extreme level of irradiation. The research has followed in recent years different paths, concerning either the development of radiation harder silicon materials and high bandgap semiconductors with increased radiation hardness or the development of new, device-engineered, ultra-rad hard detectors such as 3D structures[2,3]. In this paper we will discuss and compare the state-of-art results on the subject of the development of ultra-radiation-hard detectors.

The main radiation damage phenomena to semiconductor detectors are: the increase of the leakage current with the irradiation fluence due to the creation of generation-recombination centers, the change in the effective doping concentration at large fluences leading to increased depletion voltage and possibly involving the inversion of the space charge sign, a shortening of the carrier lifetimes due to increased trapping at radiation-induced defects, responsible for a loss of charge. We will analyse these important parameters of the detectors after irradiation with high fluence of fast hadrons (10^{14}-10^{16}cm^{-2}).

2. Expected Radiation Levels

Expected radiation levels for SuperLHC have been widely discussed in the high energy physics scientific community. Possible parameterisation with the radius for 2500fb^{-1} integrated luminosity are given in fig.1 [4,5]. A tentative division in three main tracker geometries (pixels, strips and long strips) is indicated, following suggestions given in [6].

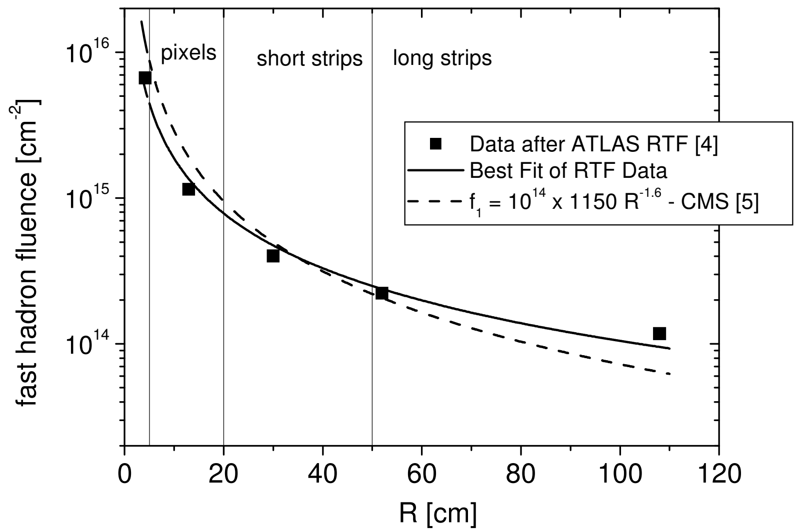

Fig. 1 Fast hadron fluence expected for an integrated luminosity of 2500fb^{-1} (5-years operation) and tentative division in optimised geometries for tracking detectors [6].

3. Leakage Current

The leakage current *I* in semiconductor detectors is mainly originated by the presence of generation-recombination deep levels which make it strongly dependent on the absolute temperature T:

$$I(T) \;\alpha\; T^2 \exp\left(-\frac{E}{KT}\right) \qquad (1)$$

with E a typical activation energy characterizing the main electrical conductivity process in the semiconductor bulk. In silicon the characteristic activation energy is half the semiconductor band gap, this evidencing that the most active generation centers are those at midgap. In SiC and CVD diamond films, characterised by a lower crystalline purity than Si, the transport processes are generally dominated by native deep traps whose activation energies are lower than half the gap. Computing leakage currents at room temperature for diamond and SiC detectors we find they should be almost 10^{-13} and 10^{-5} less than that of a Si detector with the same active volume. The experimental current actually measured can be nonetheless much higher than that expected from this calculation due to a non optimized manufacturing process or to the occurrence of larger microscopic defects in the material. Typical examples in SiC are dislocations and micropipes, while in diamond the most relevant contribution to the current is due to the passivation of dominant native defects, responsible of the setting up of a persistent current during and after irradiation.

It is a well know fact that irradiation in semiconductors causes to the creation of deep levels within the energy gap. The growth in concentration with further irradiation of these defects produces the compensation of the original dopants and of the native dominant defects in the semiconductor bulk, increasing the importance, for the evaluation of the leakage current, of those close to midgap. In diamond and SiC, where the activation energy before irradiation is mainly related to the presence of native defects, the effect of compensation by radiation-induced deep levels will bring the activation energy to become closer to midgap. As a consequence, the leakage current in such materials can be observed to decrease with increasing the fluence of irradiation. E.g., in ref. [7] authors report how the room temperature current density of epitaxial SiC pn junctions made on 55μm-thick epitaxial layer decreased from $60 nA/cm^2$ to $20 nA/cm^2$ after an irradiation of 10^{16} n/cm^2.

In silicon, the activation energy does not change significantly with irradiation, so the current is expected to increase proportionally with the increasing concentration of radiation-induced defects at midgap. This effect is well parameterised in terms of the leakage current density J as a function of the fluence Φ: $J(\Phi) = \alpha \cdot \Phi \cdot d$, with α damage constant α (usually referred to 1MeV neutron irradiation), d = depleted thickness. As the leakage current after irradiation depends on the annealing history of the detector, we have: $\alpha(60°C, 80\,\text{min}) = (3.99 \pm 0.03)x10^{-17} \frac{A}{cm}$ at the reference temperature of 20°C after a thermal treatment of 80min at 60°C [8]. Thus, the effect of the heavy fluence irradiation is to increase the volumetric current up to values far beyond the operational limits of the detector. The exponential dependence of the current given by eq. (1) is used to lower the leakage current of silicon detectors after irradiation by keeping the detector cold (typically they are kept at -10 ÷ -30°C).

4. Operational Voltage

SiC detectors are used in the form of Schottky or pn junctions. Due to intrinsic limitations in the production of the epilayer, N_{eff} is about $10^{14} cm^{-3}$ or higher. Data reported on a 55μm-thick layer show that this material is almost intrinsic already after a 1MeV neutron irradiation up to $3x10^{14} cm^{-3}$ [7]. This is suggesting a rate of generation of radiation-induced defects far higher than in silicon. Diamond detectors are produced by evaporating metals on the opposite surfaces of the sample, due to the exceptionally high resistivity (up to 10^{16}Ωcm) of the material the electrical conductivity of the device shows an ohmic behaviour. The operational voltage used for diamond detectors is that corresponding to an average electric field of 1V/μm. The operational voltage of a silicon detector coincides at null and low fluence with the full depletion voltage V_{dep} determined by capacitance-voltage measurements. After irradiation, the formation of radiation-induced defects changes the effective doping concentration in the space charge N_{eff}, defined by:

$$N_{eff} = \frac{2\varepsilon(V_{dep} + V_{bi})}{qW^2} \qquad (2)$$

with ε absolute dielectric constant, q electronic charge, V_{bi} built-in potential, W detector thickness. In p-on-n silicon detectors, an exponential decrease of N_{eff} and consequently V_{dep} with the fluence Φ is observed in the low fluence range while for higher fluences a linear increase of V_{dep} with Φ is observed. This phenomenon has been ascribed in n-type Si to the radiation-induced generation of deep acceptor-like states, which, bringing a negative contribution to N_{eff} leads for sufficiently high fluences to the inversion of the sign of the space charge [8]. The fluence at which a minimum in N_{eff} and V_{dep} occurs is called *inversion fluence*. In the very high fluence range ($\Phi > 10^{14}$ cm^{-2}) V_{dep} reaches values as high as 10^3-10^4V so that it becomes practically impossible to fully deplete the irradiated detector. In this simple picture, the change in sign of N_{eff} is attributed to the shift of the junction from the front side of the detector, near the *p* contact, to the back side, close to the *n* contact. However, it was shown that, for fluence higher than the inversion one, irradiated Si detectors appear to be sensitive on both sides for $V < V_{dep}$. To explain this experimental fact the irradiated detector is assumed to contain a double junction (DJ): one still placed at the *p* contact, with $N_{eff} > 0$, and a second at the *n* contact, characterised by $N_{eff} < 0$. In these conditions it becomes important where the region of maximum electric field is located. If the high electric field region has been shifted to the back electrode, the sample will be definitely type-inverted, and the voltage required to maximize the collected charge will be much higher then the full depletion voltage. Thus, at high fluences, p-on-n detectors need to be fully depleted or over-depleted to maximize the collected charge. The rate of increase of the full depletion voltage with the fluence in n-type silicon can be decreased by reducing the formation rate of the radiation-induced acceptor-like defects. This research line has been investigated within the RD48 and RD50 CERN collaboration by using n-type diffusion oxygenated FZ silicon. The standard FZ Si material is characterised by the presence of a concentration of interstitial oxygen content, of the order of $10^{15}cm^{-3}$, while DOFZ can be oxygen-enriched up to approximately $2x10^{17}cm^{-3}$ [8]. During irradiation oxygen is acting as a sink of vacancies, thus diminishing the rate of formation of the defects related to divacancy, usually characterised by deep acceptor-like activation energies. Results have been encouraging especially in case of gamma- and 24GeV proton-irradiation, where the lattice damage is mainly caused by point-defects, while with neutrons we see essentially no effect, as clusters, large aggregates of defects with activation energies close to midgap, are the dominant production of irradiation. Another way to reduce the rate of increase of the full depletion voltage with the fluence and possibly get rid of type inversion in n-type silicon is to increase the rate of formation of the radiation-induced donor defects. This research line has been investigated within RD50 by using n-type high resistivity Czochralski (Cz) and magnetic Czochralski (MCz) silicon. These materials are characterised by the presence of a high concentration of interstitial oxygen, typically up to $4x10^{17}$-$10^{18}cm^{-3}$. Also in this case the approach is especially successful for gamma- and 24GeV proton irradiation while with neutrons the effect is less evident. To determine the actual electric field distribution after the inversion fluence, Transient Current Technique (TCT) experiments [6] are usually performed. Reconstruction of the electric field profile shows that in 24GeV proton irradiated MCz Si detectors up to $2x10^{15}cm^{-2}$, the space charge dominant region is still at the p^+ contact, while in a similar detector irradiated with $5x10^{14}cm^{-2}$ reactor neutrons, the main high electric field region is placed at the back electrode.

As defects induced by radiation in Si are dominantly deep acceptor-like traps in n-on-p Si detectors type inversion is not supposed to show up in n-on-p Si detectors. Thus, p-type detectors have the critical advantage over customary p-on-n devices that the high electric field region is always at the readout electrode: the detector can be operated under-depleted, i.e. the bias voltage does not have to exceed the depletion voltage to be efficient. Under this assumption a number of n-on-p detectors have been up to now produced on p-type FZ, diffusion oxygenated FZ and MCz Si. First productions of detectors on p-type Magnetic Czochralski Si have shown a non-uniformity of the full depletion voltage along the wafer. This effect is probably related to the thermally activated formation of oxygen aggregates (thermal donors) [9]. Studies to optimize the manufacturing process of p-type MCz Si detectors are still under way.

5. Collected Charge

Fig. 2 shows the charge collected by single pad detectors made with different materials, after irradiation with fast hadrons up to the fluence of $10^{16}cm^{-2}$ (normalised to 1MeV neutron equivalent values) [3,10-12]. Detector thickness, operational temperature and shaping times of the electronic read-out system are listed in the legends. For polycrystalline diamond, a thickness of 300μm is considered, the highest collection distance up to now measured with this material at zero fluence [3]. A line is added to guide the eye to the qualitative trend of thick Si/diamond devices. We note that SiC is definitely less radiation hard than both diamond and silicon, at any fluence range. In terms of collected charge, diamond does not seem to be radiation harder than silicon, and single crystal diamond seems to degrade worse than polycrystalline CVD diamond films [3]. The benefit of using thicker Si substrates (typically p-type MCz and FZ) is particularly appealing for fluence lower than $2\text{-}4x10^{15}cm^{-2}$. Recent results on charge collection in MCz p- and n-type silicon after irradiation are discussed in detail in ref. [12]. For fluence higher than $4x10^{15}cm^{-2}$ Si and diamond are essentially the same collected charge around 3000e almost independent of the fluence and thickness. This can be explained considering that the formation of clusters of defects is dominating the transport properties of all the materials, equally limiting their charged carriers lifetime and collection distances. To increase the charge collection efficiency in this fluence range, it has been proposed to use 3D devices, characterised by columnar *pn* junctions inside the silicon bulk [13]. Recent results on charge collection in 3D devices made on p-type silicon are discussed in ref. [14].

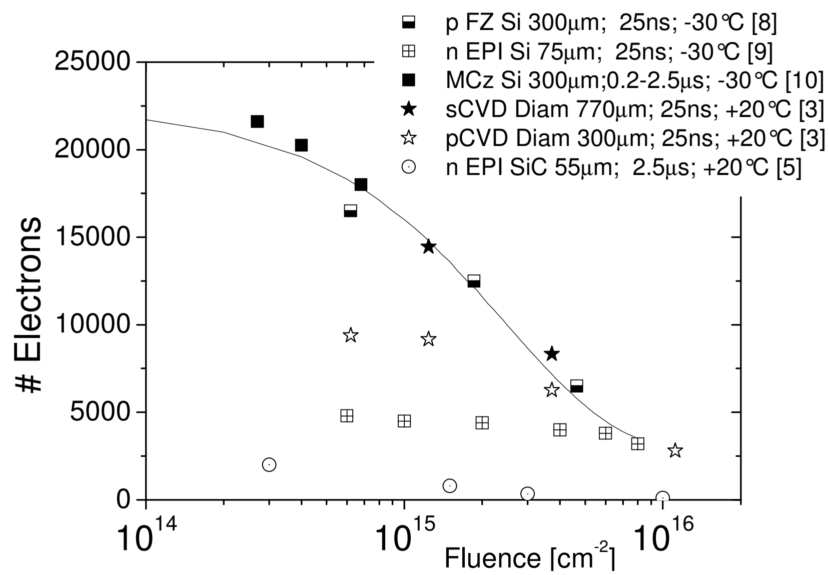

Fig. 2 Collected charge with different materials after irradiation with fast hadrons up to the fluence of $10^{16}cm^{-2}$ redrawn from refs. [3,10-12]. A guideline is added to follow the qualitative trend.

References

[1] F. Giannotti et al., "Physics potential and experimental challenges of the LHC luminosity upgrade", hep-ph/0204087, April 2002.

[2] The RD50 collaboration. CERN-LHCC-2004-031. http://www.cern.ch/rd50.

[3] W. Adam et al. (The RD42 Collaboration), Development of Diamond Tracking Detectors for High Luminosity Experiments at the LHC, CERN/LHCC 2006-010 LHCC-RD-010, Status Report/RD42, March 1, 2006.

[4] R. Horisberger **,** CMS Workshop on Detectors and Electronics for SLHC, CERN, February 2004.

[5] S.Baranov, M.Bosman, I.Dawson, V.Hedberg, A.Nisati and M.Shupe Estimation of Radiation Background, Impact on Detectors, Activation and Shielding Optimization in ATLAS Atlas Radiation Background Task Force Summary Document, ATL-GEN-2005-001, 13 January 2005.

[6] Hartmut F.-W. Sadrozinski, Abraham Seiden, Tracking detectors for the sLHC, the LHC upgrade, Nucl. Instr. Meth. A 541 (2005) 434–440.

[7] F. Moscatelli et al., Radiation hardness of minimum ionising particles detectors based on SiC p^+-n junctions, 7th RD50 workshop, Nov 14-16, 2005, CERN, Geneva.

[8] Mara Bruzzi, Radiation Damage in Silicon Detectors for High-Energy Physics Experiments, IEEE Transaction on Nuclear Science, Vol. 48 n.4 (2001).

[9] Mara Bruzzi, David Menichelli, Monica Scaringella, Jakko Harkonen, Zheng Li, Thermal Donors Formation via Isothermal Annealing in Magnetic Czochralski High Resistivity Silicon, Journal of Applied Physics 99, 93706 (2006).

[10] G. Casse, P.P. Allport, S. Martì i Garcia, M. Lozano, P.R. Turner, Performances of miniature microstrip detectors made on oxygen enriched p-type substrates after very high proton irradiation, Nucl. Instr. Meth. A 535 (2004) 362-365.

[11] G. Kramberger et al. 8th RD50 Workshop, Prague, June 25-29, 2006.

[12] Mara Bruzzi, Charge collection measurements in Magnetic Czochralski n- and p-type Si microstrip and diode detectors, this conference.

[13] S. I. Parker, C. J. Kenney, J. Segal Nucl. Instr. Meth. A 395 (1997) 328-343.

[14] M. Scaringella, H. F.-W. Sadrozinski, A. Polyakov, C. Tosi, M. Bruzzi, M. Boscardin, C. Piemonte, A. Pozza, S. Ronchin, N. Zorzi, G.-F. Dalla Betta , Charge Collection in Single-Column 3D Detectors, this conference.