Comparing radiation tolerant materials and devices for ultra rad-hard tracking detectors

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Abstract – The need for ultra-radiation hard semiconductor detectors for the inner tracker regions in high energy physics experiments of the future generation can be satisfied either with materials which are inherently more radiation hard than float zone silicon or with special detector structures with improved radiation resistance. This report compares directly the data on the performance of rad-hard materials and devices proposed for the superLHC.

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1. Introduction

The possible increase of the luminosity of the Large Hadron Collider to 10^{35} $cm^{-2}s^{-1}$ ("superLHC") [1] will result in an increase in the fluence position sensitive detectors have to withstand. For example, in the innermost tracker layers, tracking detectors would be exposed to hadron fluences of up to 1.5-3x10^{16} cm^{-2} during an 5- to 10-year operation. An intense research program is under way to increase the radiation hardness of semiconductor detectors, so that they can survive such extreme levels of irradiation. In recent years, the research has been pursued along different paths, concentrating either on the development of silicon materials and high bandgap semiconductors (SiC, diamond) with increased radiation hardness or on the development of new, device-engineered, ultra-rad hard detectors such as 3D structures [2], [3]. In this paper we will discuss and compare recent results on the performance of ultra-radiation-hard detectors.

The main radiation damage phenomena in 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 an increased depletion voltage and possibly the inversion of the space charge sign), and finally a shortening of the carrier lifetimes due to increased trapping at radiation-induced defects (with corresponding 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 2500 fb^{-1} integrated luminosity are given in Fig.1 [4], [5]. As usual, the radiation effects due to different particle species are taken into account by weighting the individual fluence with a relative damage factor and then quoting the fluence in terms of 1 MeV neutrons equivalents. A tentative division in three main tracker geometries (pixels, strips and long strips) is indicated, following suggestions given in [6]. For ATLAS, neutrons are the dominant particles in the outer tracker layers, and pions are most abundant in the pixel layers, while in the short strip layers both are important.

3. Leakage Current

The leakage current I in semiconductor detectors is mainly caused by the presence of generation-recombination deep levels which introduce a strong dependence 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 close to half the semiconductor band gap, which proves 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. Evaluating leakage currents at room temperature for diamond and SiC detectors we find that they should be lower by approximately a factor 10^{13} and 10^{5}, respectively, 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 for setting up persistent currents during and after irradiation.

Since the irradiation causes the creation of deep levels within the energy gap of semiconductors, the increase of these defects can lead to a compensation of the original dopants and of the native dominant defects in the semiconductor bulk, increasing the importance of the midgap states for the evaluation of the leakage current. 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 move closer to midgap. As a consequence, the leakage current in such materials can be observed to decrease with increasing fluence of irradiation. As an example, in ref. [7] the authors report how the room temperature current density of epitaxial SiC pn junctions made on 55 μm 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:

$$J(\Phi) = \alpha \cdot \Phi \cdot d \qquad (2)$$

with α the damage constant (usually referred to 1 MeV neutron irradiation), and d the depleted thickness. As the leakage current after irradiation depends on the annealing history of the detector, the damage constant is evaluated after a prescribed anneal history and we have: $\alpha(60°C, 80\,\text{min}) = (3.99 \pm 0.03) x 10^{-17} \frac{A}{cm}$ at the reference temperature of 20 °C after a thermal treatment of 80 min at 60 °C [9]. Thus, the effect of the high 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 with temperature 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 in the range of -10 to -30 ^{o}C).

As a comparison between different detector materials, Fig. 2 shows typical leakage current densities for Si, SiC and diamond as a function of the fluence (1 MeV n equivalent). The SiC device has a thickness of 55 μm, data are redrawn from [7]. The current density of the Si device (300 μm thick) has been calculated using eqs. (1-2) at -30 °C, a maximum applied voltage of 600 V and an effective doping generation rate $\beta = 0.005\ cm^{-1}$ [8] (see below). The knee observed around a fluence of $2x10^{15}\ cm^{-2}$ occurs when the detector ceases to be fully depleted. The data for diamond are from [8] and are for a 300 μm thick polycrystalline CVD diamond detector produced by Element Six measured after pumping the device with a ^{60}Co source at 300 K at 0.2 V/μm. We note that the leakage current of a detector made with a high-bandgap material being very low at room temperature and essentially constant or even decreasing with the fluence is one of the most advantageous features of these materials when compared to silicon.

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. Notwithstanding the low resistivity of this material before irradiation, data reported on a 55 μm thick layer show that it becomes almost intrinsic already after a 1 MeV neutron irradiation up to $3x10^{14}\ cm^{-3}$ [7], and remains almost intrinsic for any further increase of the fluence. This suggests a generation rate of radiation-induced defects far higher than in silicon.

Diamond detectors are produced by evaporating metals on opposite surfaces of the sample. Due to the exceptionally high resistivity (up to $10^{16}\ \Omega cm$) 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 1 V/μm and is independent of irradiation levels.

The operational voltage of a silicon detector coincides at low fluence with the full depletion voltage V_{fd} determined by capacitance-voltage measurements. After irradiation, the formation of radiation-induced defects changes the effective doping concentration N_{eff}, defined by:

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

with ε being the (static) permittivity of silicon, q the elementary charge, V_{bi} the built-in potential, W the 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 an increase of V_{dep} with Φ is observed. This increase has been measured to be linear with a slope β (see below). In the very high fluence range ($\Phi > 10^{15}$ cm^{-2}) V_{dep} reaches values as high as 10^3-10^4 V for 300 μm thick detectors, so that it becomes practically impossible to fully deplete the irradiated detector.

This phenomenon has been ascribed in n-type Si to the radiation-induced generation of deep acceptor-like states, which, contributing with a negative term to N_{eff}, leads for sufficiently high fluences to the inversion of the sign of the space charge [9]. The fluence at which a minimum in N_{eff} and V_{dep} occurs is called *inversion fluence*. 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 $V < V_{bias}$. To explain this experimental fact the irradiated detector is assumed to contain a double junction: one is still located 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 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 than the full depletion voltage to overcome the low field region during the drift. Thus, at high fluences, p-on-n detectors need to be fully depleted or over-depleted to maximize the collected charge. Detectors with double junctions are characterized by a lower constant field region in the center of the detector. The extend and strength of this field will determine how much of the charges drifting from the back plane will be trapped (see below).

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 approach has been investigated within the RD48 [10] and RD50 [2] CERN collaborations by using n-type diffusion oxygenated float zone silicon (DOFZ). The standard FZ Si material is characterised by the presence of a concentration of interstitial oxygen content, of the order of 10^{16} cm^{-3}, while DOFZ can be oxygen-enriched up to approximately $2x10^{17}$ cm^{-3} [9]. During the irradiation, oxygen acts as a sink of vacancies, thus diminishing the rate of formation of the defects related to di-vacancy, usually characterised by deep acceptor-like energy levels. Results have been encouraging especially in case of gamma- and 24 GeV proton-irradiation, where the lattice damage is mainly caused by point-defects, while with neutrons we see essentially no beneficial effect of the oxygen content, since in that case clusters, large aggregates of defects with energy levels close to midgap, are the dominant products of the irradiation.

An alternative method to reduce the rate of increase of the full depletion voltage with the fluence and possibly to eliminate type inversion in n-type silicon is to increase the rate of formation of 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 $4\text{x}10^{17}$-10^{18} cm^{-3}. It has been suggested that the enhanced radiation-induced donor generation in these materials is related to the presence of interstial oxygen dimers O_{2i}, not present in DOFZ , which act as precursors for the formation of shallow donors [11]. In Fig.2.a we show the dependence of the full depletion voltage on the fluence after irradiation with 24 GeV protons (CERN, Geneva) [12] and reactor neutrons in Ljubljana, Slovenia [13]. Both curves show a pronounced minimum in the full depletion voltage curve at the *inversion fluence*. To determine the actual electric field distribution after the inversion fluence, where the detector should be considered as 'type-inverted', a Transient Current Technique (TCT) experiment [14] has been performed with twin p-on-n single pad detectors made with n-type 1 kΩcm Magnetic Czochralski silicon after irradiation with 24 GeV protons up to $2\text{x}10^{15}$ cm^{-2} and 1 MeV neutrons up to $5\text{x}10^{14}$ cm^{-2}. Reconstruction of the electric field profile shows that there are three regions to consider in the n-type heavily irradiated detector. Considering the partially-depleted detector, (the proton irradiated data refer to V_{rev} = 280 V with V_{fd} ~ 500 V, and the neutron irradiated data to V_{rev} = 200 V with V_{fd} ~ 400 V), we observe two space charge regions, one at each contact, separated by a region with fairly low constant electric field produced by the reverse current flowing in the high resistivity neutral detector bulk, behaving like a resistor (TCT measurements are taken at T = 295 K). For the proton irradiated detector, at the p^+ contact there is an extended space charge region with a positive charge while the negatively charged region at the n^+ contact is rather narrow. In the neutron irradiated detector, the main high electric field region is placed at the back electrode. Thus the simple double junction picture of the irradiated detectors is confirmed, and the notion of type-inversion is traced back to the relative importance of the high field regions on the p^+ and n^+ contacts.

As defects induced by radiation in Si are dominantly deep acceptor-like traps, type inversion is not expected 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 for efficient charge collection. On the other hand, the depletion voltage is expected to be higher since the radiation generated acceptors add to the initial doping density, while in n-type they compensate it. 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 [15], [16], [17]. First productions of strip detectors with polysilicon biasing 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) [17], 18]. Studies to optimize the manufacturing process of p-type MCz Si detectors are still under way.

5. Collected Charge

Figure 4 shows the charge collected by single pad and microstrip detectors made with different rad-hard materials, after irradiation with fast hadrons up to the fluence of $10^{16}cm^{-2}$ (normalised to 1MeV neutron equivalent values) [3], [7], [15], [18], [19], [20]. Detector thickness, operational temperature and shaping times of the electronic read-out system are listed in the legend. All data refer to a measurement performed with minimum ionizing (*mip)* particles (mostly electrons from a ^{90}Sr source) except for 3D devices that are measured with a laser source. Before irradiation the most probable value of the collected charge for Si, SiC and diamond are respectively 73e/μm, 55e/μm and 36e/μm. Data for p-type FZ Si from ref. [15] have been normalized to 300μm thickness. Both data for p-type Fz and MCz Si are taken before to annealing. For silicon, we considered only those data with an applied voltage sufficiently high (typically up to 800-900V) to ensure full charge collection either by depleting the detector completely or to the thickness beyond which the charges are lost due to trapping . We normalised the data of radiation damage for polycrystalline CVD diamond (pCVD) and single crystal CVD diamond (sCVD) to a most probable charge collection at zero fluence of respectively 8000e (pCVD) and 24500e (sCVD, 770μm-thick) [3]. 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 more radiation hard than silicon, and single crystal diamond seems to degrade more than polycrystalline CVD diamond films [3]. From the plot shown in Figure 4, it is evident that for fluences below 2-4x$10^{15}cm^{-2}$, thick, planar, p-type MCz and FZ detectors exhibit superior performance in terms of radiation hardness. Beyond this fluence threshold, the highest charge collection values are measured for 3D devices [21], characterised by columnar *pn* junctions inside the silicon bulk [22]. Up to now only 3D detectors on standard n-type FZ Si with a thickness of 235μm have been tested with high radiation (although only with a laser source, which introduces a uncertainty about the absolute normalization) [20]. These devices show, at $8x10^{15}cm^{-2}$, a signal of 7130e, which is much larger than that of a 75μm thick epitaxial silicon (3200e) [18] and of a polycrystalline diamond (2800e measured at $1.1x10^{16}cm^{-2}$) [3].

The similarity of charge collection loss with fluence between the different materials is striking, and thus suggests to ascribe it to a charge trapping mechanism common to the different materials. In a simplistic model, useful to describe the behaviour qualitatively, only a part $N(\Phi)$ of the deposited charge N_o is collected. The reduction is both due to the inability to fully deplete the detector, so that depleted thickness d is less than the total detectors thickness, W, and due to trapping:

$$N(\Phi) = N_o \frac{d}{W} exp(-c\Phi \tau_s) . \tag{3}$$

where the trapping is described as an exponential decay with a factor depending on the ratio between the trapping time τ_t, and the transit time τ_s of the incident *mip* particle. At fluences below 10^{15} nep/cm^2, the trapping time is measured to be inversely proportional to the fluence:

$$1/\tau_t = c\Phi \tag{4}$$

A much more thorough treatment of trapping in both pad and strip detectors, for electrons and holes including annealing can be found in [23]. Since in n-on-p type detectors the signal is mostly due to electron transport, we concentrate here on electron trapping only, and simulate the collected signal simply with a step-wise transport of electrons in a field of a p-type microstrip detector. Early estimations of the trapping parameter *c*, the constant for neutron damaged n-type pad detectors, in eq. (4) gave $c_1 = 5.1\cdot10^{-16}$ cm^{2}ns^{-1}, using the transient current technique (TCT) [23]. The dotted line in Fig. 4 has been calculated using this value, giving a bad description of the data. If we evaluate the fluence dependence of the collected charge in proton damaged p-type microstrip detectors [15] in terms of trapping, we find a trapping constant of $c_2 \approx 2\cdot10^{-16}$ cm^{2}ns^{-1}. The solid line in Fig. 5 has been calculated using $c_2 = 1.8\cdot10^{-16}$ cm^{2}ns^{-1} giving a good description of the data. Among possible explanations for the discrepancy between directly measured and extracted trapping parameters *c* we mention the saturation of the fluence dependence eq. (4), and the existence of complicated field configurations inside the heavily irradiated detector, as described in the previous section.

6. Detector Performance

Most detector performance parameters depend on the signal-to-noise ratio S/N. While the signal S depends only weakly on the detector geometry for a given thickness (changing mainly due to charge sharing between neighboring detector elements), the noise is dependent on the geometry of the detector element being read out, since both the capacitance and the leakage current scale with the length . To determine the detector performance as a function of the fluence we make the distinction between two main detector regions, depending on the radial distance from the collision point, as indicated in Fig. 1. Detectors in the inner region, where pixel layers are foreseen, should withstand fast hadron fluences in the range $0.1\text{-}2\text{x}10^{16}\text{cm}^{-2}$, while detectors in the outer region, where short/long strips will operate, must work after fluence lower than about $1\text{x}10^{15}\text{cm}^{-2}$.

6.1 Outer Region

As we already discussed, thick, planar detectors made on p-type MCz and/or FZ silicon are most promising in this fluence range. Using an approximate linear fluence dependence for the depletion voltage of 300 μm thick silicon strip detectors (SSD):

$$V_{dep} = V_0 + \beta \cdot \Phi \qquad (6)$$

with V_0 the pre-rad depletion voltage determined by the resistivity of the wafer. It's present value of the order 150 V – 200V should be reduced in the future. There is uncertainty about the slope β in eq. (6). We estimate from [25] $\beta = 2.7{\cdot}10^{-13}$ V/cm^2 for MCz, $\beta = 2.9{\cdot}10^{-13}$ V/cm^2 for FZ. The depleted detector thickness d is given by the physical thickness W when the bias voltage V_{bias} is larger than the depletion voltage V_{dep} and scales like the square root of the ratio V_{bias} / V_{dep} when it is smaller.

$$d = W \qquad V_{bias} \geq V_{fd}$$

$$d = \sqrt{\frac{V_{bias}}{V_{fd}}} \cdot W \qquad V_{bias} < V_{fd} \qquad (7)$$