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Radiation-hard semiconductor detectors for SuperLHC

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Abstract

An option of increasing the luminosity of the Large Hadron Collider (LHC) at CERN to $10^{35}\,cm^{-2}\,s^{-1}$ has been envisaged to extend the physics reach of the machine. An efficient tracking down to a few centimetres from the interaction point will be required to exploit the physics potential of the upgraded LHC. As a consequence, the semiconductor detectors close to the interaction region will receive severe doses of fast hadron irradiation and the inner tracker detectors will need to survive fast hadron fluences of up to above $10^{16}\,cm^{-2}$. The CERN-RD50 project "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" has been established in 2002 to explore detector materials and technologies that will allow to operate devices up to, or beyond, this limit.

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The strategies followed by RD50 to enhance the radiation tolerance include the development of new or defect engineered detector materials (SiC, GaN, Czochralski and epitaxial silicon, oxygen enriched Float Zone silicon), the improvement of present detector designs and the understanding of the microscopic defects causing the degradation of the irradiated detectors. The latest advancements within the RD50 collaboration on radiation hard semiconductor detectors will be reviewed and discussed in this work.

1. Introduction

The Large Hadron Collider (LHC) at CERN has been designed to achieve the unprecedented luminosity of $10^{34}\,cm^{-2}\,s^{-1}$. Recently, a luminosity upgrade to $10^{35}\,cm^{-2}\,s^{-1}$ has been proposed (SuperLHC) [1,2]. To exploit the physics potential of the upgraded LHC, an efficient tracking down to a few centimetres from the interaction point will be required, where fast hadron fluences above $10^{16}\,cm^{-2}$ will be achieved after five years operation ($2500\,fb^{-1}$). Present vertex detectors, relying on highly segmented silicon sensors, are designed to survive fast hadron fluences of about $10^{15}\,cm^{-2}$ [3]. Semiconductor detectors seem the best option for vertex sensors also in the next generation of colliders, provided that their radiation hardness is significantly improved. The CERN RD50 collaboration"Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" was founded in 2002 with the aim to develop a new reliable detector technology available for the LHC upgrade or a future high luminosity hadron collider [4,5]. Two main research lines have been identified: Material Engineering, with the aim of producing more radiation-hard semiconductor material, and Device Engineering, to develop a more radiation-tolerant detector geometry. The activity and the most recent advances are presented and discussed in this paper.

2. Material engineering: strategies and experimental results

2.1. Defect and material characterisation

Electrically active defects are responsible for the changes in the main macroscopic properties of the particle detector: effective doping concentration of the space charge region (N_{eff}) that causes changes in detector full depletion voltage (V_{fd}), reverse current at full depletion (I_{leak}), charge collection efficiency (CCE) and electronic noise. Thus, a first fundamental step for the definition of the optimal radiation hardening procedure is represented by the exhaustive identification of native and radiation-induced defects, and of their influence on the transport properties of the device. Irradiation with high-energy particle beams creates both stable localised defect complexes (point-defects) and extended damaged regions (clusters) [6]. The main tools available for studying point-defects are Deep Level Transient Spectroscopy (DLTS), Thermally Stimulated Current (TSC) and Photo Induced Transient Spectroscopy (PITS). These techniques are used to determine the activation energy and capture cross-sections of the electrically active levels in the forbidden gap and to evaluate the concentration of the related defects in the semiconductor bulk. For trap identification, the results are compared with the defect signature from a database of parameters of defects obtained with other techniques as Infrared Spectroscopy and Electron Paramagnetic Resonance. In Table 1, a summary of the most important radiation-induced deep levels observed in Si with DLTS and TSC methods is given. In the following, we briefly present the materials studied by RD50 and the most relevant native, process-induced and radiation induced defects [7–12].

2.2. Defect engineering of Si

Defect engineering of Si consists in adding selected impurities in the silicon bulk in order to beneficially influence the microscopic damage induced by radiation. The RD50 research activity

Table 1
Trap parameters of the some relevant point-defects induced by radiation in Si [7–12]

Defect	Trap parameters	
	E_t [eV]	σ [cm^2]
V–O	E_c−0.18	1×10^{-14}
$V_2^{=}$	E_c−0.237	2×10^{-16}
V_2^{-}	E_c−0.42	3.1×10^{-15}
C_iO_i	E_c+0.36	2×10^{-15}
C_iC_s	E_c−0.17	8×10^{-18}
P–V	E_c−0.46	4×10^{-15}
"I defect" acceptor	E_c−0.545	1.7×10^{-15}
"I defect" donor	E_v+0.23	
Γ acceptor	E_c+0.68	
$X^{=}$ acceptor	E_c−232	1.3×10^{-16}
X^{-} acceptor	E_c−0.47	9.6×10^{-15}

in this field has been mainly focussed on the influence of interstitial oxygen, O_i, on the silicon radiation hardness. O_i is believed to act as a sink of vacancies: enhancing the formation of the shallower defect, V–O, it reduces the probability of generation of the divacancy-related complexes, which are responsible for deeper levels inside the gap. The O_i concentration in Si is strongly dependent on the growth technique. Table 2 reports the various kinds of Si materials investigated by RD50, together with resistivity and interstitial oxygen concentration. Si detectors are usually produced with standard Float Zone high resistivity Si (SFZ). A method was developed at Brookhaven Nat. Lab, in 1992, to produce diffusion oxygenated float zone (DOFZ) silicon [13]: the material is doped with oxygen by high temperature (1200 °C) oxidation during a period of 20–220 h. High resistivity Cz Si suitable for detector application has recently become available after proper developments in the crystal growth techniques (see e.g. [14]). Cz Si can be grown in the presence of a magnetic field to obtain a more uniform material throughout the ingot diameter; the resulting magnetic Czochralski Si (MCz) is characterised by a lower content of O_i than standard Cz (SCz).

Native and process-induced defects are quite important, as they can directly influence N_{eff} before irradiation. In Cz Si of particular relevance are the so called thermal donor (TD) and thermal double donors (TDDs), which are associated to shallow levels. To control N_{eff} in Cz Si-based diodes before irradiation TD and TDDs can be intentionally activated by a thermal treatment [15], whereas a donor killing process can be applied to partially deactivate them and thus ensure a sufficiently high resistivity material. Beside shallow thermal donors, two deep electron trap levels have been detected in MCz Si and associated with thermally induced defects [16].

Recently, important advancements in understanding the radiation damage in the case of point defects have been achieved within the RD50 collaboration. Only point defects (no clusters) are created by ^{60}Co-γ irradiation. Three levels have been correlated with the changes of N_{eff}, V_{fd}, I_{leak}: two midgap acceptor levels (I and Γ) and a bistable donor (BD). I and Γ are generated in higher concentrations in SFZ silicon than in oxygen enriched silicon, while the BD is mainly found in oxygen enriched silicon [17–21]. The Γ defect is characterised by a linear dose dependence and can explain about 10% of the damage. The I defect, of amphoteric nature, having both an acceptor and a donor states, has a quadratic dose dependence and is proven to be the main cause for the observed inversion of the space charge sign in the depletion region of standard FZ diodes (it accounts for more than 85% of the damage caused by gammas).

Defect studies on various kinds of Si materials irradiated with hadrons of different energies and fluences have also been carried out. High resolution photo-induced transient spectroscopy of MCz-Si after 10 MeV proton irradiation with fluences up to $1.2\times10^{14}\,cm^{-2}$ are shown in Fig. 1. Eleven traps with activation energies in the range of 15–430 meV have been detected. Levels T1–T3 are likely to be shallow donors characteristic of proton irradiation. The formation of these shallow donor states was found to be stimulated by hydrogen in the silicon lattice [22]. The deep centres T4–T7 are related to typical irradiation-induced defects in silicon, were also observed in the material irradiated by high-energy neutrons and electrons [22,23].

The correlation between the observed traps and the changes in macroscopic parameters such as

Table 2
Si materials investigated by RD50

Material	Manufacturer	Symbol	ρ [Ω cm]	O_i [cm^{-3}]
n- and p-type float zone	Various	SFZ	$1–7\times10^3$	$<5\times10^{16}$
Diffusion oxygenated float zone	Various	DOFZ	$1–7\times10^3$	$\sim1–2\times10^{17}$
Czochralski	Sumitomo, Japan	Cz	$\sim1\times10^3$	$\sim8–9\times10^{17}$
Magnetic Czochralski	Okmetic, Finland	MCz	$\sim1\times10^3$	$\sim4–9\times10^{17}$
Epitaxial layers on Cz-substrates	ITME, Warsaw	EPI	50–100	$<1\times10^{17}$

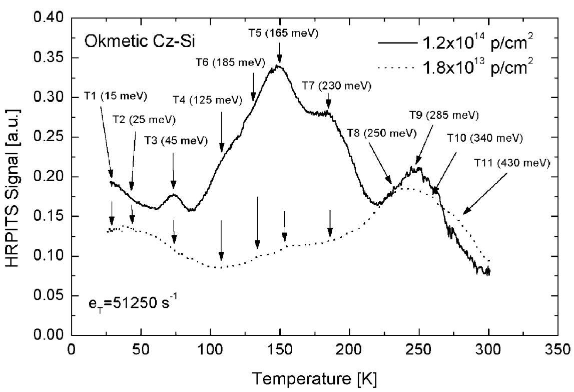

Fig. 1. Comparison of high-resolution PITS spectra for high-resistivity Cz-Si after 10-MeV proton irradiation ($1.8\times10^{13}\,cm^{-2}$ dashed line and $1.2\times10^{14}\,cm^{-2}$ solid line).

N_{eff}, V_{fd} and I_{leak} due to fast hadron irradiation is still a matter of study. This task is more complex than for ^{60}Co irradiation because in this case defect clusters [6], which are difficult to quantify with DLTS, should also be taken into account.

The association of the energy levels observed with the DLTS and TSC techniques to radiation induced lattice defects can be sometimes difficult and controversial. This happens in particular for the divacancy-oxygen defect, V_2O. A model proposed to explain the higher radiation hardness of oxygen-enriched silicon is based on the following reactions for the formation of V_2O: $V+O_i\rightarrow VO$, $VO+V\rightarrow V_2O$ [21]. The formation of V_2O is suppressed in oxygen rich material: increasing the concentration of interstitial oxygen reduces the probability of the second reaction, thus increasing the VO concentration and reducing the formation of V_2O. A possible interpretation of the results on SFZ and DOFZ Si after ^{60}Co-γ irradiation relates the levels of the *I* defect to the V_2O [17–19]. The quadratic increase of the *I*-defect concentration with dose supports the hypothesis that V_2O is formed via a two-steps reaction. However, another possible interpretation identifies V_2O with the double acceptor centre called X defect [12]. This defect is observed in SFZ and DOFZ Si diodes after irradiation with 15-MeV electrons up to $4\times10^{12}\,cm^{-2}$ and subsequent annealing at 250 °C. Deep levels related to $V_2^{=}$, V_2^{-} and VO were observed after irradiation. After 285 min at 250 °C in DOFZ Si a change in position of the V_2^{-} and $V_2^{=}$ peaks is observed, further annealing for 765 min leads to a considerable shift in the position of both peaks to new positions attributed to the levels X^{-} and $X^{=}$. In SFZ Si no shift in the position of V_2^{-} and $V_2^{=}$ is observed until an extended heat treatment lasting 3165 min: the transformation from V_2 to X results considerably slower in the SFZ sample. The variation in the transformation rates for the DOFZ and SFZ samples is in direct correlation and even proportional, within the experimental accuracy, to the oxygen content: this supports the identification of X as V_2O which is formed through the interaction of migrating V_2 with interstitial oxygen: $V_2+O_i\rightarrow V_2O$. It is important to note that, if this second interpretation is correct, the V_2O defect would not play a key role anymore in modelling the radiation damage of Si detectors.

2.3. Si enriched with oxygen-dimers

Oxygen dimers in silicon, O_{2i}, could be also beneficial in terms of radiation hardening of silicon detectors, though very little is known at the moment about the possible advantages of this material. O_{2i} can influence the reaction of vacancies and reduce the formation of the V_2O defect while alternatively leading to the creation of the V_2O_2 defect, possibly less damageable to detectors. Furthermore, O_{2i} can act as a sink for migrating interstitials by forming the IO_{2i} defect, detected in Cz [24] as well as in DOFZ Si [20]. Moreover, it is now generally accepted that O_{2i} are precursors for the formation of earlier stage thermal donors [25].

O_{2i} can be produced in the silicon crystal by carefully playing with the existing oxygen impurities and other defects present in the original material. This can be achieved by creating point defects in the crystal (e.g. with low energy electron radiation), and by forming O_{2i} through the following reactions with vacancies and interstitials: $VO_i + O_i \rightarrow VO_{2i}$, $I + VO_{2i} \rightarrow O_{2i}$.

It is possible to convert O_i into O_{2i} in silicon by performing high-temperature, high-dose electron irradiation [25]. The dimerisation process performed by RD50 was made using the 6 MeV electrons beam (doses up to 1×10^{18} e cm^{-2}) at the KTH (Stockholm) facility on three types of diodes: SFZ (initial V_{fd}~60 V), DOFZ (initial V_{fd}~50 V) and SCz (initial V_{fd}~200 V). After dimerisation diodes could not be fully depleted: V_{fd} was evaluated from N_{eff} as determined by the slope of $1/C^2$ vs. voltage characteristics. The material presented a very low resistivity probably because, besides O_{2i}, many other charged defects are produced (observed by TSC). After irradiation with 24 GeV c^{-1} proton fluences of up to 1.05×10^{14} p cm^{-2}, very different behaviours, depending on the oxygen content of the starting material, were found. For the standard float zone diode the inferred V_{fd} was in the order of 550 V and significantly decreased with fluence while for the DOFZ and Cz diodes $V_{fd} \approx 10^5$ V, constant as a function of fluence. These preliminary results suggest that the dimerisation process does not lead to a material suitable for particle detection purposes, more studies on this research line are still in progress.

2.4. Epitaxial Si

A different approach for increasing the radiation tolerance of silicon detectors is the use of thin epitaxial silicon layers. Single crystal epitaxial layers of different resistivity and thickness can be grown on different substrates (Cz, Fz). Low resistivity (50 Ω cm) 50 μm thick epitaxial layers were grown by ITME (Poland) on low resistivity (0.015 Ω cm) Cz substrates. Due to the high oxygen content in the Cz substrate and the high temperature during the epitaxial growth process, oxygen atoms diffuse into the epi-layer with an average concentration of about 9×10^{16} cm^{-3}.

Irradiation produce the generation of a bistable donor (BD) in epitaxial Si diodes [15,26]. A tentative explanation of this phenomenon is based on the fact that oxygen dimers (O_{2i}) present in the Cz-substrate migrate into the epitaxial layer during the high temperature process steps, so that the ratio of dimers to mono-atomic interstitial oxygen (O_i) is much higher in epitaxial silicon than in standard or oxygenated Fz silicon. Dimers are known to be precursors for radiation induced thermal donor generation [25]. This leads to an increase of the net positive space charge, more than balancing the negative space charge generation seen in SFZ Si devices due to generation of deep acceptors.

2.5. New materials

RD50 investigates the use of semiconductor or semi-insulating materials alternative to silicon with enhanced radiation hardness properties. The main focus is now on silicon carbide (SiC): the large bandgap of this material would ensure a very low leakage current even after irradiation with very high fluences of fast hadrons, and the charge collection properties of SiC lie between those of Si and diamond. Studies have been performed with bulk (~100 μm thick) and epitaxial (~7–50 μm thick) SiC. Bulk semi-insulating single crystal 4H–SiC, 550 μm thick, produced by CREE Research (USA) with vanadium compensation to achieve high resistivity ($>10^{11}$ Ω cm) has been thinned by lapping and polishing to ~100 μm. Schottky detectors produced with this material have been measured with 5.48 MeV α-particles with applied reverse voltages in the range 50–600 V. At the maximum reverse voltage the charge collection efficiency was found to be only about 60%. Four energy levels at 0.32, 0.39, 0.63 and 0.92 eV below the conduction band edge were measured in as-grown material [27]. The 0.92 eV, related to vanadium compensation, is believed to be the main responsible for the incomplete charge collection. This analysis suggests that vanadium compensated materials should be avoided for particle detection. Recently, vanadium-free SiC has become available from Okmetic to the RD50 community. First results found with this new material by the Glasgow and Vilnius groups are promising.

Good results in term of sensitivity to ionising radiation have been obtained with epitaxial 4H–SiC Schottky barriers. A 100% charge collection efficiency was obtained with Schottky diodes made on a 40 μm thick 4H–SiC epi-layer with a β-^{90}Sr source. The measurements, carried out by the Florence group on a single dot detector processed by a collaboration between Modena group and Alenia-Systems (Rome), have been performed with a low-noise read-out electronics with 2 μs shaping time at room temperature [28]. In Fig. 2 the pulse height spectrum at full depletion voltage (60 V) is shown. 4H–SiC epi-layer with thickness of 50 μm, produced by IKZ, Berlin, are now under process and tests by RD50.

Triode structures with epitaxial SiC have also been manufactured by Ioffe group in St. Petersburg, Russia and tested with α-particles before and after irradiation with 8 MeV protons up to the fluence of $2 \times 10^{14}\,cm^{-2}$ [29]. The main idea for the development of triode structures is to get amplification of the charge generated in the detector bulk. Irradiation of the 6H–SiC triode resulted in a significant change of the shallow donors: the full depletion voltage of the epilayer, characterised by an initial $N_{eff} \sim 7.5 \times 10^{14}\,cm^{-3}$ was reduced from approximately 500 V to 2.5 V after irradiation. A 100% CCE was measured before and after irradiation at full depletion; maximum value of gain was 18, obtained at a reverse voltage $V_{rev} = 125\,V$. p+n junctions are also produced within RD50 by the Perugia group and CNR-IMM (Bologna, Italy) through Al^{+} implant on CREE and IKZ epilayers.

Schottky Diodes on epilayers of 4H-SiC substrates (30 μm thick, $N_{eff} = 2.5 \times 10^{15}\,cm^{-3}$) of CREE Research Inc. were investigated with DLTS to study deep levels induced by electron irradiation

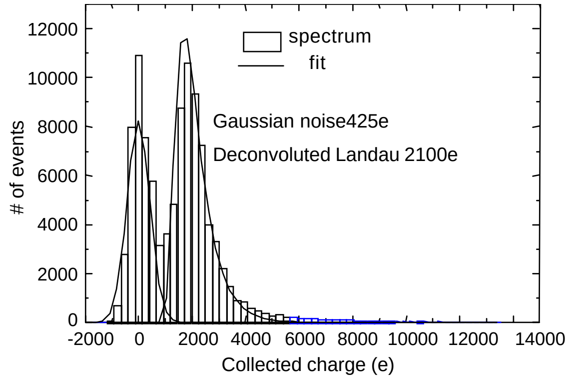

Fig. 2. Pulse-height spectrum of a 40 μm-thick epitaxial 4H-SiC measured with a β-^{90}Sr source.

[30]. The epilayer was n-type and the irradiation was carried out at CNR-ISOF Italy Laboratory with 8.6 MeV electrons of an LINAC accelerator up to 40 Mrad. DLTS analysis was performed in the range 77–500 K. Two traps, E_c—0.15 eV and E_c—0.89 eV, were found in the as-prepared diodes. After electron irradiation four traps appeared at 0.23, 0.39, 0.63 and 0.75 eV, with maximum concentration of $1–4 \times 10^{14}\,cm^{-3}$ after 40 Mrad. Correspondingly, N_{eff} decreased almost a factor 10 after irradiation at the highest dose. A rearrangement in the structure or in the charge state of some defects was observed during annealing after irradiation in the temperature range 360–400 K. The value of $N_{eff} \sim 5 \times 10^{14}\,cm^{-3}$, measured after annealing, is probably related to the disappearance of the 0.39 eV level.

Also, gallium nitride (GaN) epitaxial grown layers have been investigated by RD50 [31,32]. Preliminary results after irradiation of Schottky diodes made with this material have shown a CCE of 92% before irradiation and 77% after $5 \times 10^{14}\,n\,cm^{-2}$. High-resistivity GaN epitaxial detectors obtained from a 2″ wafer with a thickness of 13 μm from Lumilog (France) are now under test.

3. Device engineering: strategies and experimental results

The study of the operational characteristics of detectors made on radiation tolerant materials is carried out within RD50 in the frame of the three projects discussed below.

3.1. Pad detector characterisation

The PDC project deals with radiation-damage studies performed with the simplified geometry of a single pad detector (SPD), i.e. a single-pad p^+nn^+ structure surrounded by a set of guard-rings. The use of SPD's provides the cost-effective development of radiation tests mainly concentrated on the study of parameters (N_{eff}, V_{fd}, I_{leak}, CCE) as a function of the fluence. The radiation hardness of SPDs made with DOFZ, Cz, MCz and epitaxial Si has been investigated by several irradiation campaigns at different facilities, with different particles and energies. We give here a brief summary of the results. MCz Si [33,34] shows a definitely higher inversion fluence after low energy protons (10–30 MeV) irradiation than standard and DOFZ Si, while after ^{60}Co gamma irradiation up to 1.2 Grad there is no type inversion and V_{fd} increases slowly with dose due to a build-up of positive space charge. Fig. 3 shows N_{eff} evaluated for MCZ Si after neutron and 24 GeV proton irradiation as compared with SFZ Si. When SCZ Si for detectors is used [35] no type inversion was observed after irradiation with 190 MeV pions (PSI) and 24 GeV c^{-1} protons (CERN) up to 10^{15} particles cm^{-2}. In Cz Si detectors, the change of V_{fd} as function of fluence is considerably smaller than that of standard FZ or DOFZ silicon devices. The epi-diodes show superior radiation tolerance compared to those fabricated with all other silicon materials. Fig. 4 shows a comparison between epi-diodes and diodes fabricated with SFZ and DOFZ materials (different total thicknesses). In the full range of measured fluences (up to 1 MeV neutron equivalent fluence of 8×10^{14} cm^{-2}) the epi-diodes do not exhibit type inversion, as observed by TCT measurements, and show a reduced variation of the full depletion voltage, as compared with FZ Si thin detectors. Annealing studies have also been performed. An advantage of DOFZ Si is that the amplitude of the reverse annealing N_Y is saturating at high fluences, while in standard Si this parameter is increasing linearly with the fluence.

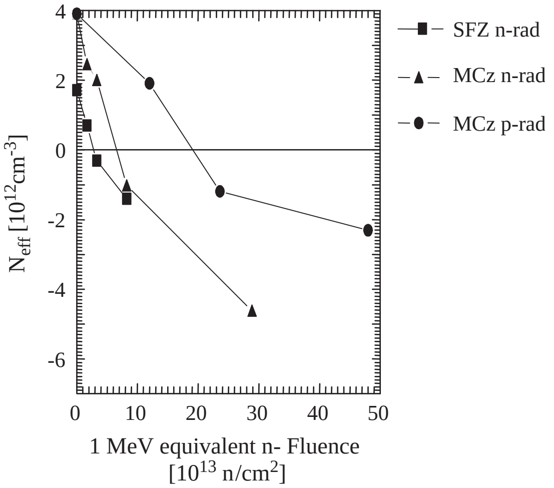

Fig. 3. N_{eff} (10^{12} cm^{-3}) as a function of the fluence for SFZ and MCz Si after irradiation with neutron (1 MeV) and protons (24 GeV c^{-1}).

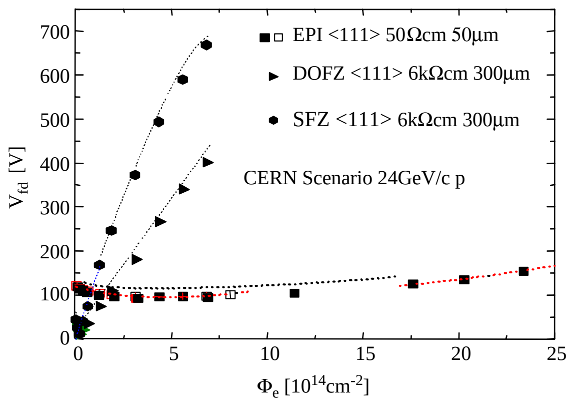

Fig. 4. Full depletion voltage as a function of the fluence (1 MeV neutron equivalent) for epitaxial, SFZ and DOFZ Si.

Moreover, the time constant of reverse annealing is increasing with the fluence in DOFZ, while in standard float zone it is constant. Noticeably, epitaxial Si detectors show an even more interesting and quite encouraging behaviour with annealing, as shown in Fig. 5. The annealing curve shows two components: a fast one with decrease of N_{eff} and a slow component with increase of N_{eff} up to a maximum of the reverse annealing. The annealing temperature of 80 °C is used to speed up the process. It is possible to project the annealing curve at 80 °C on the time scale at room temperature, as shown in the upper scale of Fig. 5. According to this prediction, the change of the depletion voltage with time at room temperature takes place slowly enough that the detectors made with epitaxial material may not need any cooling during LHC maintenance up to 10 years. This could be a tremendous advantage in term of operation and cost.

Charge collection efficiency is mainly degraded in semiconductor detectors by trapping through a factor proportional to $\exp(-t_c/\tau_t)$, where t_c is the collection time and τ_t is the trapping time constant. To evaluate τ_t, Transient Current Technique measurements (TCT) were performed by various groups within RD50 at different temperatures and after different irradiation particles, energies and fluences. Trapping time constants are seen to increase linearly with fluence up to the maximum investigated value of 10^{15} $n_{eq}\,cm^{-2}$, with trapping damage constants of the order of $4–8 \times 10^{-16}\,cm^{-2}\,ns^{-1}$ [36–41], depending on the carrier type and measurement temperature (−10–20 °C) and particle of irradiation (24 GeV c^{-1} protons, reactor neutrons, high energy pions). No significant differences were observed in different Si materials such as SFZ, DOFZ and MCz.

Recently, the performance of single pad diodes produced by three different technologies (p-in-n, n-in-p and n-in-n) has been compared by CNM Barcelona using a mask designed by Liverpool University in standard and oxygenated substrates of 280 μm thickness [42]. The detectors were irradiated with a 24 GeV c^{-1} proton beam at CERN PS facilities up 10^{15} p cm^{-2}. In order to optimise the breakdown voltage, in n-in-p and n-in-n technologies, different values of p-stop implant doses have been evaluated. n-in-n detectors with p-stop of 10^{14} cm^{-3} have lower values of breakdown voltage than detectors with a p-stop of 10^{13} cm^{-3}, this is also valid for n-in-p detectors, while for p-stop concentrations of 10^{12} cm^{-3}, both type of detectors do not work because the leakage current flows from the guard ring to the central pad. The effective doping concentrations and full depletion voltages vs. fluence have been studied for the three different technologies: n-in-n and p-in-n detectors present the expected space charge sign inversion at fluences higher than 10^{13} p cm^{-2}, while the n-in-p detectors also showed a minimum of V_{fd} at 3×10^{14} p cm^{-2} followed by an increase, although, as the substrate is p-type, no space charge sign inversion would be expected.

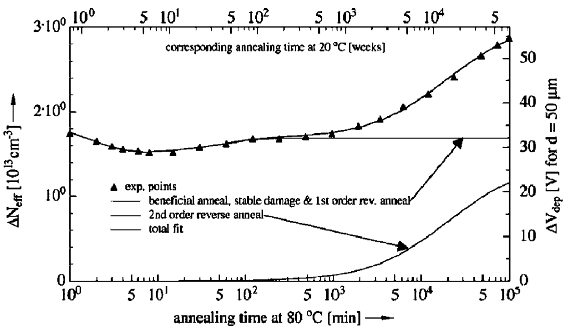

Fig. 5. Annealing curve (ΔN_{eff}) at 80 °C for epitaxial Si diodes after 24 GeV c^{-1} proton irradiation. The upper scale is the corresponding annealing time at 20 °C.

3.2. New structures

The main research activity in New Structures (NS) is to develop novel detector geometries to increase the device radiation hardness. It is known that the active thickness of the device after heavy fluence irradiation is limited by the carrier effective drift lengths, estimated for electrons and holes, respectively, to be ~150 and ~50 μm after 1 MeV neutron irradiation at 10^{15} cm^{-2} [36,37]. When the detector suffers high radiation damage, full depletion cannot be achieved anymore and charge trapping reduces the amount of the collected charge drifting for longer distances. A novel type of device (3D silicon detectors) was introduced [43] to reduce the electrode distance, therefore increasing the amount of charge collected after heavy irradiation, while keeping the same detector thickness. In 3D devices, the generated charge drifts in the plane of the wafer and the electrode separation is independent of the material thickness. Thus, the 3D geometry may be designed to both maximize signal response to incident radiation and minimize sensitivity to defects arising from radiation damage. 3D detectors have been produced in the frame of RD50 at Glasgow by plasma etching with 200 μm thick silicon and 85 μm pore spacing and characterised with *I–V* and *C–V* measurements. Several silicon 3D detectors were irradiated at the 300 MeV c^{-1} pion beam at the Paul Scherrer Institute (PSI), Villigen-CH, up to $5\times10^{14}\,\pi\,\mathrm{cm}^{-2}$. The C–V measurements show that full depletion is reached at progressively smaller voltages from the initial value of 32–18 V after a fluence of $10^{14}\,\pi\,\mathrm{cm}^{-2}$ [44]. Currently, 3D detectors are processed within RD50 by a joint program of the CNM Barcelona, IRST Trento and Glasgow groups [45].

Besides 3D detectors, other new geometries are investigated within RD50, such as thinned Si detectors to get constant and low V_{fd}, limited leakage currents and high inversion fluences. The latter effect is achieved by means of low resistivity bulk material (typically 50–100 Ω cm), as the high initial shallow doping will shift type inversion to the very high fluences. Two technical approaches have been investigated: thinning of Si and use of epitaxial Si wafers [46–48]. Processing and electrical characterization of Si thinned detectors have been performed by the group of IRST Trento. C–V and I–V tests have shown that a first production of thinned devices has been successful. Semi-3D devices [49] have been also proposed as a mean to sensibly reduce the V_{fd} value after irradiation. This research activity is carried out by the US-RD50 groups. In semi-3D detectors both p^+ and n^+ strips are implanted on an n-type substrate while the backside has a uniform n^+ implant. After the inversion fluence, the depletion develops both from the n^+ strips in the front side, and the n^+ plane towards the p^+ readout electrodes. Thus, a reduction in full depletion voltage of about a factor of 3–4 is expected. First test structures have been produced and preliminarly tested, irradiation with 200 MeV proton is now in progress.

3.3. Full detectors systems

The FDS project is focussed on radiation damage studies on prototype microstrip and pixels detector modules with LHC-like read-out electronics at the speed of 40 MHz.Pixels are currently in process on MCZ, SFZ, DOFZ n-type Si with Sintef using CMS/FPix masks by Purdue University, MCZ n-type Si with pixel and strips is under process at BNL (joint activity of Purdue, Rochester and BNL groups) [49,50]. An intense research activity has been carried out to simulate the response of pixel detectors in working conditions after irradiation up to fluences of $10^{16}\,\mathrm{cm}^{-2}$. To this purpose, trapping time constants given in [36–41] were used. The calculated collected charge as a function of the fluence for n^+-n and p^+-n $70\times70\,\mu\mathrm{m}^2$ pixels showed that at the highest fluence of $10^{16}\,\mathrm{cm}^{-2}$ at best only 2000*e* are collected, with small differences between different pixel thicknesses in the range 25–100 μm [51]. A simulation has been performed considering different Si materials and taking into account the ATLAS pixel detectors geometry [52]. A comprehensive study of the CMS pixel response after irradiation has been developed [53]. The research activity of the "pixel working group" within the FDS project is also focussed on the development of CMOS active pixel detectors, which are studied by the groups of Perugia [54] and Liverpool.

Miniature microstrip detectors have been produced or are under process withSFZ, DOFZ, MCZ, epitaxial n-type and p-type Si by CNM Barcelona & Liverpool, IRST-Trento with a network of Italian groups (Bari, Firenze, Padova, Pisa, Trieste) and Helsinki HIP. Liverpool and Barcelona investigated in the frame of RD50 the charge collection properties of microstrip n-in-p detectors made with oxygenated p-type Si substrates, comparing their performances with p-in-n standard and oxygenated Si detectors [55]. The detectors have been irradiated with 24 GeV c^{-1} protons in the CERN/PS T7 irradiation area, up to $\sim7.5\times10^{15}\,\mathrm{cm}^{-2}$ and read-out with an SCT128A LHC speed (40 MHz) chip [56] at –20–25 °C. The charge collected at the maximum applied bias (900 V) by these n-in-p miniature microstrip detectors is over 6500 electrons. This value of collected charge is higher by approximately a factor 2.4 than what should be expected by the estimations made considering the trapping time constant values measured with p-in-n detectors, corresponding at the highest investigated fluence, to a charge collection distance of approximately 90 μm. For a systematic investigation of this quite encouraging result, a common RD50 process dedicated to n-in-p microstrip detectors made with oxygenated Si is now under way.

4. Conclusions

Previous sections have reviewed the wide range of research activities carried out by the RD50 to achieve the final goal of producing semiconductor position-sensitive detectors able to survive fast hadrons fluence as high as $10^{16}\,cm^{-2}$. Projects aimed at studying different aspects of radiation damage and radiation hardening have been started and are still under intense investigation. A number of important results have been already achieved so far: (1) the proven radiation hardness of cost-effective high resistivity CZ Si devices, (2) the superior radiation tolerance evidenced for epitaxial Si and (3) the high CCE showed by p-type oxygenated Si microstrip detectors read-out with LHC-like electronics after $24\,GeV\,c^{-1}$ p irradiation up to $7.5\times10^{15}\,cm^{-2}$. These results bring RD50 closer to its main goal of optimizing ultra-radiation hard detectors able to operate after a luminosity upgrade of LHC to $10^{35}\,cm^{-2}\,s^{-1}$.

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