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P-type Sensor Results from the RD50 collaboration

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The development of radiation hard sensors in preparation for the tracker and vertex detectors for the present CERN Large Hadron Collider (LHC) lasted well over a decade. The detector community in high energy physics was challenged to produce devices able to operate efficiently in the harsh radiation environment created by this high luminosity collider (~10^{34} cm^{-2} s^{-1}). After an intense R&D phase the sensors were finally qualified for doses up to 10^{15} n_{eq} cm^{-2} (the pixel sensors for the inner layers). Nonetheless, a luminosity upgrade of about a factor of ten of the present LHC (the Super LHC) will bring the tracker detector technology beyond the limit investigated during the preparation for the current machine. A new R&D phase targeted to the development of detectors able to operate after the extreme radiation fluences anticipated for the inner layers at the upgraded machine was therefore necessary. The CERN-RD50 collaboration was started in 2002 to fulfil this need. One of the strategies within the collaboration is the development of p-type substrate silicon detectors, instead of the more standard n-type. This paper reports the present status of this development.

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[1] Speaker

1. Introduction

The upgrade of the CERN-LHC accelerator (SLHC) will aim to an unprecedented luminosity close to $10^{35}cm^{-2}s^{-1}$ [1]. In order to exploit the physics potential of the machine, the experiments will have to upgrade the vertex and tracker detectors both in term of granularity and radiation hardness. The granularity requirements come from the need to keep a similar occupancy as for the present machine and possibly from improvements on the trigger concepts where more precise tracking would be used in the lower trigger levels [2]. This requirement is certainly specific to the individual experiments (ATLAS, CMS, LHCb). On the other hand, the extreme radiation tolerance of the inner detectors is a common challenge. The maximum dose predicted for the innermost layers is in excess of 10^{16} hadron cm^{-2} (for a physics program of $3000fb^{-1}$ integrated luminosity), about a factor of ten higher than the most exposed detectors in the LHC. The tracker detector systems are currently based on silicon sensors because of their speed, low mass and high granularity. They have been qualified to the maximum doses expected in the LHC, but they will not be able to operate after a dose several times higher. A new generation of radiation tolerant detectors is needed.

The RD50 collaboration [3] was started in 2002 to develop radiation hard semiconductor devices for very high luminosity colliders, in particular referring to the final doses anticipated for the SLHC. Several strategies were outlined to carry out this investigation, namely the study of the defect formation and dynamics in silicon, impurity engineering of the silicon crystal, semiconductor materials other than silicon (with the exception of diamond, which is the subject of a specific R&D) and novel structures (different geometry of the segmented diodes, e.g. 3-d devices). Among the various strategies, the development of p-type bulk silicon detectors to take advantage of the better charge collection provided by segmented n-side read-out has lead to significant improvement of the radiation tolerance of the sensors.

2. Evaluation of the radiation hardness

It is well known that the radiation induced damage to the silicon crystal changes the electrical properties of the devices. The radiation causes point-like defects (a single silicon atom displaced from its lattice position) or *cluster* defects (high concentration of damaged crystal in a small volume [4]). This crystal defects can be electrically neutral or active: in the second case they can act as generation-recombination or trapping centres of charge carriers, influencing the properties of the detectors. In particular, they induce considerable changes of the full depletion voltage (V_{fd}), reverse current (I_r) and the signal size. Moreover, after irradiation, the defects can interact with other mobile impurities in silicon (mainly hydrogen, carbon or oxygen impurities, interstitial silicon etc.) and form permanent complexes with a possibly different electrical nature than the original ones. This process is a function of time and temperature and would again change the electrical properties of the detectors. Many progresses have been registered in the field of the microscopic studies of defect formation and dynamics (see e.g. [5]). In principle, the complete knowledge of the damages created by the radiation in term of introduction rates as a function of impinging particle and energy, energy level of the defect in the silicon band-gap, charge carrier trapping and de-trapping cross section could lead to an accurate description of the changes of the electrical properties with irradiation and time. Nonetheless, the overall model is still not available and the description of the macroscopic detector properties from the microscopic point of view of the defect dynamics cannot be obtained. Therefore, the changes of the electrical properties as a function of irradiation and time have been extensively measured with dedicated devices. The studies carried out with simple pad diodes have allowed the accurate parameterisation of the changes of the full depletion voltage and the reverse current as a function of irradiation and time after irradiation (an extensive literature is available on this subject, for a summary see e.g. [6]). The V_{fd} is proportional to the effective space charge density (N_{eff}). The changes of N_{eff} in the case of n-type silicon are described by the following equation:

$$N_{eff}(\phi) = N_D e^{-c\phi} - N_A - \beta\phi \quad (1)$$

where N_D is the initial donor concentration, N_A is the initial acceptor concentration (the compensation level), c describes the removal rate of initial donors and β is the parameter accounting for the introduction of acceptor-like defects. This empirical function describes the initial exponential decrease of N_{eff} with irradiation until it reaches a minimum and than starts rising again linearly with the fluence, but with opposite sign (Fig. 1a). This effect is usually called the space charge sign inversion, because the dominant space charge becomes negative (effectively p-type) from the original positive sign (n-type doping). No space charge inversion is measured with p-type bulk devices.

The I_r increases linearly with fluence:

$$\Delta I_r(t) = I_r(\phi) - I_r(\phi = 0) = \alpha\phi \quad (2)$$

where the constant α is called the *reverse current damage factor*. A compilation of the values of the different constants used for these parameterisations in the case of high energy neutron or proton irradiations can be found in [6]. Although these electrical parameters are important for defining the properties of irradiated silicon, they don't give any direct indication of the expected performances of the detectors.

The evolution of V_{fd} has often been used as a qualifying parameter, because in non-irradiated detectors the capacitance versus voltage characteristic saturates at the same value of the charge collection (V_{fd}). The ability of biasing the detector at voltages above V_{fd} was considered a criterion for assessing the functionality of the device. It can be seen from Fig. 1b that V_{fd} in the fluence region of interest for SLHC goes from >500V (1×10^{15} n_{eq} cm^{-2}) to >5000V (1×10^{16} n_{eq} cm^{-2})! If V_{fd} was the qualifying parameter it is evident that silicon detectors couldn't be use for SLHC doses due to limitation to provide bias voltages $\geq$ 1000V in any practical large detector system.

The efficiency of a detector can be more directly inferred by the signal over noise (S/N) ratio. The noise of a particular detector system depends on the electronics and on the detector geometry, which can be estimated during its design phase. The signal deteriorates with fluence due to the charge trapping at radiation induced defect centres. The measurement of the charge collection efficiency (CCE) as a function of the fluence is the key parameter to calculate the S/N ratio for a given detector system and therefore to determine its performances (track efficiency, purity) after irradiation.

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The full detector system research line of RD50 is dedicated to demonstrate the operation of segmented silicon detector prototypes read out with LHC speed electronics and stimulated by minimum ionising particles.

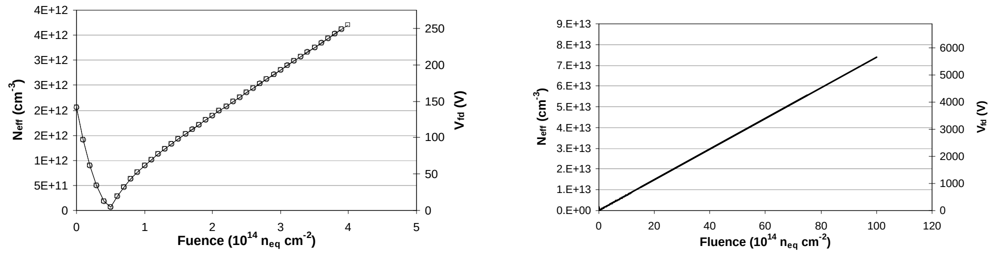

Fig. 1 Changes of the absolute value of N_{eff} (V_{fd}) for a n-type detector with fluence: (a) the exponential decrease at lower doses until type inversion is shown (b) at high fluences N_{eff} (V_{fd}) increases linearly with dose.

3. P-type bulk silicon detectors for enhanced radiation tolerance

As already mentioned, due to the introduction of defects acting as acceptor doping with the radiation damage, the silicon bulk is effectively p-type after a few 10^{13} cm^{-2} of hadron irradiation, irrespective on the original space charge sign. The electric field of inverted n-type silicon detectors is stronger under the n^+ contact [7], like in p-type bulk detectors, although a narrow region with high field is present also on the p^+ contact (double junction)[7,8]. Due to the profile of the electric field, it is advantageous, in term of charge collection, to segment and read-out the detectors from the n-side. In fact the signal deficit caused by trapping of the charge carriers at radiation induced defect centres can be described by the following equation:

$$N_{e,h}(t) = N_{e,h}(0)\exp\left(-\frac{t_c}{\tau_{e,h}}\right) \quad (3)$$

where $N_{e,h}$ is the number of collected charges (electron or holes respectively), $N_{e,h}(0)$ is the number of ionised electrons and holes, t_c is the collection time and $\tau_{e,h}$ is the electron and hole effective trapping time. The charge carrier effective trapping time decreases as a function of fluence like:

$$\frac{1}{\tau_{e,h}} = \beta_{e,h}\phi_{eq} \quad (4)$$

where ϕ_{eq} is the 1MeV neutron equivalent fluence and $\beta_{e,h}$ are the trapping damage constants for electrons and holes respectively. The measured values are 6.2 x 10^{-16} cm^2 ns^{-1} for β_e and 4.1 x 10^{-16} cm^2 ns^{-1} for β_h [9]. From eq.(1) it is clear that shorter t_c provides substantial advantages in term of collected charge. If segmented n-type silicon devices are read-out from the n^+ side (n-in-n detectors), they will benefit from a shorter t_c, with respect to the standard p-in-n, due to the collection of the electron current (with three times higher mobility than holes) transported by the high electric field. This is more readily achieved with n-side read-out on p-type substrates (n-in-p), where no inversion takes place with irradiation and the main electric field is always located on the original n^+-p junction side. Another motivation for favouring this choice is the simpler and cheaper processing. For these reasons, the use of p-type bulk detectors for improved radiation tolerance was proposed to take advantage of the shorter t_c with respect to the more standard p-side read-out of n-type silicon [10].

Extremely good results were obtained with large area [11] and miniature p-type bulk detectors [12] irradiated with protons. These early results encouraged the systematic investigation of p-type substrate detectors within the framework of RD50.

4. Different types of silicon p-type substrates

The results mentioned above were based on high resistivity float-zone (FZ) p-type silicon substrate. Alternative silicon substrates could be used instead of the high purity FZ. Epitaxial grown silicon and Magnetic Czochralski (MCz) are lower resistivity materials with higher impurity contents than FZ. It has been shown that some impurities (in particular oxygen) can have a positive effect in improving the radiation tolerance of silicon detectors [13]. Epitaxial silicon was found to have possible higher radiation tolerance than FZ in term of changes of the V_{fd} with irradiation [14].

The MCz technology is a refinement of the standard Czochralski (Cz) method for growing silicon single crystal with higher resistivity. High resistivity silicon is required in order to keep the initial full depletion voltage low enough to achieve complete charge collection with a bias voltage compatible with the system constraints. It has been suggested that the higher oxygen content of the MCz crystals could lead to a better radiation hardness with respect to FZ silicon [15]. The RD50 collaboration is performing a systematic study on the various substrates.

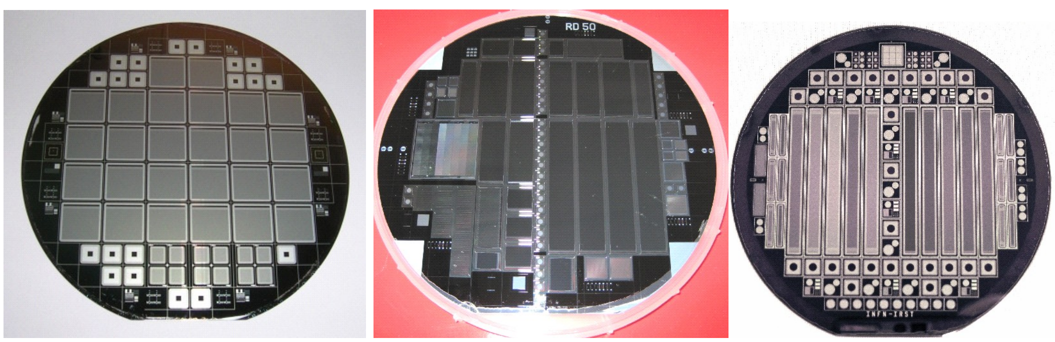

Fig. 2 RD50 wafer types: by CNM with a 4" RD50 mask (left), Micron Semiconductor with a 6" RD50 mask (centre), by IRSTwith a 6" SMART mask (right).

5. RD50 processing runs

A few different photolithographic mask sets and several processing runs with three different manufacturers were performed for the studies of p-type substrates. Figure 2 shows a wafer produced with a 4" mask set that includes 20 pad diodes, 26 miniature strip and 12 pixel detectors. The miniature detectors are 1x1 cm^2 devices, with 130 AC-coupled 80µm pitch strips. This mask has been used by the IMB-CNM institute of Barcelona to process 22 wafers of different silicon materials (epi, MCz and FZ), 14 of which were p-type substrate silicon.

A similar mask set, with the same type of devices, has been used by Micron Semiconductor Ltd. (UK) to process thin (140µm) and standard (300µm) high resistivity p-type wafers. A total of 10 wafers have been produced.

Micron has also produced 12 (6 p-type) wafers using the 6" mask set that includes pad diodes, pixel and microstrip detectors with strip of various length (1, 3 and 6 cm) and pitches (50, 80 and 100µm), as shown by Fig. 2. Various materials have been used: FZ n-type (5 wafers), FZ p-type (6 wafers), MCz p-type (5 wafers) and MCz n-type (7 wafers).

Figure 2 also shows the 6" mask produced by the SMART [16] collaboration of Italian institutes within RD50. The mask includes 10 microstrip (4.5 cm long) detectors with different pitches, 24 pad diodes and several test structures. A total of 46 substrates have been processed by the IRST institute in Trento (IT), namely 22 n-type and 24 p-type wafers.

A large number of detectors have been produced by RD50 and their characterisation before and after pion, proton and neutron irradiation is on going. Nonetheless, several results are available with some of the produced devices

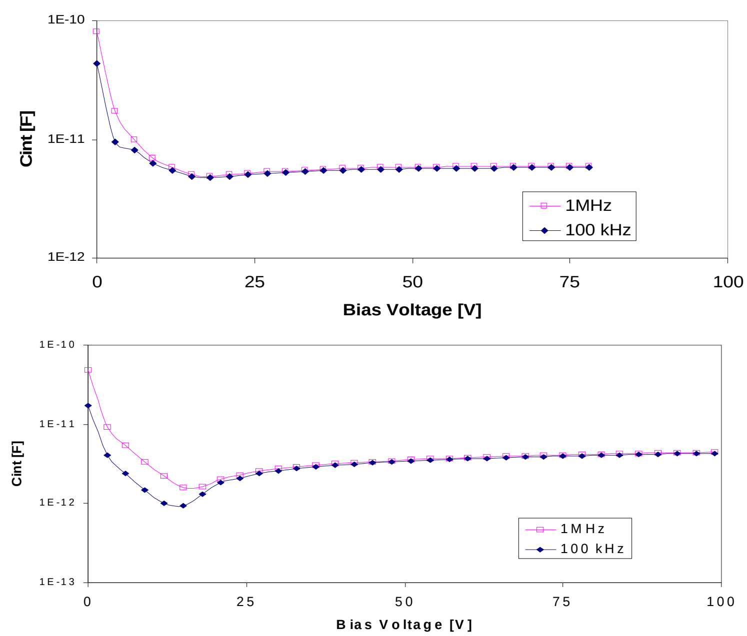

Fig. 3 Interstrip capacitance of microstrip detectors: n-type substrate (above), p-type substrate (below).

6. Experimental results

6.1 Interstrip capacitance

The noise of a silicon detector system depends on the electronics and the geometry of the detector, in particular on the reverse current and input capacitance to an individual electronics channel. Both of these factors are proportional to the size of the segmented electrode (diode size). The input capacitance is the main source of noise with the high speed electronics (40MHz) used in LHC and SLHC experiments and the interstrip capacitance (C_{int}) is the dominant contribution. It is therefore important to verify that no increase of this capacitance is due to the substrate material. Figure 3 shows the interstrip capacitance of strip detectors (100µm pitch) made by Micron with n-FZ and MCz p-type substrates [17]. The capacitance reaches its geometrical value at about 25V and it doesn't depend on the substrate. Figure 4 shows a similar plot for detectors made by IRST before and after gamma irradiation [18]. The gamma irradiation produces damage in the SiO_2 layer that can influence C_{int}. Already after a low dose of irradiation the minimum value of C_{int}, that correspond to the geometrical value, is reached below 200V both for n-type and p-type substrates. In the case of the p-type substrate, this particular detector showed a strong dependence of C_{int} on the applied bias voltage, and it didn't reach the minimum before irradiation because of an early breakdown (<200V). The same detector was able to withstand bias voltages up to 1000V after gamma irradiation.

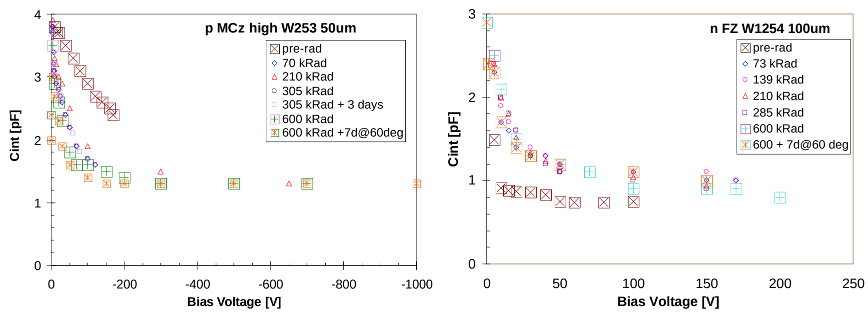

Fig. 4 Interstrip capacitance of microstrip p-type (50µm pitch) and n-type (100µm pitch) detectors before and after gamma irradiation.

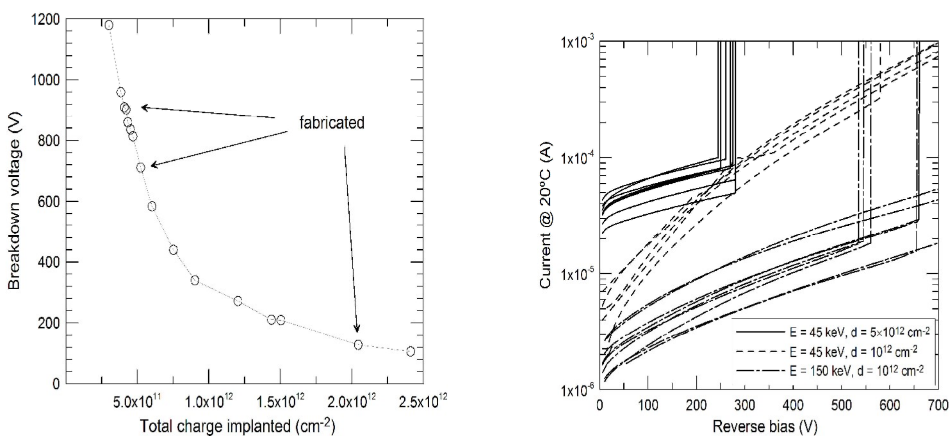

Fig. 5 Left: variation of the breakdown voltage as a function of the total implanted charge for the definition of the p-spray insulation in non-irradiated detectors. Rigth: Current-voltage characteristics of n-in-p pad detectors fabricated with three different p-spray implants.

6.2 Strip isolation

N-side read-out detectors require an isolation structure between the segmented electrodes to operate correctly. A positive charge builds-up at the Si-SiO_2 interface and creates a mirror electron accumulation layer that shorts the segmented n-type implanted diodes. To break the conductive channel a layer of negative charged ions must be implanted between the read-out electrodes. In the case of microstrip detectors, three methods can be used: a blanket p-type implantation (p-spray), the implantation of a p-type strip between every pair of read-out strips (p-stop) or a combination of the two techniques (moderated p-stops). The p-spray is a relatively light boron implant over the whole wafer prior to all the other processing steps. The p-stop is a higher dose implant of a boron strip defined by a dedicated photolithographic mask. The moderated p-stop allows a finer tuning of the p-spray and p-stop implant doses. The p-spray is the simpler and cheaper method because it does not require photolithography. The drawback is that the blanket implantation reduces the breakdown voltage (VBD) of non-irradiated detectors. An accurate choice of the implant parameters (dose and energy) has to be performed to keep a high V_{BD} with good interstrip isolation. A study of the changes of V_{BD} has been performed within RD50 [19]. Fig. 5 shows the simulation and some experimental measurements of V_{BD} as a function of the p-spray dose. The work was performed by CNM according to their production parameters and shows that V_{BD} decreases with p-spray dose. It must be pointed out that the dependence of V_{BD} on implanted p-spray dose is manufacturer dependent. The same isolation technique has been used by Micron with both the 4" and 6" processing runs with satisfactory pre-irradiation V_{BD} and good strip isolation.

A common feature of all the processed detectors (both with p-spray and p-stop isolation) is the increase of V_{BD} with fluence. Figure 6 shows this effect with detector irradiated with gamma rays to create radiation induced interface charge in the silicon dioxide layer [18]. A substantial increase of V_{BD} is found. This improvement has also been confirmed by charge collection measurements after heavy irradiation, where bias voltages up to 1100 volts have been applied to p-type detectors with a substantially lower V_{BD} before irradiation (see eg [12, 20, 21]).

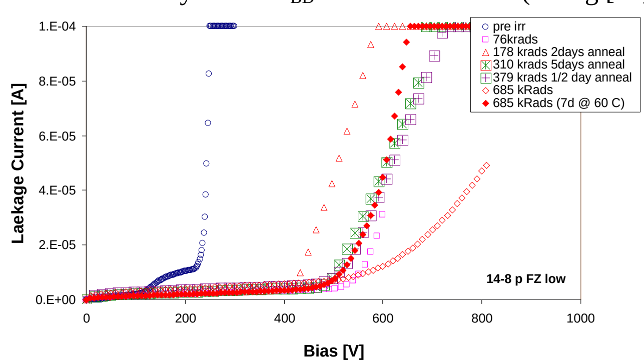

Fig. 6. Reverse current as a function of bias voltage for several gamma irradiation steps. The breakdown voltage is increased considerably with increased dose.

6.3 Charge collection efficiency as a function of irradiation

As mentioned before, the most direct measurement to assess the radiation tolerance of silicon detectors is the charge collection efficiency as a function of the bias voltage (CC(V)). Besides, the most relevant measurement are performed with segmented detectors read-out with electronics with similar performances to the one anticipated for the SLHC. LHC speed custom electronics (40MHz clock speed) is representative of the electronics anticipated for the upgrade of the experiments, where the clock speed of the front-end of the chips should stay unchanged.

Figure 7 shows the CC(V) performances of 300μm thick miniature microstrip detectors made by Micron and irradiated with neutrons, with dose rates up to $5x10^{12}$ n cm^{-2} s^{-1}, to various fluences up to $1x10^{16}$ n cm^{-2} [24]. Severe signal degradation due to the increase of the charge trapping with fluence is found, but for the first time segmented detectors were measured after such a heavy irradiation, setting an important reference value for the CCE at fluences corresponding to the final doses expected for the innermost layers of the upgraded experiments in the SLHC.

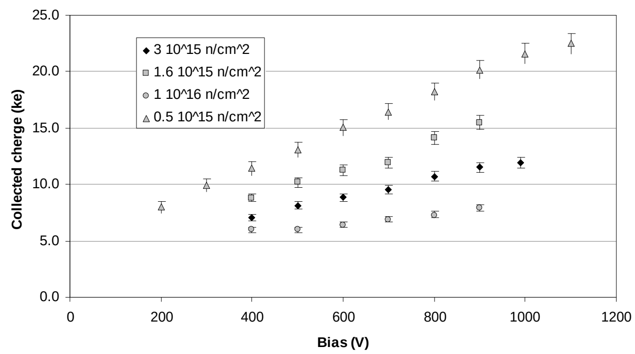

Fig. 7 Collected charge as a function of the applied voltage for miniature microstrip detectors read-out with 40MHz analogue electronics after neutron fluences up to $1x10^{16}$ cm^{-2}.

6.4 Annealing studies of the CCE

In order to qualify the p-type devices for high radiation environments, it is also necessary to address the question of the reverse annealing.

The changes of the full depletion voltage (V_{fd}) with time after irradiation are well known and accurately parameterised. After a decrease during ~10 days at room temperature (20^oC), the V_{fd} increases with time after irradiation (*reverse* annealing) for several years to reach saturation at a value about four times higher than the one immediately after irradiation. The reverse annealing has always been considered detrimental to the sensor operations: the V_{fd} was commonly linked to the CCE, in the sense that both quantities were thought to saturate at the same voltage, as for non-irradiated devices. The substantial increase of V_{fd} with annealing time would entail a corresponding decrease of the charge collected at a given voltage below V_{fd}. This trend has been measured by mean of the Capacitance-Voltage characteristics (CV) after accelerated annealing stages at high temperature. The annealing is a strong function of the temperature and the acceleration factor at 60 and 80^oC is about 540 and 7400 times with respect to room temperature.

The annealing has been studied in term of changes of the CCE for the first time in [20] after heavy proton irradiation. The results of these measurements have changed the way the reverse annealing is regarded in the experiments, because the charge collection didn't show the expected decrease corresponding to the increase of V_{fd}. Further accelerated annealing studies were performed after neutron irradiation to 1.6 and 3×10^{15} cm^{-2} [23]. Figure 8 shows the collected charge as a function of the equivalent time at 20^oC (RT_{eq}) for these two neutron doses.

While V_{fd} is expected to change from 900V (1800V for the higher dose) to >3900V (7000V), the charge collected after three years RT_{eq} for both doses is the same at the different voltages. The collected charge increases noticeably (10-15%) during the first 50 days for the two different fluences and the different bias voltages. This could be due to the annealing of the effective charge trapping time that has been measured after neutron irradiation [9]. Nonetheless, the CCE doesn't have the same dependence on time after irradiation of the V_{fd}.

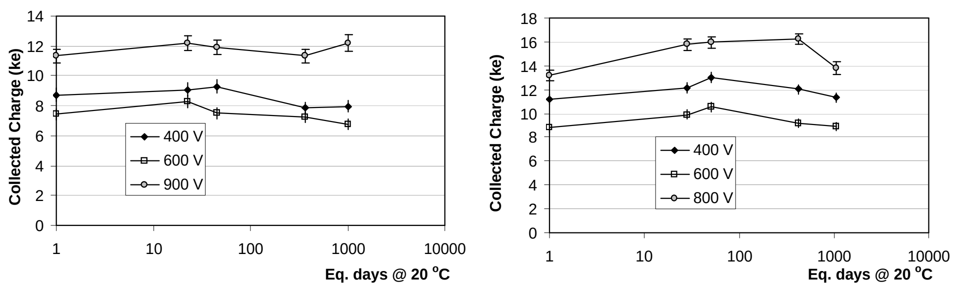

Fig. 8 Collected charge as a function of the annealing time at different bias voltages with a detector irradiated with neutrons to 1.6×10^{15} cm^{-2} (left) and 3×10^{15} cm^{-2} (right).

7. Conclusions

An extensive investigation of segmented p-type detectors is being carried out within the RD50 collaboration. Four masks set and several processing runs to produce almost one hundred wafers and several hundred detectors have been performed by three manufacturer. The characterisation of detectors as produced, the irradiation with protons [24], pions [25] and neutrons [26] and the post-irradiation measurements are on going activities that involve many RD50 institutes to carry out a large systematic study of the radiation tolerance of p-type devices in comparison with n-type. Nonetheless a significant amount of data before and after gamma and neutron irradiations is already available and it is here summarised. The pre-irradiation measurements show that the issues of strip isolation and high break-down voltage can be optimised for good performances of over-biased detectors. The interstrip capacitance corresponds to the expected geometrical value and it is not influenced by the substrate type. Very good performances in term of break-down voltage have been achieved after irradiation, with several devices being operated up to 1000V. Also extremely good results of charge collection after neutron irradiations are here presented that establish the first reference value for the inner layers of the SLHC. Although further work is needed to fully characterise the various type of substrate materials and the different designs included in the various RD50 masks and to study the performances of the devices after proton and pion irradiations, the n-in-p planar devices have established themselves as a mature technology able to reliably produce state of the art radiation tolerant detectors.

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