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Silicon detectors operating beyond LHC conditions: scenarios for radiation fields and detector degradation

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Abstract. The behaviour of silicon detectors obtained in different crystal growth technologies for hypothetical use in detector systems at LHC, SLHC, VLHC is taken into discussion, in order to evaluate which material is harder to irradiation and consequently to minimise the degradation of device parameters in conditions of long time operation. Physics requirements and different scenarios to LHC up-grade are considered.

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INTRODUCTION

Particle physics makes its greatest advances with experiments at the highest energies. The way to obtain a higher energy is through hadron colliders, or through cosmic sources. In the near future, the Large Hadron Collider (LHC) will be operational, and beyond that, its upgrades: the Super-LHC (SLHC) and the hypothetical Very-LHC (VLHC).

The investigation of detector requirements for the next generation of experiments is necessary. At the present time, there are no detailed studies for future accelerators, except those referring to the LHC. The main goal of this paper is to analyse the expected long time degradation of silicon detectors in the extreme hostile conditions supposed for these acceleration installations. Different scenarios of upgrade for detectors are considered. Different silicon material parameters are considered, resulting from different crystal growth technology, with the aim to evaluate which material is harder to irradiation, and consequently to minimise the degradation of device parameters in conditions of long time operation. Contrary to current investigations, continuum irradiation conditions are considered, in order to obtain the results that simulate most realistically the environment conditions. The contributions of primary defects (vacancy and self-interstitial) are first time considered as contributions to the leakage current. These defects are the main source of modifications in device parameters in respect to the contributions of other defects as V_2, VP, VO, V_2O, CO and C_iC_S.

Physics potential at future hadrons colliders

Particle physics has made striking advances in the last fifty years in describing the intimate structure of matter and the forces that determine the architecture of the universe. The current view of the universe is based on a small number of matter constituents acted on by four forces in a four-dimensional space-time. The simple structure of elementary constituents and forces form the theoretical framework called the "Standard Model", which has been able to predict with very good accuracy the values of many quantities that have been measured by experiments at modern accelerators. But this theory is incomplete because:

gravity is not included,

some aspects, as for example electroweak symmetry breaking, responsible for the striking asymmetry between the massless photon and the massive W and Z, or the difference by many orders of magnitude between the masses of neutrinos (now, it is nearly established that neutrinos have masses) and those of the heavier quarks are not yet understood;

it requires as input a large number of parameters such as the masses of the constituents and the coupling constants of all forces.

Major steps towards answering these questions would come from developing global theories but invoke energy scales that are far beyond the reach of conceivable accelerators and obtaining new experimental results at higher energies, as Higgs boson(s), or at least observable traces of these theories at accessible energies. Experiments relevant to this quest are not restricted to the high-energy frontier; they are also possible at low energy scales.

The Higgs boson is responsible in the Standard Model for electroweak symmetry breaking. Its discovery would be a fundamental confirmation of the Standard Model, and the precise measurement of its characteristics would open the way towards a more global theory. One possible example of an extension of the Standard Model is "supersymmetry". It predicts that more than one Higgs boson will ultimately be found, at least one of which is light. It also predicts that each constituent of matter has a supersymmetric partner with zero spin and that each force carrier has partners of spin ½, realising a complete symmetry between forces and matter. Until now searches for these supersymmetric particles at the existing accelerators have been negative. If these particles exist, they should be revealed between about 100 GeV and a few TeV.

For the next three years, the Fermilab Tevatron Collider will be the frontier machine. If the Higgs boson is a light particle, it could be discovered at the Tevatron if its mass is less than about 170 GeV, assuming an integrated luminosity of 30 fb^{-1}, otherwise by experiments at the CERN LHC for masses up to 1 TeV.

The Large Hadron Collider at CERN, first proposed in 1984, is being constructed and is expected to operate from 2007. The main research goals for the two general experiments, ATLAS and CMS, are the exploration of the electroweak symmetry breaking mechanism, and in particular the discovery of the Higgs particle and the search for physics beyond the Standard Model and in particular supersymmetry. Most probable, around 2010 the results will be conclusive: or the Higgs boson will be firmly experimentally observed as well as the electroweak symmetry breaking via Higgs mechanism, or the theoretical ideas will require a major revision. Similarly, the discovery or rejection of supersymmetry should be possible within the first two years of LHC operation. If the supersymmetry exists, many new particles are expected to be produced and detected at LHC if the masses are of the order of 2 TeV. The partners of the leptons will mostly be seen in cascade decays and will be difficult to identify above 300 GeV.

Despite the technological difficulty, significant upgrades, in energy and luminosity of the accelerator are considered as Super-LHC and Very-LHC respectively [1, 2]. The upgrade path will be defined by the results from the initial years of LHC operation. Possible scenarios would dictate exploration at high energies up to 240 TeV (as the final project energies) includes:

search of supersymmetric particles; if only a few are discovered at lower energies other partners with masses as a few tens of TeV could be discovered,

search for new heavy fermions,

search for the existence of heavy neutral Z' and/or charged W' vector bosons,

search of quark compositness if traces are observed with a scale of a few tens of TeV,

possible indications for large extra spatial dimensions confined to distances of the order of femtometers, a scale that can be probed only with collisions energies larger than 100 TeV,

existence of a new strong W-W interactions.

VLHC will open a complete new energy regime, which could be probed for new physics.

The main characteristics of LHC and of its up-grades are summarised in Table I.

Table I. Characteristics of the LHC accelerator and of its possible up-grades

	LHC	SLHC	VLHC (stage 1)	VLHC (stage 2)
Year when will be operational	2007	possible 2010	after 2014	?
$\sqrt{s}$ [TeV]	14	14÷28	40	up to 240
L x10^{34} [cm^{-2}s^{-1}]	1	10	1	1-2/10
Bunch spacing [ns]	25	12.5	6, 18	6, 18
σ_{pp} inelastic [mb]	≈ 80	≈ 80	≈ 100	≈ 140
N=$L\sigma_{pp}\Delta$t	20	100	20	25-50/250
$\langle E \rangle$ charged particles	450 MeV	500 MeV		600 MeV

Requirements for detectors at the next generations of hadron colliders

At the present time it is possible to discuss only general requirements imposed to detectors. Here we will concentrate on semiconductor options for future experiments.

An important part of the detector design is the shielding necessary to reduce background. A major source of background is the interaction of proton fragments with the beam pipe and other interaction region components. Special shielding design could reduce the background flux by orders of magnitude, reducing this way the radiation dose to the detector components. These characteristics are important for detector design, in particular for luminosities of L=10^{35} cm^{-2}s^{-1} or higher.

Major challenges for detector operation at such high luminosities are related to the following aspects [3]:

The detectors must operate at high luminosity that supposes a large number of interactions per crossing. For example, at a luminosity of $10^{34}cm^{-2}s^{-1}$ and beam crossing time of 18.8 ns, the average number of interactions per crossing will be 19 and this number will increase to about 62 for a luminosity of $10^{35}cm^{-2}s^{-1}$ and for a bunch spacing of 12.5 ns.

The radiation fluxes are different than the present situations. U. Bauer et. al. [1] has shown that the total and inelastic cross sections increase only slowly with energy one can extrapolate for energies for future accelerators. Thus, the radiation dose in the central region is a function mostly of the luminosity, not the energy. This conclusion permits to give some predictions for the particle spectra in the central cavity.

These suppositions are not true in the very forward region where particle momentum scales with beam energy.

A very good triggering capability is necessary and special fast trigger electronics need to be developed. The trigger system should reduce the initial interaction rate of about 50 MHz to a rate of about 50 Hz for writing events to tape. With a high occupancy of detector elements and a large number of readout channels a typical event size is in multi Mbyte range. This translates to a Gbyte/s tape rate. It is important to select only interesting classes of events at the trigger level and reduce the huge data sample manipulation after events are written to tape.

Semiconductor detectors are mainly used in the central tracking system. Typically this region consists of two sub-detectors: a precision vertex detector and a tracking system for momentum measurement.

Interactions of particles in the detector

Damage mechanisms

When an incident particle is slowed down in silicon, it produces different types of damage. It depends on the competition between the cross sections of the corresponding processes, e.g. energy transfer to atomic electrons (ionisation) and energy transfer to translational motion of the atom as a whole. While ionisation is the basis of particle detection and is reversible, displacement effects produce defects in the lattice, determining changes in the material and consequences in device characteristics.

The nuclear interaction between the incident particle and the lattice nuclei produces bulk defects. As a result of the interaction, depending on the energy and on the nature of the incident particle, one or more light particles are formed, and usually one (or more) heavy recoil nuclei. The nucleus has charge and mass numbers lower or equal with that of the medium. After this interaction process, the recoil nucleus or nuclei are displaced from the lattice positions into interstitials. Then, the primary knock-on nucleus, if its energy is large enough, could produce the displacement of a new nucleus, and the process continues as long as the energy of the colliding nucleus is higher than the threshold for atomic displacements. This phenomenon can be regarded as a cascade process. We denote by primary displacements all the displacements produced as a results of the primary interactions, without any further rearrangement of the vacancies and interstitials. The physical quantity characterising the process is the concentration of primary defects (or related quantities, for example the non ionising energy loss) produced per unit of fluency of the incident particles.

In all subsequent discussions related to damage effects, the primary recoil is the particle whose energy partition must be calculated. As specified before, the primary recoil is either a nucleus of the medium, or a nucleus with a lower mass and charge numbers. As a consequence, for each medium a whole family of curves of e.g. energy spent into non-ionising processes versus recoil energy could be obtained. These Lindhard curves could be used directly in the evaluation of the damage produced in materials by ion beams, if the energy of particles in the beam is identified with recoil energy.

Model calculations for the bulk degradation and relevant quantities

Due to the fact that there is no theory that describes these processes of interaction, phenomenological models are used. A possible physical quantity is related to the number of atoms displaced, and conduces to the concentration of primary radiation induced defects per unit particle fluence (CPD). In the model developed previously by the authors, (see, e.g. Ref. [4]), the main steps in calculating CPD are the consideration of the primary interaction incident particle – nucleus of the lattice, and the redistribution of the energy of recoil nucleus (nuclei) in the lattice between displacements and ionisation. Thus, the energy transferred into displacements is calculated in direct correlation with the characteristics of the incident particle and with the properties of the crystalline target.

In the present discussion and the proposed model, we consider the process of partitioning the energy of the recoil nuclei (produced due the interaction of the incident particle with the nucleus, placed in its lattice site) by new interaction processes, between electrons (ionisation) and atomic motion (displacements) in the frame of Lindhard’s theory.

CPD is not proportional to the modifications of material parameters after irradiation, due to the subsequent interactions of vacancies and interstitials with other defects and impurities in the lattice. In figure 1 the incident energy dependence of CPD is presented in relation with different incident particles.

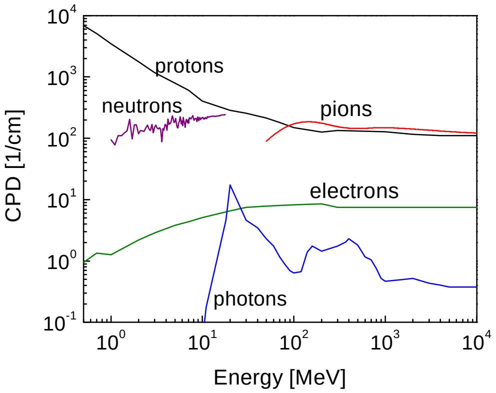

Figure 1 - CPD produced by different particles in silicon

It could be observed that the primary degradations induced by hadrons are more important than those due to leptons, at least one order difference as effect.

Present silicon technology used for detectors in HEP

Traditionally, silicon sensors have been fabricated using the float zone (FZ) crystal growth technique. For detector applications, the float zone technique ensures high-purity and defect-free silicon. Due to the high resistivity of the material, the detector can be full depleted at relatively low voltage. Naturally the silicon obtained by FZ growth is characterised by low oxygen concentration. A technique to incorporate oxygen in the bulk of the material to improve the radiation hardness of silicon has been developed at BNL [5]. For this material we refer as DOFZ (diffusion oxygenated FZ).

Czochralski growth technology (Cz-Si) is generally characterised by low resistivity. In the last period, silicon with sufficiently high resistivity has been obtained (MCz Magnetic Czochralski), permitting to obtain detectors.

In the analysis that follows, only the presence of phosphorus, oxygen and carbon impurities is considered in the silicon bulk, and the impurities are supposed to be uniformly distributed. The impurity concentrations of the materials considered in this paper are listed in Table II.

Table II. Silicon characteristics used in the calculations

Material	[P] [atoms/cm^3]	[O] [atoms/cm^3]	[C] [atoms/cm^3]
FZ	$4\ 10^{11}$	10^{15}	10^{16}
DOFZ	$4\ 10^{11}$	$4\ 10^{17}$	10^{16}
MCz	$3\ 10^{12}$	$8\ 10^{17}$	10^{16}
Cz	10^{13}	$4\ 10^{18}$	10^{16}

Modelling of the kinetics of defects in silicon exposed to radiation fields

Because the impurities in solids have a major importance in the kinetics of primary defects (vacancies and interstitials) produced after irradiation, Damask and Dienes, developed in the 1960s [6] a theoretical model where this problem is treated in the simplest form by solving the corresponding differential equations.

In the phenomenological model developed by the authors [7, 8, 9, 10, 11, 4, 12], the primary incident particle, having kinetic energy in the intermediate up to high-energy range, interacts with the semiconductor material. The recoil nuclei resulting from these interactions lose their energy in the lattice. Their energy partition between displacements and ionisation is considered in accord with Lindhard's theory [13, 14] and after this step the concentration of primary defects is calculated. The basic assumption of the present model is that primary defects, vacancies and interstitials, are produced in equal quantities and are uniformly distributed in the material bulk. They are produced by the incoming particle, as a consequence of the subsequent collisions of the primary recoil in the lattice, or thermally. The generation term (*G*) is the sum of two components: G_R accounting for the generation by irradiation, and G_T, for thermal generation. The concentration of the primary radiation induced defects per unit fluence (CPD) is calculated as the sum of the concentrations of defects resulting from all interaction processes, and all characteristic mechanisms corresponding to each interaction process, using the explicit formula (11). Due to the important weight of annealing processes, as well as to their very short time scale, CPD is not a direct measurable physical quantity.

The primary defects, vacancies and interstitials, are essentially unstable and interact via migration, recombination, and annihilation or produce other defects. The processes involving primary defects are discussed in the description of chemical reactions in silicon, around room temperature, in Reference [4]

Possible scenarios for radiation environments at LHC, SLHC and VLHC

Contrary to current experiments which test the behaviour of semiconductors device, in the radiation field, in the concrete situations that these will work, the radiation field will exist continuum long time, usually 5 to 10 years, so it is expected a different long-time degradation than other conditions.

The Large Hadron Collider at CERN, proposed in 1984, is expected to operate from 2007. The main research goals of physics, to be realised in two major experiments, ATLAS and CMS, have intensively being discussed; see for example Refs. [15, 16, 17, 18, 19]. Despite the technological difficulties, significant upgrades of the accelerator in energy and luminosity are considered as Super-LHC and Very-LHC respectively. The upgrade path will be defined by the results from the initial years of LHC operation.

At the present time the radiation fields in approximate experimental configurations are estimated only for LHC. At LHC energies, for bunch spacing of the order 25 ns and a luminosity of the order of $L = 10^{34}$ cm^{-2}s^{-1}, the minimum bias events are assumed to have $n_{ch} \cong 6 \div 7$ particles per unit of pseudorapidity, and the average value of transverse momentum is $< p_T >= 0.45 \div 55 \;\; GeV/c$. Inside the tracking cavity the hadrons represent around 54% of all the produced particles, and charged pions are the most abundant, around 64% of all hadrons [20]. In the concrete case of the CMS future experiment the simulated charged hadron spectra at different positions inside the tracking cavity have been published in Reference [17]. The shape of the spectra as well as the maximum in particle distributions is dependent on the position inside the tracking cavity. In the spectra, the main contribution is due to pions, followed by protons, other hadrons being irrelevant in the distributions. The two positions considered are: a) r = 20 cm, z = 0÷60 cm, which corresponds to the maximum in flux, and b) r = 100 cm, z = 140÷280 cm; associated with the minimum hadron fluxes; from Ref. [17].

For LHC upgrades, in the absence of detailed studies, only suppositions are possible. Following the idea exposed by F. Gianotti in Ref. [2], we supposed [12] the following conditions for the SLHC and VLHC respectively:

For SLHC environments, the following scenarios are considered:

a) the pion and proton spectra remain the same as in LHC conditions but with one order of magnitude increase in intensity, corresponding to the order of magnitude increase of luminosity (no upgrade in energy considered),

b) the luminosity is increased as in a), but the beam energy is increased with a factor of two, the energetic distribution of pions and protons is the same as for LHC conditions, but the average energy of the spectra is shifted to higher energy with 50 MeV;

For the upgrade to VLHC, in the estimation of the generation rate we supposed:

c) the same geometrical configurations as for LHC, the same distributions of particles in the corresponding positions in the tracking cavity, but with the maximum in the spectra shifted to higher energies with about 150 MeV at the same luminosity,

d) one order of magnitude increase in the luminosity, in respect to c), respectively.

In the LHC conditions (considering in the concrete discussions the particular case of CMS and ATLAS experiments) the hadrons are the predominant particles in the tracker, especially low energy charged pions and protons. The maximum in the rates of primary defects generated by pions comes from the region around 200 MeV while the protons the major contribution comes from the lowest energy region, see for example [9]. In the concrete calculations, the CPD distribution induced by pions is cut at 20 MeV. This cut represents only a contribution below 0.5% in the integrated defect spectra.

The differential energetic generation rates of defects for SLHC and VLHC conditions are calculated in agreement with the hypotheses discussed, starting from the spectrum simulated for CMS. In Figure 2, the differential energetic generation rates of primary defects, from left to right, for the LHC, SLHC and VLHC environment, for protons (triangles) and pions (asterisk and cross), for two extreme possible positions in the tracking cavity are represented. The SLHC and VLHC differential generation spectra have been obtained by increasing the average energy with 50 MeV and 150 MeV respectively.

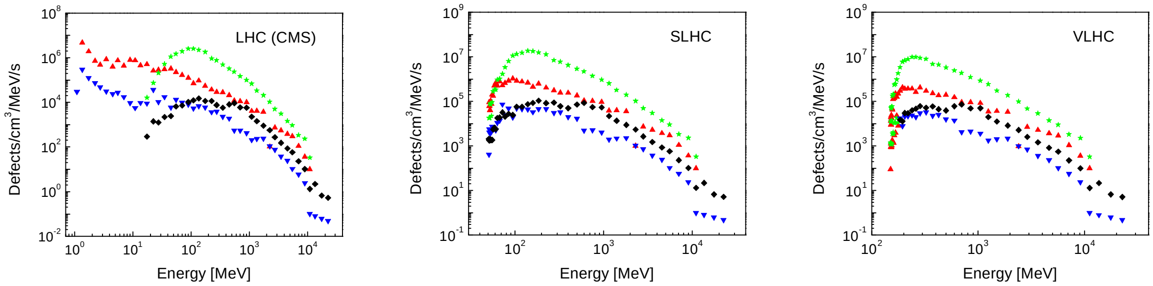

Figure 2 - Differential energetic generation rates of primary defects, from left to right, for the environment of LHC, SLHC and VLHC, for protons (triangles) and pions (asterisk and cross), for two extreme possible positions in the tracking cavity, r=20 cm, z=60 ÷120 cm and r=100 cm, z=140÷280 cm respectively. The SLHC and VLHC defects spectra are obtained by increasing the average energy distribution with 50 MeV and 150 MeV respectively, and the luminosity with one order of magnitude – see text.

In the two extreme radiation fields existent in the tracker cavity and considered in this work, the rates of generation of defects (induced by pions and protons) are: 6.8 x 10^8 VI/cm^3/s in the LHC conditions and

6.8 x 10^9 VI/cm^3/s, (SLHC, hypothesis a)), 7.2 x 10^9 VI/cm^3/s (SLHC, hypothesis b)), 6.9 x 10^8 VI/cm^3/s for VLHC, hypothesis c) and 6.8 x 10^9 VI/cm^3/s, VLHC, hypothesis d) respectively. For these generation rates, the contributions coming from proton spectra represent 8.2%, 8.2%, 6%, .8% and 8% respectively.

In the considered scenarios, the maximum of the generation rate of primary defects is obtained in the hypothesis b) for the SLHC upgrade. VLHC conditions are less dangerous for silicon detectors that the SLHC environment.

Predicted effects at the device level: leakage current modifications

Most of the radiation detectors are based on the properties of the p-n junction. Consequences of irradiation processes, some characteristics of the devices could be influenced by the formation of secondary defects which are unstable and which could be electrically active - with energy levels located in the band gap of silicon. In this case, they could capture free electrons or holes and change the initial concentrations of charged donors and acceptors in the space charge region of the detector. The principal effects are: change of the depletion voltage, increase of the leakage current, bulk material resistivity modification, change of electric field distribution in irradiated silicon p-n junction, charge in the collection efficiency and capacitance contribution to the noise.

Only aspects related to the increasing of the leakage current are discussed here.

The increase of the leakage current component that is due to the generation of electron-hole pairs on the defect levels could be evaluated in the frame of the simplified Shockley-Read-Hall model [21], [22]. The defects, which have an important contribution to the leakage current, are those with energy positions near the intrinsic level and with high cross sections for carrier capture. Currently, in order to calculate detector characteristics, the Shockley-Read-Hall model is combined with the defects concentrations, measured or predicted. In this model each defect is considered with one or more levels in the bandgap, uncoupled, and thus the current is simply the sum of contributions of all energy levels. In fact for the defects with more energy levels in the bandgap, these are coupled, and the effects are different. This effect is discussed in Choo's paper [23]. The defects relevant for the modifications of leakage current are those with deep energy levels in the band gap, in the neighbourhood of the intrinsic level, and are listed in Table III.

An important old observation consists in the good or reasonable agreement between model and data for the leakage current and effective carrier concentration after lepton or gamma irradiation, and discrepancies up to 2 orders of magnitude (smaller in model calculation) after hadron irradiation. Different models, more theoretical or phenomenological, were developed to explain these aspects. The formation of cluster defects after hadron irradiation and their absence in lepton case is the current explanation. [24]. In this contribution we argue that the main discrepancies between model calculations and experimental data for macroscopic detector characteristics (leakage current and concentration of effective carriers) after hadron irradiations could be solved naturally considering for the first time the contributions of the deep levels of primary point defects in silicon: vacancies, interstitials, whose complete characteristics have recently been put in evidence experimentally and theoretically justified. An extensive analysis could be found in Reference [25].

The native point defects in silicon can affect the evolution of silicon in various conditions especially immediately after irradiation and during continuous irradiation.

The vacancy takes on five different charge states in the silicon band gap: V^{2+}, V^{+}, V^{0}, V^{-}, and V^{2-}. The charge states V^{2+}, V^{+}, V^{0}, form the so-called negative U system, caused when the energy gain of a Jahn-Teller distortion is larger than the repulsive energy of the electrons, case in which the (0/+) level is inverted in respect to (+/++) level, which are the striking consequence of the fact that the V^{+} charge state is metastable.

The self-interstitials in silicon can exist in four charge states [26]: I^{-}, I^{0}, I^{+} and I^{2+}.

Historically, it was considered that vacancy and self-interstitial annihilate. In fact, recent calculations have demonstrated they that forms Frenkel defects, a I-V bound system, tetracoordinated; [27] which produced a delay of annihilation process, a few hours at the room temperature.

The deep energy levels of defects with relevant contributions to modifications of the leakage current are presented in table III.

Table III. Energy levels of defects with major contribution to device damage

Defect	Energy level	Type of defect	Charge state	Reference
V	E_V+0.52	Donor	0/-	[1)]
I	E_C-0.41	Acceptor	0/-	[1)]
V_2O	E_C-0.54	Acceptor	0/-	[28]
V_2	E_C-0.41	Donor	+/0	[29]
VP	E_C-0.45	Acceptor	0/-	[29]
CO	E_V+0.36	Donor	+/0	[29]

[1)] Average between the values from Ref. [26], [30] and references cited therein

In Figure 3 the results obtained in this model in leakage current calculation is compared with experimental data after irradiation. In the figure, the dashed curve is calculated considering only contribution from…. defects, and continuous curves consider also the contributions that come from vacancies and self-interstitials. In calculations the following values are considered for primary defects: migration energy for interstitials: 0.3 eV, migration energy for vacancies: 0.7 eV; sink concentration: 10^8 cm^{-2}; capture cross section on the deepest level of the vacancy: 1.5 10^{-15} cm^{-2}, and of interstitials 10^{-15} cm^{-2}. A more detailed analysis related to the contributions of primary defects will be published elsewhere.

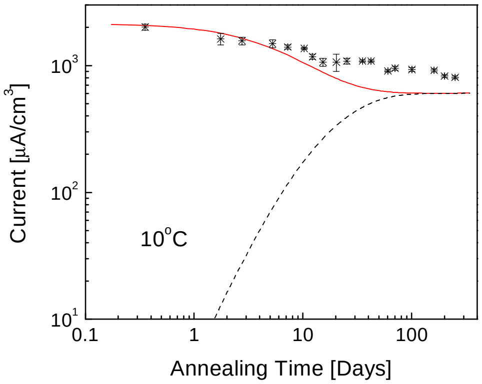

Figure 3 - Time dependence of the leakage current after proton irradiation at 10°C: experimental data from Ref [31] (points) and model calculations: continuous line: all defects from Table III, dashed line: without vacancies and interstitials.

Starting from the concentrations of defects calculated in the in the model and considering the scenarios supposed in this contributions (the very hostile environments for SLHC), the time evolution of the leakage current is represented in Figure 4 for the four technologies used for detectors. The contributions of primary defects are included.

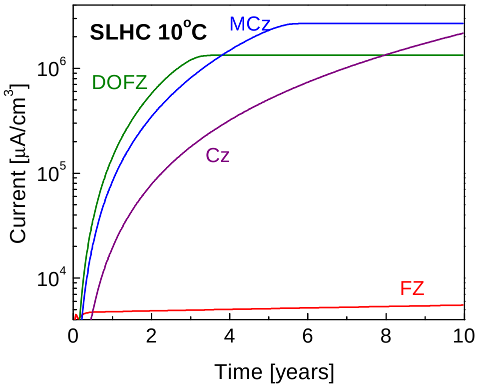

Figure 4 - Predicted time dependence iof the leakage current in continuous hadron irradiation conditions supposed to exist at SLHC. Are considered Cz, Fz DOFZ and MCz crystal growth technologies. The contributions of primary defects are included.

CONCLUSIONS

In the hypothesis considered in this paper for scenarios to up-grade LHC collider, and differential hadron spectra around the interaction region, the Float Zone technology of silicon detectors could be more adequate to obtain harder materials, considering as interest parameter the modification of the leakage current.

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