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Charge collection in Si detectors irradiated *in situ* at superfluid helium temperature

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ABSTRACT

Silicon and diamond detectors operated in a superfluid helium bath are currently being considered for the upgrade of the LHC beam loss monitoring system. The detectors would be installed in immediate proximity of the superconducting coils of the triplet magnets. We present here the results of the *in situ* irradiation test for silicon detectors using 23 GeV protons while keeping the detectors at a temperature of 1.9 K. Red laser (630 nm) Transient Current Technique and DC current measurements were used to study the pulse response and collected charge for silicon detectors irradiated to a maximum radiation fluence of 1×10^{16} p/cm^2. The dependence between collected charge and irradiation fluence was parameterized using the Hecht equation and assumption of a uniform electric field distribution. The collected charge was found to degrade with particle fluence for both bias polarities. We observed that the main factor responsible for this degradation was related to trapping of holes on the donor-type radiation-induced defects. In contrast to expectations, along with formation of donors, acceptor-type defects (electron traps) are introduced into the silicon bulk. This suggests that the current models describing charge collection in irradiated silicon detectors require an extension for taking into account trapping at low temperatures with a contribution of shallow levels. New *in situ* irradiation tests are needed and planned now to extend statistics of the results and gain a deeper insight into the physics of low temperature detector operation in harsh radiation environment.

1. Introduction

The High-Luminosity upgrade of the LHC (HL-LHC) aims at a tenfold increase of beam luminosity [1]. In this case both the collider machine and the experimental facilities will undergo major upgrades. The higher luminosity emphasizes the importance of a reliable Beam Loss Monitoring System whose main purpose is machine protection from the beam losses and especially quench prevention of the superconducting magnet coils. The present configuration of the LHC beam loss monitors (BLMs) based on ionization chambers placed outside the magnet cryostat makes it difficult to estimate exactly energy deposition in the coils due to the debris which masks the beam loss signal [2]. The alternative option suggested by the CERN-BE-BI-BL group [3,4] for the HL-LHC is based on the application of semiconductor detectors located as close as possible to the superconducting coils of the magnets. These detectors, preferably silicon and diamond ones, will be immersed in superfluid helium and operate at a temperature T of 1.9 K. Silicon detectors have the advantage of well-developed technology for mass-production, low production costs and a well-known behavior when irradiated. One point that has still to be addressed is whether silicon detectors can withstand high radiation environment when being immersed in superfluid helium. The models of radiation damage predict a different defect behavior at LHe temperature when compared to room temperature (*RT*). Among the primary defects in silicon, only interstitials are mobile at $T\sim4$ K and can participate in the creation of interstitial-related defect complexes (mainly donor-type defects), whereas primary vacancies are immobile at such low T [5,6]. This hinders from the introduction of vacancy-related acceptor-type defects (VV, V_2O, *etc.*), which control the accumulation of negative charge in the detector bulk and are responsible for the degradation of silicon detector characteristics, including charge collection. This gives us hope that the radiation hardness of silicon detectors will be adequate in superfluid helium media. The study of this issue was the aim of the *in situ* irradiation test.

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The work on this project started at CERN in 2011 included tests of nonirradiated silicon and diamond detectors operating at ~2 K and *in situ* irradiation test of these detectors at 1.9 K [7–9]. Irradiation test was performed at the CERN PS beam line where the detectors were irradiated with 23 GeV protons. A detailed description of the *in situ* experiment and the characterization of irradiated detectors are given in [9]. The collected charge Q_c was derived from the data on the detector DC current induced by proton spills, and the dependences of the charge on the bias voltage V and irradiation fluence F were obtained and qualitatively explained.

In this work the results of the *in situ* irradiation test of silicon detectors operated at 1.9 K undergo extended analysis. The data on the current pulse response changes with accumulated fluence are described. An approximation of $Q_c(F)$ dependences is performed using the Hecht equation. The aim is the estimation of the trapping effects and possible electric field transformations under irradiation at 1.9 K. We analyze the experimental results looking for specific features of radiation-induced defect formation at such low temperature.

2. Experimental conditions

The investigated silicon detectors were p^+–n–n^+ structures processed on wafers with a resistivity of 10 kΩ cm, 500 Ω cm and 4.5 Ω cm and a thickness of 300 μm. The sensitive area was 5×5 mm^2 for the samples used in the measurements of collected charge and 1×1 mm^2 in a single sample for which the current pulse response was measured [9].

Irradiation of the detectors was carried up to the maximum fluence of 1×10^{16} p/cm^2. The measurement points were within the range 5×10^{13}–1×10^{16} p/cm^2, being different for taking TCT and DC current data. The error in the fluence estimation was ±7% [10].

The current pulse response was measured using the Transient Current Technique (TCT) [11] with a LeCroy WavePro 7300A oscilloscope with a 3 GHz analog bandwidth and a sampling rate of 10 GS/s. A red laser with a 630 nm wavelength was applied to induce the transient charge in the detector. The laser pulse width was 45 ps and the diameter of the light spot was 1 mm. The laser frequency was 10 kHz, and in some cases 100 Hz, in order to estimate a possible influence of the charge generated by the laser on the pulse signal. Because of the technical problems with the radiation hardness of the cables used in the TCT measurements [9], the pulse signal was recorded only from the back n^+ side. To assure a proper spread resistance of the surface at 1.9 K, the aluminum contact in this detector was made as a mesh.

Special attention was paid to the reduction of pickup in the pulse signals. Since the measurement apparatus for TCT was located at a distance of 12 m from the cryostat in which the detectors were installed, the pickup and noise disturbed a small signal of irradiated detector. This restricted the sensitivity of the TCT measurements for detectors irradiated beyond $(5–7) \times 10^{14}$ p/cm^2.

The collected charge was determined by an integrating the detector output DC current induced by the proton beam and measured by a current meter [9]. Integration was made over 20 proton spills, the duration of each being 400 ms. To avoid a systematic error, the current was measured and averaged within a random 16.67 ms period and an interval of 60 ms between the records. In this case a statistical error of the estimated charge was ±15%. The measurements were performed for detectors irradiated up to 1×10^{16} p/cm^2.

The data were recorded at both reverse and forward bias, V_{rev} and V_{forw}, respectively, in the interval 50–500 V, the latter mode corresponding to the detector operation as a current injected detector (CID) [12].

It should be noted that this was the first *in situ* radiation test at 1.9 K, therefore it was difficult to anticipate all issues in the experiment, which explains why not all measurements and obtained results are systematic.

3. Evolution of the current pulse response under *in situ* irradiation at 1.9 K

3.1. Electric field distribution in silicon detectors irradiated at 1.9 K

The detector operation is controlled by two factors: the electric field distribution $E(x)$ in the detector bulk (x is the coordinate), and transport properties of the radiation generated nonequilibrium carriers, *i.e.* their mobility and trapping parameters. The main source of information on the electric field distribution is the study of the current pulse response using TCT [11]. In the case of a nonirradiated silicon detector with the trapping time constant τ significantly exceeding the charge collection time t_{col}, it is possible for the $E(x)$ profile to be reconstructed from the detector current pulse response initiated by generation of the electron–hole (e–h) pairs in a narrow layer adjacent to one of the detector contacts. The same can be achieved for a detector irradiated below $(5–7) \times 10^{14}$ p/cm^2 [13,14]. For detectors processed from high-resistivity detector grade silicon the experimental data, including the measurements at 1.9 K, show well predictable shapes of the pulse responses which correspond to a nearly constant electric field and a negligible density of space charge [8]. This result indicates that at $T = 1.9$ K the carriers at the energy levels in the detector bulk are frozen. This also applies to shallow levels of donors (phosphorus) and acceptors (boron), whose activation energies are 45 meV. Obviously, in pure and nonirradiated Si the concentration of the centers responsible for the bulk generated current is extremely low, and trapping of the carriers from this current does not affect the electric field distribution differently from what is observed in irradiated Si detectors operated at *RT* [13].

Before the presentation and discussion of the TCT data, it is important to determine the steady-state electric field distribution at 1.9 K in irradiated detectors without externally induced free carrier generation. Although a low bulk current is indication of a small concentration of deep energy levels (DLs), we cannot infer from this the free carrier trapping effect to be small as well. Indeed, the detrapping probability $1/\tau$ from the trapping centers with DLs is also close to zero at 1.9 K, therefore the balance of emission and capture processes can be hardly predicted. To estimate the $E(x)$ distribution in irradiated silicon detectors, we extended simulation of the $E(x)$ profile developed for detectors operated at *RT* [13] to the LHe conditions, keeping the same spectra of the effective DLs and changing the operational temperature. *E.g.*, the calculated $E(x)$ profiles in the detector operated at V_{rev} of 300 V and irradiated to 5×10^{15} p/cm^2 are depicted in Fig. 1 at T of 200–4 K. The profile has a double peak (DP) shape at $T = 200$ K. At $T = 100$ K and below the electric field

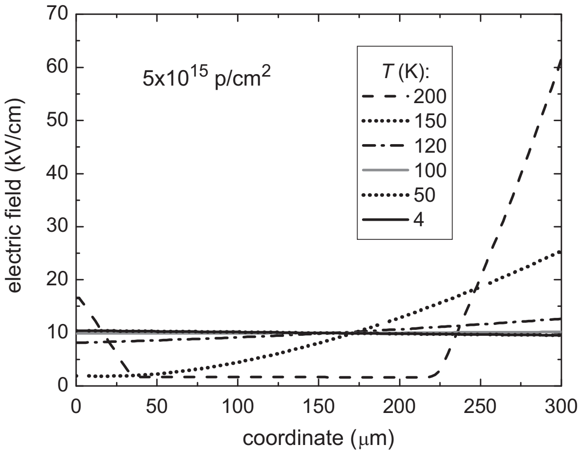

Fig. 1. Calculated electric field distributions in the detector irradiated at 1.9 K. $V_{rev} = 300$ V, $F = 5 \times 10^{15}$ p/cm^2; $x = 0$ is at the p^+ contact.