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CERN-RD39 collaboration activities aimed at cryogenic silicon detector application in high-luminosity Large Hadron Collider

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ABSTRACT

Beam Loss Monitors (BLM) made of silicon are new devices for monitoring of radiation environment in the vicinity of superconductive magnets of the Large Hadron Collider. The challenge of BLMs is extreme radiation hardness, up to 10^{16} protons/cm^2 while placed in superfluid helium (temperature of 1.9 K). CERN BE-BI-BL group, together with CERN-RD39 collaboration, has developed prototypes of BLMs and investigated their device physics. An overview of this development—results of the *in situ* radiation tests of planar silicon detectors at 1.9 K, performed in 2012 and 2014—is presented. Our main finding is that silicon detectors survive under irradiation to 1×10^{16} p/cm^2 at 1.9 K. In order to improve charge collection, current injection into the detector sensitive region (Current Injection Detector (CID)) was tested. The results indicate that the detector signal increases while operated in CID mode.

1. Introduction

Beginning of Run II of the High-Luminosity Large Hadron Collider (HL-LHC) in June 2015, opens a new stage in the fulfillment of its global research goals. The success of Run II depends strongly on the smooth and technically appropriate accelerator operation. The proposed way to ensure future safe operation of HL-LHC and prevent quench-provoking events is placing the beam loss monitors (BLMs) based on semiconductor detectors in the intimate vicinity to the magnet coils, i.e. inside superfluid helium [1,2]. This approach increases the sensitivity of the BLM system and potentially would trigger signals before critical radiation load towards the superconductive coils. The benefits of proposed silicon detectors are small size, well adopted manufacturing technology, widely studied radiation-hardness properties and relatively low operational voltage.

Our on-going activity related to the silicon detectors for BLM application (CryoBLM project) was started in 2011 as joint effort of the CERN-BE-BI-BL group and CERN-RD39 collaboration “Radiation-hard cryogenic silicon detectors” [3]. Participation of the RD39 collaboration stems from its research lines and previous results on silicon detector operation at cryogenic temperatures: finding and explanation of the so-called “Lazarus effect” at $T \sim 180$ K [4] and development of Current Injection Detectors (CID) which require cooling below 230 K [5,6].

Formation of vacancy-related radiation-induced acceptor-type defect complexes is the main mechanism of the silicon detector degradation at room temperature (*RT*). Among primary radiation-induced defects, vacancies are immobile at T below 70 K; therefore formation of vacancy-related complexes will be suppressed at liquid helium (LHe) temperature. On the other hand, primary interstitials are known to be mobile at $T \geq 4$ K and can contribute to the formation of donor-type defect complexes [7]. Thus, when starting BLM development project, silicon detectors operated at LHe temperature appeared to be a promising approach. This behavior of primary defects, however, was evinced in irradiation of the raw silicon material by electrons, which is different from the conditions in BLM where silicon detectors will be biased over the operational period of a few years and *in situ* irradiated by multiple particles including relativistic protons.

In this report, results of the two *in situ* irradiation tests of silicon detectors operated in superfluid helium (at the temperature T of 1.9 K) are summarized. These tests, T1 [8,9] and T2, were carried out at CERN PS in 2012 and 2014. The modules with

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detectors installed in the cryostat with superfluid helium were irradiated by the 23 GeV proton beam.

Silicon detectors used in the tests were planar p^+-n-n^+ pad detectors designed and processed jointly by the Ioffe Institute, St. Petersburg, and Research Institute of Material Science and Technology, Zelenograd, both Russia. The detectors processed on the wafers with resistivity of 10 kΩ cm, 500 and 4.5 Ω cm and a thickness d of 300 µm were investigated in T1. The goal of the test T2 was the comparative study of thin detectors, with a thickness of 100 µm. The cassette with detector modules studied in T2 is shown in Fig. 1 before its installation in LHe.

2. Results of the *in situ* test T1

Test T1 included the measurements of the collected charge (Q_c) via integration of the detector current generated by spills and of the current pulse response shapes using Transient Current Technique (TCT) with a 630 nm pulse laser [8,9]. The detectors were irradiated to a maximal fluence F of 1×10^{16} p/cm^2. The study of the current pulse response showed an unexpected space charge sign inversion in the depleted region of irradiated detector. The observation was explained by assuming that, along with the predicted formation of the donor-type defects, acceptor-type defects as well were induced into the silicon bulk. This was confirmed via the simulation/fitting of the $Q_c(F)$ curves using the Hecht equation, which allowed deriving the trapping time constants τ for electrons and holes [9]. It was concluded that the degradation of the silicon detector sensitivity was dominated in the first place by hole trapping.

Cryogenic environment allowed utilizing current injection detectors as BLMs. Such detectors require the material to be damaged by defects with deep energy levels, as well as operation at T below 230 K for filling the energy levels. The CID mode is realized via carrier injection from the forward biased contact, and the injected current is suppressed via Space Charge Limited Current effect [5]. Our earlier results showed that CID operation gave a twofold increase of Q_c for detectors irradiated at $F\geq1\times10^{15}$ p/cm^2, while the dark current and noise remained negligible [6,8]. The T1 test confirmed the advantages of CID operational mode at 1.9 K as well.

Summing up the findings in the physics obtained in the test T1, it was possible to conclude that [8,9]:

- all detectors survived with appropriate charge collection efficiency (CCE) irradiation up to 1×10^{16} p/cm^2, and at this fluence the CCE was not influenced by the silicon resistivity;
- the rate of the signal degradation was about seven times higher than that at room temperature irradiation due to significant reduction of the trapping time constants;
- silicon detector operation in the CID mode was feasible.

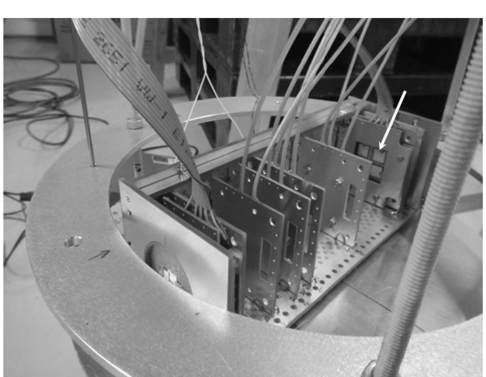

Fig. 1. Cassette with detector modules studied in test T2. Arrow shows silicon beam telescope.

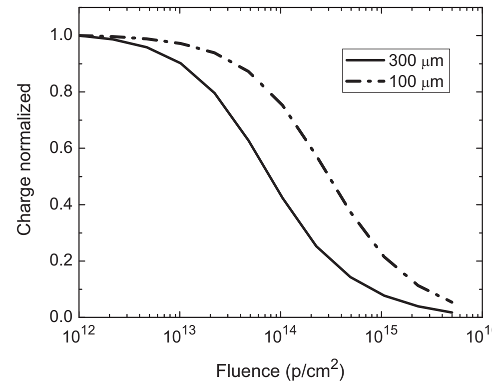

Fig. 2. Calculated dependences of normalized collected charge on fluence for silicon detectors with standard and reduced thicknesses. T=1.9 K.

3. Results of the *in situ* test T2

Application of detectors with a reduced thickness as BLMs is determined by two factors. The first one is extension of the operational fluence range illustrated in Fig. 2, which shows the fluence dependences of the normalized charge collected in 100 µm and 300 µm thick detectors. The curves are calculated for detectors processed from 10 kΩ cm silicon using the values of τ defined from the data of T1 [9]. The second favorable factor is that a mean electric field in the detector bulk, $\bar{E}=V/d$, is higher at the same bias voltage V, which is helpful in suppressing the possible effect of the polarization.

In the experiment only the detectors made of high resistivity (>10 kΩ cm) silicon were investigated. The depletion voltage at RT was ~30 V and only few volts for the 300 µm and 100 µm detectors, respectively. Since this study was focused on operation of 100 µm thick detectors, TCT measurements were not applied because of the insufficient timing resolution of about 1 ns, comparable to the carrier collection time. The detectors were irradiated by 23 GeV protons during 10 days, and the data from almost 27×10^3 spills with duration of 400 ms were recorded. The beam position and profile were controlled by three Beam Position Monitors whose data were used for evaluating the fluence. As in T1, two silicon beam telescopes (one is shown by arrow in Fig. 1), each with four pad detectors with the area of 1.5 cm^2, were used for the on-line monitoring of the beam position with respect to the cassette. Similar to T1, the collected charge was evaluated via integration of the detector current generated by spills, which gave a statistical error of about ±15% of the obtained charge [8].

The full set of data taken in T2 is the subject of further comprehensive analysis, and in this report we present only two illustrative examples. The shapes of the voltage scan curves, $Q_c(V)$, at different fluences (Fig. 3) were similar to those observed in T1. In detectors operated as CIDs, i.e. at forward (positive) bias V_{forw}, the signal increase was more apparent and the collected charge was larger than that at reverse bias V_{rev}. This is an advantage of CIDs, whose sensitive volume is depleted at any bias, and therefore they can operate effectively even at low voltages.

Electric field related effects were studied at the maximal fluence of 1.7×10^{15} p/cm^2. In Fig. 4, the data of the voltage scans are plotted in the coordinates charge vs. a mean electric field $\bar{E}$. This

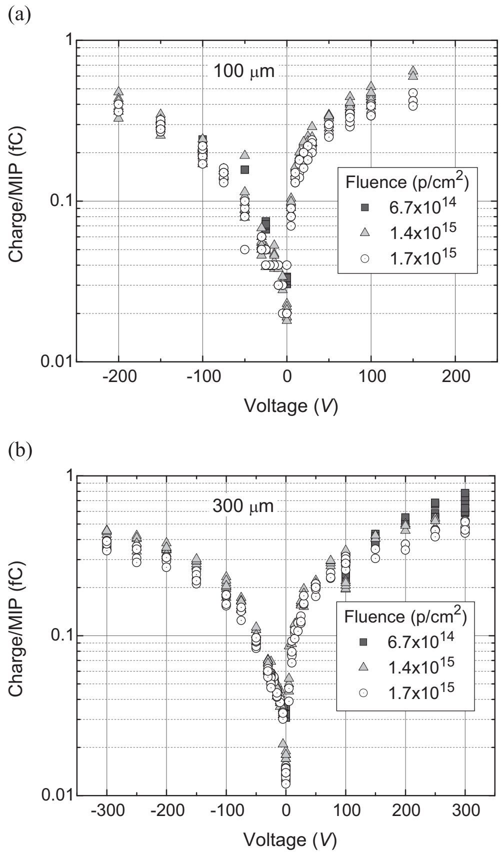

Fig. 3. Experimental dependences of the charge collected in 100 µm (a) and 300 µm (b) detectors on bias voltage.

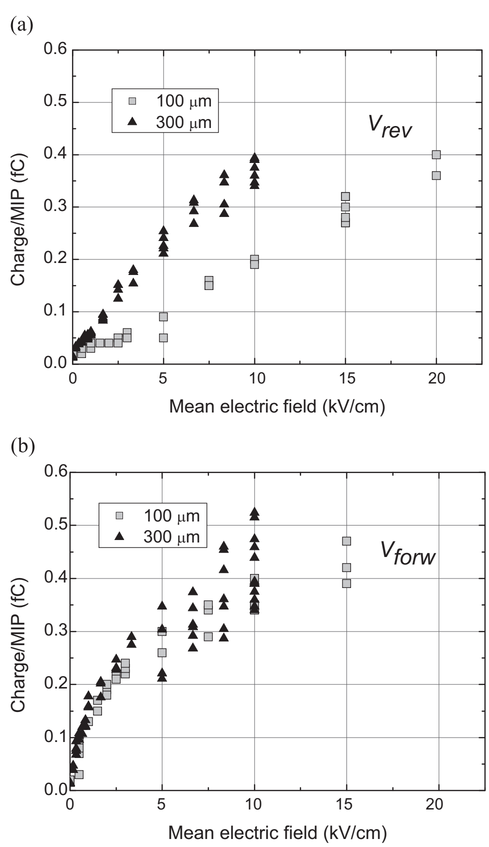

Fig. 4. Dependences of the collected charge on the mean electric field at reverse (a) and forward (b) bias.

allowed comparing the effectiveness of carrier transport and charge collection irrespective of the diode thickness. The $Q_c(\bar{E})$ dependences showed a monotonic rise without any specific features, such as an abrupt change in the slope at V_{rev} eventually due to a transition of the detector from nondepleted to fully depleted state. This behavior allowed to verify the carrier freezing at the energy levels of impurities and radiation-induced defects and stable depletion of the detector bulk (i.e. absence of polarization). In Fig. 4 it is also possible to observe that the $Q_c(\bar{E})$ dependence does not show any saturation effect, as it should follow from the drift velocity saturation at electric fields higher than 10^4 V/cm at *RT* and 10^3 V/cm at 4 K. Moreover, the experimental data for the 100 µm detector operated at V_{rev} did not show even a slight evidence of saturation at the electric field up to 1.5×10^4 V/cm. We conclude that the drift velocity saturation effect is compensated by the reduction of the carrier trapping cross-sections of the energy levels in the detector bulk.

Using the values of τ determined for a 300 µm detector operated at reverse bias in [9], the carrier drift length estimated for detectors irradiated to 2×10^{15} p/cm^2 is 50–80 µm, which is comparable to the thin detector thickness of 100 µm. Thus, an essential part of the carriers generated by spills is involved in drift and charge collection.

4. Conclusions

The common efforts of the BE-BI-BL group, responsible for the beam monitoring at LHC, and the group of CERN-RD39 collaboration, expert in the physics of cryogenic detectors, focused on the upgrade of BLMs, gave positive results. The *in situ* radiation test in 2014 with thin silicon detectors confirmed previous results and showed their possibility to operate in harsh radiation environment at 1.9 K.

It has been shown that current injection developed as a tool for increasing the tolerance of silicon detectors to irradiation at moderate cooling, is still effective at 1.9 K.

The data give clear indication that at 1.9 K the carrier transport parameters are strongly influenced by the electric field. The effect is important for the detector operation and can give significant increase in the collected charge.

Thanks to the CryoBLM project, during the LHC stop period, silicon detector modules were installed on the end of the cold mass containing superconductive coils of the magnets, for their operation as BLMs [10].

Acknowledgments

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