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Recent results of CERN RD39 collaboration on development of radiation hard Si detectors operated at low to cryogenic temperatures

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ABSTRACT

Recent results of CERN RD39 collaboration on the development of radiation hard Si detectors operated at low to cryogenic temperatures will be presented in this paper. It has been found, in comparisons of results of simulation and charge collection data of pad and strip detectors, the charge-injected-diode (CID) operation mode of Si detectors reduces the free carrier trapping, resulting in a much higher charge collection at the SLHC fluence than that in a standard Si detector. The reduction in free carrier trapping by almost a factor of 3 is due to the fact that the CID mode pre-fills the traps, making them neutral and not active in trapping of particle-induced free carriers (signal). It has been found that, electron traps can be pre-filled by injection of electrons from the n^+ contact. The CID mode of detector operation can be achieved by a modestly low temperature of ≤ -40 °C and a operation bias of <600 V. Results of one CID detector application as LHC beam-loss-monitor (BLM) will be presented. Non-irradiated Si detectors has been shown, with tests by laser using our cryogenic transient-current-technique (TCT), to work quite well at LHe temperature (4 K), which are very stable with no polarization and good charge collection efficiency.

1. Introduction

For the large-hadron-collider (LHC) upgrade, with maximum fluence up to 1×10^{16} n_{eq}/cm^2 (1 MeV neutron-equivalent/cm^2), trapping of particle-generated free carriers is the main limiting factor for the charge collection in Si detectors [1,2].

Near the maximum radiation fluences of LHC upgrade, the collected charge can be approximated in terms of carrier trapping times by radiation-induced deep level traps [2]:

$$Q_c \cong Q_0\left(v_{dr}^e\tau_t^e + v_{dr}^h\tau_t^h\right) \equiv Q_0\left(d_t^e + d_t^h\right) \tag{1}$$

where Q_0 is 80 e's/μm for MIP, v_{dr} is the carrier drift velocity, τ_t is the trapping time constant, and $d_t$is the trapping distance, with the notation of e for electrons and h for holes. The collected charge at high radiation fluences has no explicit dependence on detector thickness and depletion depth as long as they are much greater than the trapping distances, which are in the order of 20 μm at 1×10^{16} n_{eq}/cm^2 for standard detectors and detector operations.

There are basically three ways to improve the collected charge:

1. Increase the bias voltage to increase the carrier drift velocity. But since $v_{dr}^{e,h} \leq v_s^{e,h} \leq 1\times10^7 cm/s$, the saturation velocity, one cannot do too much here;
2. Reduce the carrier drift distance d_{dr} such that $d_{dr}^{e,h} \cong d_t^{e,h}$—this is the case of 3D-electrode detectors [3–8] with small electrode spacing;
3. Reduce the free carrier trapping (or increase the trapping time)—this is the approach of CERN RD39 collaboration with the charge-injected-diode (CID) operation [2], which will be studied in this work.

The carrier trapping time is related to the concentration of empty traps $N_{t,empty}$ as the following:

$$\tau_t = \frac{1}{\sigma v_{th} N_{t,empty}} \tag{2}$$

where σ is the carrier capture cross section, and v_{th} the carrier thermal velocity. To increase the carrier trapping time, one needs to reduce the concentration of empty traps. One way of doing that is to fill the traps by carriers injected through the contacts via

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forward biasing [9–11]. One example is using the CID concept to inject electrons through the n^+ contact in a Si detector by forward biasing the "inverted" (or irradiated beyond the space-charge-sign-inversion (SCSI)) $p^+/n/n^+$ detector, as shown in Fig. 1, where the main junction is located near the n^+ contact. By injecting electrons with a substantial DC current, one can reach a dynamic equilibrium between trapping and detrapping at a given temperature, in which most of electron traps are filled up, and therefore no longer active in trapping free electrons generated by particles to be detected.

In this paper, we will present the recent data on charge collection by CID microstrip detectors irradiated up to 5×10^{15} n_{eq}/cm^2 with muon beams. The effective trapping time of carriers in CID strip detectors will be determined with a previously proposed model [2]. A possible application of CID detectors as beam-loss-monitor (BLM) for LHC Upgrade will be discussed together with preliminary laser test results.

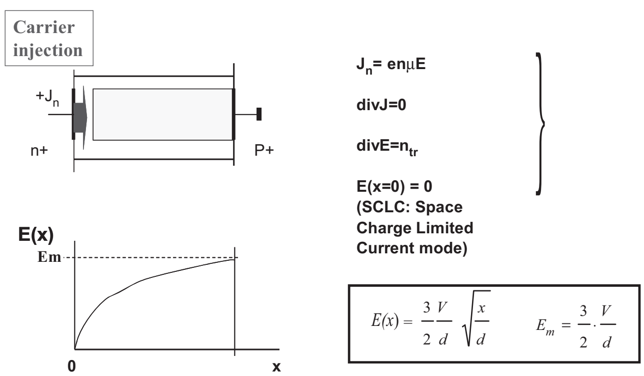

Fig. 1. Electric field in a CID for N-injection (a); and weighting field in a CID for P-strips (b). (Ninj–Pstrip).

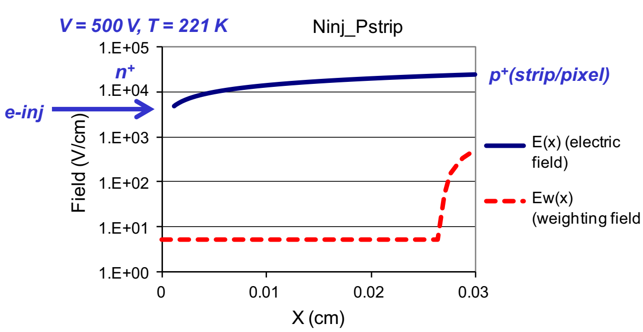

Fig. 2. The electric and weighting field profiles of a CID strip detector. High electric filed and weighting field are on the strip side.

2. Principle of CID operation

As shown in Fig. 1, when charge is injected in to a Si detector with defects/traps, at a sufficiently high injection current level, a space-charge-limited-current mode will be reached [1], under which the space charge is dominated by the filled traps, and the electric field is zero at the injection contact (it is at $x=0$ for the case of n^+ injection, as shown in Fig. 1). The electric field profile in a CID Si detector depends on the square root of x, without apparent dependence on the radiation fluence.

For a typical CID microstrip detector with 50 μm pitch (P), 10 μm strip width (W) (CMS specifications), and 300 μm thickness (d), the detector electric filed (solid) and weighting field are plotted in Fig. 2. All microstrip detectors used in this work, standard and CID, both for simulation and for beam tests, will have these specifications.

Fig. 3 shows the simulated electron transient current (and collected charges) for a microstrip detector operated in standard mode (no charge injection) (a), and in CID mode with electron injection (b). It is clear that by increasing the electron trapping time of the CID microstrip detector by a factor of 3.3 with electron injection, the total collected charge increases by almost a factor of 3 as compared to those of the standard microstrip detector. Since the collected charge is dominated by electrons due to weighting field, no improvement in hole trapping affect little to the charge collection.

3. Beam test results

Recently, beam tests were carried out at CERN H2 beam with 225 GeV/c muons on irradiated (up to 5×10^{15} n_{eq}/cm^2) CID microstrip detectors with CMS specifications mentioned before. The temperature was 221 K and the data was taken at various forward biases as shown in Fig. 4. The average collected charge at a modestly low voltage (600 V as compared to over 1000 V for standard operation) is 8000 electrons, and the maximum charge of 9000 electrons can be reached at 700 V. This result is very close to our simulation where a total collected charge of 9700 e's was predicted. Therefore the trapping time constant in a CID mode was increased by 3.3 times to 1.33 ns from that (0.4 ns) of the

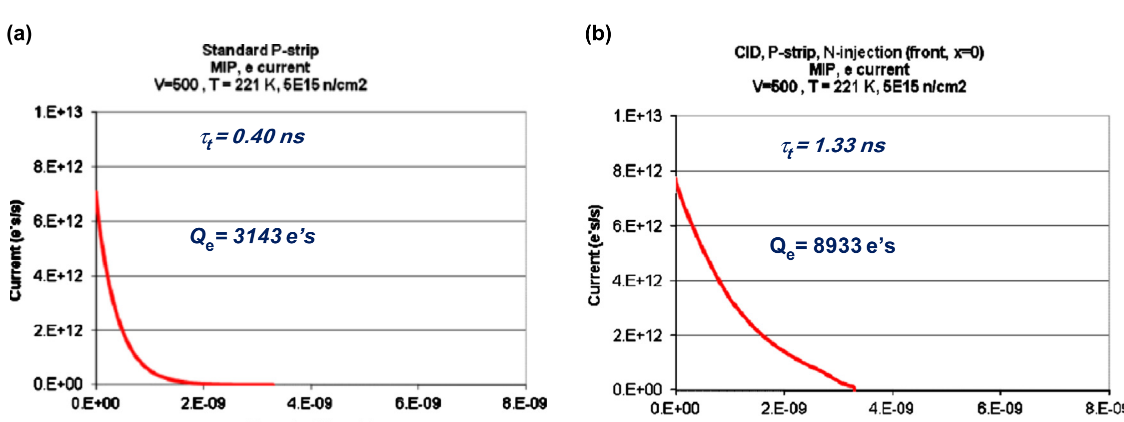

Fig. 3. Simulated electron transient current for irradiated (5×10^{15} n_{eq}/cm^2): (a) a standard strip detector; and (b) a CID strip detector with electron injection.