CRYOGENIC OPERATION OF EDGE-SENSITIVE SILICON MICROSTRIP DETECTORS

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In the frame of RD39 CERN Collaboration

The CERN RD39 Collaboration is developing radiation hard cryogenic Si detectors for use in the LHC tracking systems after their future upgrades. Within this framework, we are studying the operation of silicon microstrip detector with readout electronics at low temperature. In addition, we have studied the operation efficiency of the silicon micro-strips detectors very close to the physical border of the silicon crystal, in order to reduce as much as possible the insensitive part of such a device.

1. Introduction

Silicon sensors are widely used in existent high energy physics experiments and future upgrades. Given that as high as 10^{16} n_{eq}/cm^2 fluence is required by experiments for LHC upgrades, new strategies are developing to make silicon and Si sensors more tolerant and hard at particle radiation.

During the operation, the silicon sensors suffer from severe radiation damages, which lead to performance degradation. The defects accumulation in the silicon bulk cause an increase of the reverse leakage current due to the radiation induced deep level defects that act as generation-recombination centers. Another effect is the full depletion voltage increase, causing either breakdown if operated at high biases or an incomplete non-equilibrium charge collection, if operated at partial depletion.

Since the process of carrier generation via the deep levels is an activated process, the resulting leakage current is extremely sensitive to temperature: it decreases exponentially with decreasing temperature. This allows the operation of silicon microstrip detectors at low temperature with greatly reduced leakage current, fast charge colection due to higher mobility and faster readout electronics with less noise.

The benefit of cryogenic temperature operation of Si detectors was first highlighted in 1998 [1], when CERN RD39 put in evidence the so called Lazarus effect, which means a significant charge collection efficiency (CCE) recovery at cryogenic temperature for very heavily irradiated Si detectors (>10^{15} n/cm^2) that have, though, minimum CCE at room temperature. Detailed modeling of Lazarus effect was presented and explained in [2]. However, this effect is limited since a decrease of CCE in time, even at cryogenic temperature, from 80% down to around 20%, is observed for heavily irradiated silicon. This effect is due to the trapped charge that can accumulate and lead to the detector medium polarization resulting in a not uniform, time-dependent electric field. In forward bias operation, CCE stays to values that are about 3 times higher than in inverse bias operation [3]. Therefore, current-injection mode operation might be an answer in keeping the CCE at high level. In cases when heavy irradiation is expected, the detector could be used with reverse bias until the resistivity is such that forward bias can be applied. This alternative requires, nevertheless, bipolar readout electronics and bias voltage supply.

For certain experiments that have their tracking system as close as possible to the colliding beams (few mm), special geometry with the active area extended all the way up to the dicing edge is needed. Such sensors/devices were developed by RD39 as a direct application of the cryogenic detectors, since low temperature is a key factor in keeping the surface leakage current at few nA level.

RD39 shares resources and hardware development with the current experiments at CERN. Essential results will be summarized here, that were achieved during the progress in cryogenic silicon microstrip and edge sensitive detectors study.

2. Development of cryogenic silicon microstrip detector module

The key problem in the thermoelastic design of a cryogenic module arises from the thermal stress developed during cool down due to thermal dilatation mismatch of the components, which may lead to the silicon sensor breaking. A prototype of such a cryogenic module using silicon as a structural material can be seen in figure 1 [4], [5], [10]. It was built with a standard design full size FZ silicon detector (processed in HIP, Helsinki), 520µm thick, with p+/n/n+/Al layout, [12]. All strips are connected to the CMS-experiment type hybrid with 4 APV25 readout chips, [9]. Under the pitch adapter a carbon fiber spacer is glued, with two embedded Cu/Ni micropipes for liquid nitrogen flow.

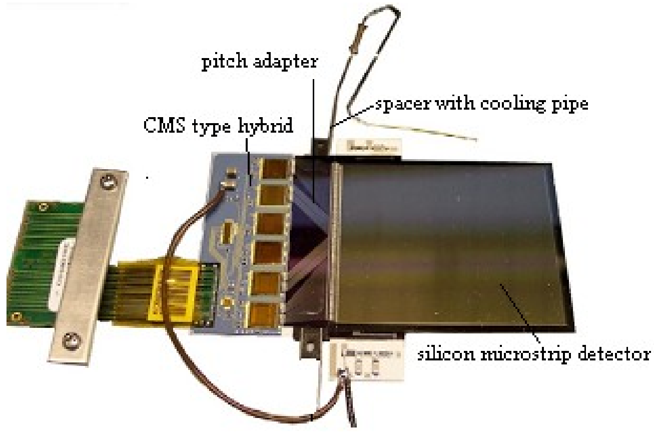

Figure 1. First cryogenic module built with FZ silicon microstrip detector 380 μm thick, 512 strips.

During operation, the liquid and gaseous phase are separated in such a way that just liquid enters the cooling pipe. The gas flows back and cools the thermal shield of the cryogenic transfer line. With this system good results were obtained, showing a uniform cooling of the module over a wide mass flow range (between 40 up to 170 mg/s). The temperature varied between 145 K, for the Al_2O_3 hybrid support and 135 K for the Si sensor and it was stable for several days, being limited in time only by the liquid nitrogen supply.

A dedicated test setup has been designed for module operation cooled down in direct contact to liquid nitrogen and thermal regulated by several resistors. The module was tested using the standard CMS-experiment setup for detectors testing with Front-End Driver [6], Front End Controller [7] and Trigger Sequencer Card [8] devices. For detector biased at 400 V, much over the full depletion voltage, the reconstructed pulse shape given by one single strip is presented in Figure 2, in both polarities, inverter on and inverter off. The CMOS readout electronics performance is strong temperature dependent, due to the cryoacceleration effects. At lower temperature the carrier mobility increases, entailing higher current-signal speed, which explains the observed shorter signal rising time. The APV25 readout chips functionality at low temperature was well demonstrated [11], down to 130K. Other electronic components from the module hybrid, like Phase Locker Line (PLL, [12]) that distributes the *clock* and *trigger* signals to the readout chip, at low temperature, is not in phase anymore, therefore our results are correct just down to 220 K. Further investigations will be concentrated to make the readout operational at much lower temperatures.

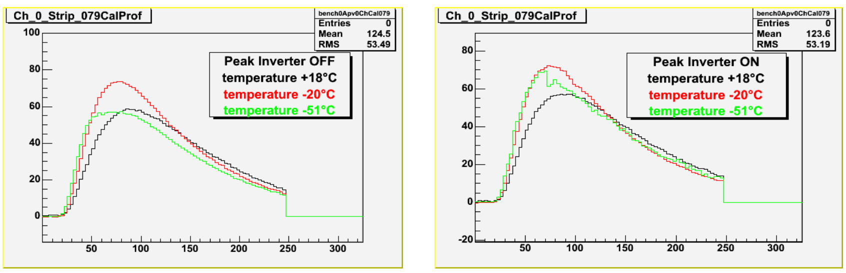

Figure 2. Detector response signal shape at different temperatures.

3. Development of edge-sensitive silicon microstrip module

The edge-sensitive detectors were conceived as microstrip detectors where the dead, insensitive area, around the dicing edge, is reduced to minimum. Several single-sided 1.5 cm long baby-microstrip detectors from 320μm thick wafers were chosen, with p+/n/n+/Al implant layout. Before cut and chemical treatment, the leakage current was around few nA/cm^2 at full depletion voltage. The dicing tool used in this study was the standard laser-dicing machine and the operation was performed at BNL, USA. Two different geometries have been chosen for our purpose. In the first layout, the silicon margin is along the strip, as close as few μm.

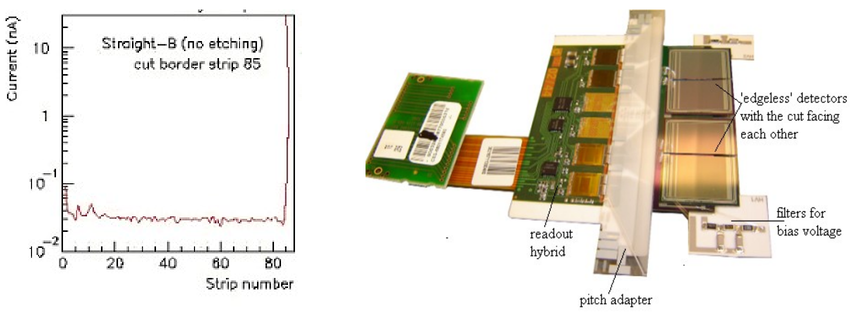

Figure 3. (a) single strip current measurement for an 'edgeless' detector where the cut is along strip number 85 at 10μm distance; (b) 'edgeless' module.

In the second geometry the angle between the cut edge and the strip direction is of few degrees. After dicing the leakage current increased drastically by five orders of magnitude.

Single-strip current measurements (Figure 3, (a)) showed that responsible for the dramatic current increase are the two strips nearest to the cut, at 120 μm inter-strip distance. Both geometries were used for the 'edgeless' module, the detectors being mounted in a way that the cuts are facing each other at a distance of around 1mm (Figure 3 (b)). The twenty strips nearest to the margin were wire bonded to the readout channels. Our goal is to test this module at very low temperature, with a Picosecond Injection Laser setup in order to determine the edge strips charge collection efficiency with respect to the strips that are far from the silicon crystal cut and belong to the same detector. By placing the 'edgeless' detector between a telescope planes, the beam particles tracks reconstruction can give us an image of the effectiveness of the strips close to the diced border. A good evaluation will be made by comparing the physical distance between the detectors that are facing their cuts, with the distance determined by tracks reconstruction.

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