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Development of radiation hard edgeless detectors with current terminating structure on p-type silicon

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ABSTRACT

The development of edgeless Si detectors was stimulated by the tasks of the total pp cross-section study in the TOTEM experiment at the Large Hadron Collider at CERN. For this, the dead region at the detector diced side should be reduced below 50 μm. This requirement is successfully realized in edgeless Si detectors with current terminating structure (CTS), which are now operating at LHC. The development of the experiment and future LHC upgrade need the elaboration of radiation hard version of edgeless Si detectors. The current investigation represents an extension in understanding on edgeless detectors operation and development of a new issue – edgeless detectors with CTS on p-type Si.

1. Introduction

Development of edgeless detectors started in the beginning of 2000 was initiated by the requirements of the TOTEM experiment at the Large Hadron Collider (LHC) at CERN. The experiment will measure the total pp cross-section and study elastic scattering and diffractive dissociation at LHC [1,2]. These measurements are accomplished in part by silicon detectors placed in the Roman Pots located at 147 and 220 m from IP5 point (see figure 4.1 in Ref. [1], pp. 29). Since the diffractive physics requires a prompt detection of protons scattered at very small angles the detector sensitive area should be placed as close as possible to the LHC beam. According to the TOTEM technical design [1], the appropriate dead region at the detector sensitive diced edge should be minimized down to 50 μm or less. Different approaches for edgeless detectors performance were proposed and tested earlier starting from a direct cut across the p–n junction [3] and extending the idea in 3D active edge detectors [4], which were not, however, accepted for future application. A novel design of silicon edgeless detectors was developed in 2004 – edgeless detectors with current terminating structure (CTS) [5–7], which satisfies the major TOTEM requirements. This structure includes two rings: current terminating ring (CTR) and clean-up ring (CR), which suppress the contribution of free carriers generated at the damaged cut edge to the current of the sensitive region. Additionally, the design prevents detector breakdown and matches well to the detector mass production. The requirement on the reduced dead region was nicely fulfilled in p-on-n strip detectors, which was verified by the beam test in which they demonstrated the minimized dead region at the detector edge less than 50 μm [8]. The pitch of the parallel strips of 66 μm allows the achievement of a resolution of less than 20 μm.

The investigation of edgeless p-on-n detectors properties was carried out simultaneously with the detector development. Numerous studies have been made, which concern the concept of CTS and detector electrical characteristics [8–11]. Among them, the electric field distribution at the cut edge and nearby is the key property that controls edgeless detector operation. Still, two aspects were missed in the previous considerations: the influence of silicon resistivity on the cut edge properties, and the role of the cut p^+–n junction of CTR in the characteristics of edgeless detectors. These aspects are revised and extended in this study and new findings are done for Si edgeless detectors.

Since the detectors in the TOTEM experiment may pick up higher fluence (up to 10^{15} n_{eq} cm^{-2}) and taking into account the future LHC upgrade for achieving high luminosity beam operation, the development of radiation hard version of edgeless detectors becomes essential. Therefore the main subject of the investigation deals with characteristics of new edgeless detectors processed on the p-type Si. This study may clarify their potential in the planned experiments at SuperLHC in which the proton beam luminosity will be tenfold larger.

2. Background from p-on-n edgeless detector development

The p-on-n edgeless detector (Fig. 1) compiles the n-type silicon wafer, the sensitive area covered by the p^+ contact and the current terminating structure with two p^+ rings: current terminating ring and the clean-up ring. Both rings are grounded together with the biasing electrode BR providing the ground

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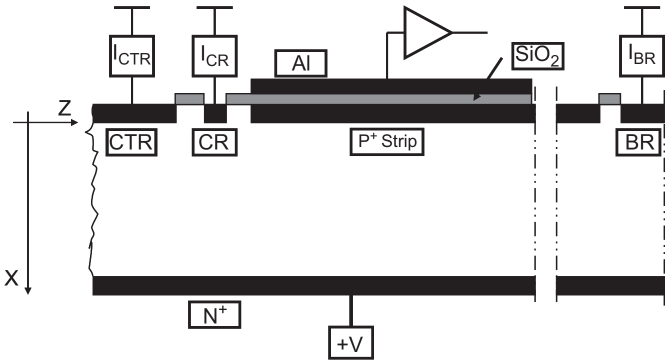

Fig. 1. Schematic cross-section of an edgeless detector with CTS.

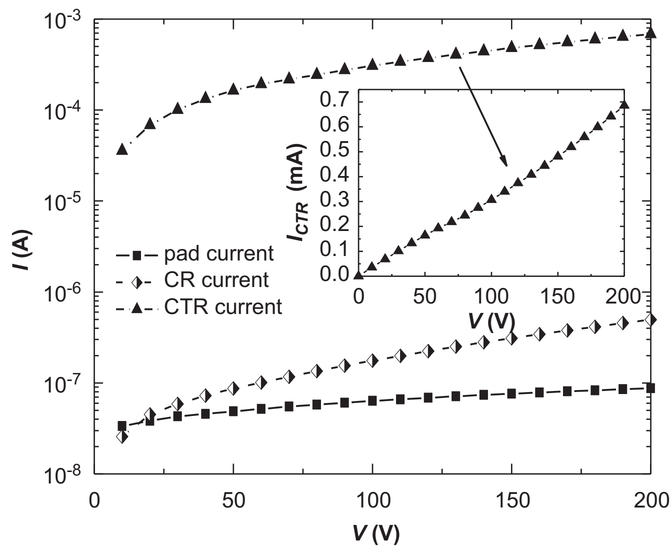

Fig. 2. *I–V* characteristics of edgeless p-on-n pad detector. Inset: *I–V* characteristic of CTR in a linear scale.

potential distribution via punch-through mechanism to the sensitive stripped area. A high CTR current is drained out to the ground and its small rest fraction is collected by the clean-up ring, which is also grounded. Typical *I–V* characteristics of the elements of edgeless detector are shown in Fig. 2. For these detectors the following understanding and results have been achieved:

(1) For as-processed detectors the ratio I_{det}/I_{CTR} is about 10^{-4}. Thus, the contribution of the CTR current to the total detector current is negligible [5,8].
(2) Two models of the cut edge were initially considered for the behavior of a surface potential across the cut edge, V_{xs} [9–11]. Within the framework of the resistive model it was suggested that the observed ohmic behavior of the current along the cut surface is a result of the ohmic-like properties of the damaged edge. Consequently, the surface potential V_{xs} is linear and in any point of the cut it is less positive than the potential in the bulk V_{xb}. This prevents diffusion of the holes generated at the cut into the detector bulk and explains a low current of the detector sensitive area.
The amorphous edge model considered additionally the electron and hole exchange between the damaged surface and the bulk. The electrons may transfer to the sensitive bulk via diffusion and drift mechanisms whereas the hole current flows in the vicinity of the cut edge. The escape of electrons from the surface layer leads to a nonuniform current density across the cut edge that causes the difference between the potential on the cut and in the bulk.
(3) The experimental results on the distribution of the potential V_{xs} and the electric field E_{xs} at the cut edge confirmed a model of amorphous edge layer [10,11]. The major consequence was an explanation of the non-ohmic behavior of the cut, i.e. a nonlinear, namely, quadratic-law distribution of the potential across the cut edge.
(4) The study of charge collection efficiency (CCE) of small size prototypes of edgeless detectors, which was carried out in the test with muon beam gave the width of the insensitive region at the edge of about 60 μm [5]. For the final size edgeless strip detectors the measured mean width of the insensitive region was 45 μm [8]. In both experiments the signal-to-noise ratio was 22.
(5) Experimental study of CCE in edgeless detectors irradiated by 1 MeV neutrons showed that they can withstand the fluence of 5×10^{13} n_{eq} cm^{-2} with 100% efficiency and require the increase in operational bias up to 450 V to realize 100% CCE at 1.4×10^{14} n_{eq} cm^{-2} [8].

Though significant progress in the development of edgeless detector physics has been achieved, some issues are not yet clarified. The major one is the origin of the ohmic behavior of the current flowing across the cut, i.e. CTR current, which cannot be explained by any process on the cut edge. Also the evolution of the cut edge properties with the changes in the electric field in the bulk related with different silicon bulk resistivity was not clarified in the experiments.

The modeling of the electric field distribution normal to the cut edge ($E_z(x)$) in the frames of the developed models predicts an increasing contribution of the edge current to the current of the sensitive region in irradiated edgeless p-on-n detectors. These predictions were confirmed by the *I–V* characteristics of p-on-n edgeless detectors irradiated by proton fluence F_p up to 8×10^{14} p/cm^2 [11]. The main reason for that is space charge sign inversion in p-on-n detector sensitive region when the initially positive sign of the space charge then changes to the negative. This leads to an inverse electric field distribution at the cut edge, which stimulates the hole current flow to the detector bulk. To avoid this negative effect, the detectors should be processed on the p-type silicon, which initially has negative space charge due to dominating acceptor concentration.

3. Experimental

Two types of edgeless detectors with CTS were investigated: detectors on the n-type Si with different resistivity, and detectors on the p-type Si produced by Topsil Semiconductor Materials, Denmark. The parameters of Si grades are specified in Table 1. The choice of medium resistivity n-type Magnetic Czochralski (MCZ) silicon follows from the fact that this material showed reduced degradation with respect to 23 GeV protons as compared to the other grades of n-type Si. This result was shown in the investigations, which are performed within the framework of CERN-RD50 collaboration program [12,13]. The detectors on the n-type Si had

Table 1
Parameters of Si edgeless detectors.

Si	ρ (kΩ cm)	N_{eff} (10^{11} cm^{-3})	U_{fd} (V)
FZ, n	18.6	2.3	16
FZ, n	4.6	9.4	65
MCZ, n	1.1	38	265
FZ, p	28.2	4.9	34