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p-Bulk silicon microstrip sensors and irradiation

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Abstract

Anticipating the requirement for highly radiation-tolerant silicon microstrip sensors suitable for the SLHC application, we have fabricated n-in-p microstrip sensors in p-FZ and p-MCZ industrial wafers which we then irradiated with 70 MeV protons. Studies were made of the leakage current, onset of microdischarge, body capacitance, charge collection efficiency, and n-strip isolation at the fluences of nil, 0.7×10^{14}, and 7×10^{14} 1-MeV neutrons equivalent (neq)/cm^2. The bias and edge structure achieved holding the bias voltages up to 1000 V. The full depletion voltages were about 160, 250, and 600 V in the p-FZ and 1190, 500, and 840 V in the p-MCZ at nil, low, and high fluences, respectively. The radiation damage helped to reduce the density of electron accumulation layer. The strip isolation in the p-MCZ sensors was found to be much better than in the p-FZ sensors; even the no-isolation structure isolated the strips at nil fluence at bias voltage above 50 V. The lower density of electron accumulation layer in the p-MCZ could be attributed to an order less interface trap density in the $\langle 100 \rangle$ surface than that of $\langle 111 \rangle$, the negative potential in the inter-strip region by the bias voltage, and the possible effect of high oxygen content in the MCZ bulk.

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1. Introduction

The 14 TeV centre-of-mass proton–proton colliding accelerator at CERN, the large hadron collider (LHC) [1], is about to start collisions at the end of 2007. In order to exploit the physics potential of the LHC maximally, a major luminosity upgrade (SLHC) [2] is planned after the LHC has accumulated an integrated luminosity of 700 fb^{-1}. The instantaneous luminosity will be increased to 10^{35} from the 10^{34} cm^{-2} s^{-1} of LHC. Each experiment will accumulate an integrated luminosity of about 3000 fb^{-1}, thus reducing the statistical errors by half, and in addition enabling access to fundamental processes such as Higgs self-coupling [3].

In the inner detector of the ATLAS detector, the total fluence of the particles at a radius of 30 cm, normalized to an equivalent number of 1-MeV neutrons scaled with the non-ionizing-energy-loss (NIEL) values [4], will be $\sim 2 \times 10^{14}$ 1-MeV neq/cm^2 at the LHC (700 fb^{-1}) and $\sim 9 \times 10^{14}$ 1-MeV neq/cm^2 at the SLHC (3000 fb^{-1}) including similar safety factors of two. The radial region of 30–60 cm of the inner detector is currently equipped with the p-strips in n-bulk (p-in-n) silicon microstrip sensors, the SemiConductor Tracker (SCT) [5], which are designed only to cope with the fluence expected in the LHC. The p-in-n sensors, after type inversion of the bulk due to the radiation damage, require full depletion to collect charges efficiently [6]. With the increased fluence expected in the SLHC, the p-in-n sensor would no longer be fully depleted.

In order to cope with the very high fluence of the SLHC with a reasonably low bias voltage, new silicon microstrip sensors being designed are to be read out from the n-strips,

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fabricated either in n-bulk or p-bulk material. Since acceptor states are created by radiation damage, the silicon bulk will inevitably become p-bulk and thus the n-strips become the side of p–n junction and full depletion will not be required. In the case the initial material is n-bulk, the sensor is denoted as n-strips in n-bulk (n-in-n); in the case of p-bulk, it is denoted as n-strips in p-bulk (n-in-p). The n-in-n sensor requires the p–n junction to be on the backside that entails double-sided mask processing. The n-in-p sensor requires single-sided mask processing which is more cost-effective, and thus a natural choice for large-area applications. Another possibility is the use of wafer material in which the full depletion voltage develops more slowly as a function of fluence, as shown by RD50 with the oxygen-rich materials grown with the Czochralski method [7]. Realization of the n-in-p silicon microstrip sensors for high fluence environments has several further technical design issues: (1) edge structure holding high bias voltage, (2) strip-region structure suppressing the onset of the microdischarge, and (3) isolation structure of the n-strips.

2. n-in-p R&D sensor fabrication

We have previously shown the potentiality of n-in-p microstrip sensors for the LHC application [8,9]. Those sensors were fabricated in p-bulk wafers made with the float-zoning method to a resistivity of about 10 kΩ cm. Working towards the SLHC application, a new program of R&D into n-in-p sensors has been initiated with the wafer materials available in industry in Japan [10]: p-type with the float-zoning method (p-FZ; resistivity of 5–10 kΩ cm, orientation of ⟨1 1 1⟩ or ⟨1 0 0⟩) and p-type with the magnetic-field applied Czochralski method (p-MCZ; 0.6–1 kΩ cm, ⟨1 0 0⟩). Other materials: n- or p-type with the standard Czochralski method (CZ) (~10 Ω cm) and n-type MCZ (n-MCZ) (~100 Ω cm) are not regarded as suitable due to the initial high full depletion voltages (FDVs).

A new batch of R&D sensors, called ATLAS05, was fabricated in 4-in. wafers: p-FZ of 8–20 kΩ cm and ⟨1 1 1⟩, and p-MCZ of 0.7–1 kΩ cm and ⟨1 0 0⟩. The n-strip isolation structures were implemented in six different zones as in the Ref. [10]. As the full depletion voltage of the p-bulk of 1 kΩ cm is expected to be about 950 V, we have set the maximum operation voltage of the sensor to be 800 V and the design bias voltage to be 1000 V. As the ATLAS05 sensors showed relatively low onset voltages of microdischarge, as described in the next section, the mask set was modified and another batch of R&D sensors, called ATLAS05-M, was fabricated out of the same lot of wafers as ATLAS05. The layout of ATLAS05-M mask set is shown in Fig. 1. The features of ATLAS05 and ATLAS05-M are summarized in Table 1. All the results given in this paper were made with 1 cm × 1 cm miniature sensors.

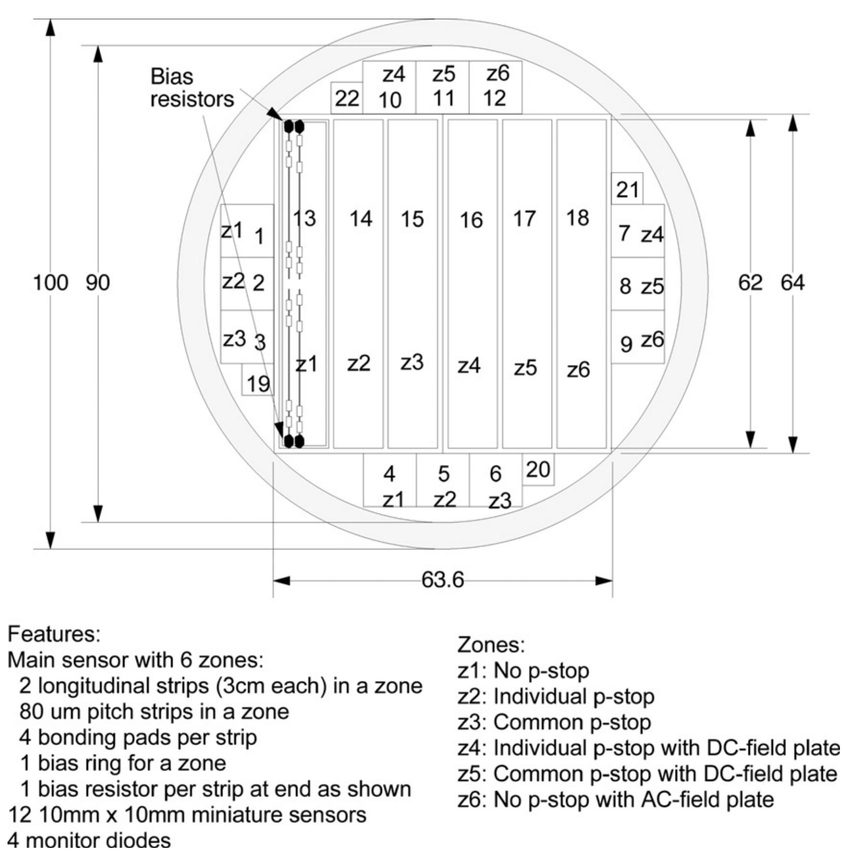

Fig. 1. Layout of the ATLAS05-M R&D sensors.