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3D silicon sensors: Design, large area production and quality assurance for the ATLAS IBL pixel detector upgrade

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ABSTRACT

3D silicon sensors, where electrodes penetrate the silicon substrate fully or partially, have successfully been fabricated in different processing facilities in Europe and USA. The key to 3D fabrication is the use of plasma micro-machining to etch narrow deep vertical openings allowing dopants to be diffused in and form electrodes of pin junctions. Similar openings can be used at the sensor's edge to reduce the perimeter's dead volume to as low as $\sim$4 μm. Since 2009 four industrial partners of the 3D ATLAS R&D Collaboration started a joint effort aimed at one common design and compatible processing strategy for the production of 3D sensors for the LHC Upgrade and in particular for the ATLAS pixel Insertable B-Layer (IBL). In this project, aimed for installation in 2013, a new layer will be inserted as close as 3.4 cm from the proton beams inside the existing pixel layers of the ATLAS experiment. The detector proximity to the interaction point will therefore require new radiation hard technologies for both sensors and front end electronics. The latter, called FE-I4, is processed at IBM and is the biggest front end of this kind ever designed with a surface of $\sim$4 cm^2. The performance of 3D devices from several wafers was evaluated before and after bump-bonding. Key design aspects, device fabrication plans and quality assurance tests during the 3D sensors prototyping phase are discussed in this paper.

1. Introduction

The Large Hadron Collider (LHC) has been successfully running since December 2009. All experiments are gathering data and confirming the physics expected with the current accelerator settings. The LHC will interleave colliding runs with shut-down periods to allow the upgrade of both accelerator and experiments' hardware, which are expected to degrade with time and after exposure to neutrons, non-ionizing and ionizing radiation. In 2013, during its first long shut-down, the LHC is expected to increase its centre of mass energy to 13 TeV while the ATLAS experiment will insert a novel pixel layer, called Insertable B-Layer (IBL) to improve tracking performance [1].

3D silicon sensors were originally proposed in 1994 and active edges in 1997 at the Stanford Nanofabrication Facility (SNF) in Stanford, USA [2–4], to overcome the limitations of traditional planar silicon sensors after exposure to high fluences of non-ionizing particles. The study of microscopic and macroscopic properties of irradiated silicon has been the subject of extensive study since the 1960s. These efforts led to the identification of several stable defects that are generated after exposure to neutral or charged particles, which make the use of silicon as a detector in high energy physics experiments challenging. While some of these defects act as effective generation centres, others act as effective traps for the moving carriers produced by the particles generated after the primary accelerator beams' collisions. The three most severe macroscopic consequences for silicon tracking detectors have been found to be (i) higher leakage currents due to

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the creation of generation/recombination centres, (ii) changes in effective doping concentration, that at high fluences lead to an increase of the full depletion voltage, and (iii) decrease of the charge collection efficiency due to carrier trapping. The CERN RD39 [5], RD48 [6], RD50 [7], ATLAS planar sensors [8] and 3D sensor [9] collaborations, in the past and more recent years, have made extensive breakthrough studies on radiation effects in particle physics sensors. Amongst the most recent findings is charge multiplication in heavily irradiated detectors, resulting in much larger signals than expected from the extrapolation of the trapping time constants. Charge multiplication has been observed in planar pad and microstrip detectors after exposure to very large fluences of particles ($\sim 10^{16} n_{eq}/cm^2$), provided that a high bias voltage ($\sim$1000 V) can be applied [10–12]. Charge multiplication is currently the object of several studies, e.g., by edge-TCT techniques [13], aimed at its deep understanding and modelling, which are fundamental in order for this phenomenon to be reliably exploited in future experiments.

Another key finding of the above collaborations was the evidence that a reduced proximity of the electrodes compared to a standard (e.g., 300 μm) not only reduces the depletion voltage but also lowers the trapping probability of generated carriers after radiation induced defects are formed [14]. This reduces the degradation of the signal efficiency, defined as the ratio of irradiated versus non-irradiated signal amplitudes, after exposure to increasing fluences [15].

In 3D sensors the distance between the p^+ and n^+ electrodes can be designed to optimize the signal efficiency, and the signal amplitude, at the expected maximum fluence, as can be seen schematically in Fig. 1. In standard planar sensors (Fig. 1 left), the electrodes are implanted on the top and bottom surfaces of the wafer, so that the depletion region grows vertically and the full depletion voltage depends on the substrate thickness (Δ). On the contrary, in 3D sensors (Fig. 1 right) the electrode distance (L) and the substrate thickness (Δ) can be decoupled: the depletion region grows laterally between the electrodes, whose distance is much smaller than the substrate thickness, so that the full depletion voltage can be dramatically reduced with respect to planar sensors.

The amount of charge generated by a Minimum Ionizing Particle (MIP) is the same for both sensor types if they have the same substrate thickness. However, the charge collection distance could be much shorter in 3D sensors. Furthermore high electric fields, as well as carrier velocity saturation, can be achieved at very low voltages, so that the charge collection times can be much faster. Besides easing applications requiring very high speed [16],

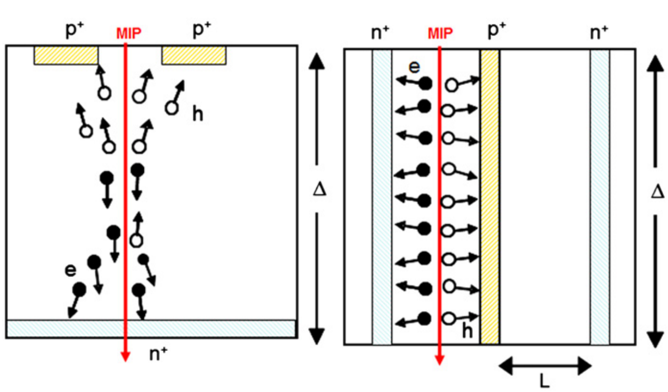

Fig. 1. Schematic cross-sections of (left) planar sensor, and (right) 3D sensor, emphasizing the decoupling of active thickness (Δ) and collection distance (L) in 3D sensors.

Table 1
Comparison of some relevant parameters in 3D and planar sensors. The depletion voltage quoted is for a detector prior to irradiation.

Sensor geometry	3D	Planar
Collection path	$\sim$50 μm	200–300 μm
Depletion voltage	$<$10 V	30–100 V
Charge collection time	$\sim$ns	Tens of ns

this property can mitigate charge trapping effects due to high levels of radiation.

The main parameters for planar and 3D sensors are compared in Table 1 [17]. In the development of the 3D sensor specifications reported in Section 5, these remarkable differences between 3D and planar sensors, and particularly the very low depletion voltages, must be carefully considered. A 3D sensor reaching full depletion at less than 10 V can be operated at just 20 V providing full tracking efficiency. A breakdown voltage of 50 V, that would be small for a planar sensor, is in fact much larger than the operation voltage required for a 3D sensor before irradiation.

After irradiation at large fluences, the operation voltages of 3D and planar sensors are constrained by different requirements. Planar sensors with n-type readout can be effectively operated in partial depletion conditions [18], but the bias voltage should be as high as possible in order for enough charge to be collected [19]. For the IBL planar sensors, it is expected to have a maximum bias voltage of 1000 V [20]. In irradiated 3D sensors, the bias voltage should allow for full lateral depletion and sufficiently high electric field between the electrodes in order to obtain full efficiency [2]. Owing to the short distance between the electrodes, this is normally achieved at voltages lower than 200 V, even after very large radiation fluences [21–23], thus providing a significant advantage compared to planar sensors in terms of power dissipation. At larger voltages, in the order of 250 V, charge multiplication has been observed in 3D sensors [21–24], even though with a non-uniform charge collection pattern over the surface of the device, that could make this effect more difficult to exploit compared to planar sensors.

The remaining part of the paper is organized as follows: in Section 2 the different 3D technological approaches and related manufacturers are presented; in Section 3 the main features of the common design effort pursued within the 3D ATLAS Collaboration for the IBL are described; in Section 4 the production strategy is outlined; in Section 5, the 3D sensor specification are summarized; in Section 6, selected results from the electrical characterization of 3D pixel sensors are reported; and conclusions (Section 7) end the paper.

2. 3D processing options and manufacturers

3D silicon sensors are currently manufactured on standard 4″ FZ p-type high resistivity wafers using a combination of two well established industrial technologies: Micro-Electro-Mechanical Systems (MEMS) and Very Large Scale Integration (VLSI). Peculiar of MEMS are the Deep Reactive Ion Etching (DRIE) steps applied to etch deep and very narrow apertures within the silicon wafer using the so called Bosch process [25] followed by thermal diffusion steps to form the n^+ and p^+ electrodes. Fig. 2 shows SEM micrographs of deep columns etched using DRIE by different manufacturers belonging to the 3D ATLAS collaboration. The high aspect ratio (i.e., depth to width ratio) and high uniformity between top and bottom of the columns can be appreciated from the figure.