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Future silicon sensors for the CMS Tracker Upgrade

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ABSTRACT

For the high-luminosity phase of LHC (Large Hadron Collider) at CERN a campaign was started in the CMS (Compact Muon Solenoid) experiment to investigate different radiation hard silicon detectors. Therefore 6 in. silicon wafers were ordered to answer various questions regarding for example the radiation tolerance and the annealing behavior of different sensor material. The testing variety includes sensor versions n-in-p and p-in-n in thicknesses from 50 μm to 300 μm. In terms of sensor material the difference between floating zone, magnetic Czochralski and epitaxial grown silicon is investigated. For the n-in-p sensors, the different isolation technologies, p-stop and p-spray, are tested. The design of the wafer contains test structures, diodes, mini-sensors, long and very short strip sensors, real pixel sensors and double metal routing variants. The irradiation is done with mixed fluences of protons and neutrons which represent the rates of integrated hadrons that are expected in the CMS tracker after the LHC upgrade. This paper presents an overview of results from measurements of non-irradiated test structures with different technologies and also the results after irradiation.

1. Motivation

The LHC high luminosity upgrade will introduce an increase of the luminosity to $L=5\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ by about 2022. This will lead to an expected fluence in the inner tracker layers of about $10^{16} n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$, where n_{eq} refers to the equivalent damage of 1 MeV neutrons. The current CMS strip detector will reach the end of its lifetime after radiation damages will increase the full depletion voltage to the maximum voltage of the power supply. Furthermore, the higher the luminosity, the higher the track density and thus the occupancy of the detectors. One possible solution is to increase the granularity of the strips by using shorter strips. This introduces further challenges for the readout electronics as there are more channels to handle. There is also a need of a new powering and cooling system. The challenge for powering is to reduce power losses and heat dissipation of existing supply cables. In conjunction, cooling has to be more efficient with the constraints of reducing the mass of cooling pipes. Additionally, there will also be an earlier upgrade for the pixel tracker which will be implemented during the winter shutdown 2016/2017. A campaign within CMS has been initiated to define the sensitive parts of the new tracker after the LHC high luminosity upgrade.

2. Testing variety

The campaign involves a collaboration of 17 research institutes, which started the investigations on radiation hard material and layout. In total, 158 silicon wafers were ordered from Hamamatsu Photonics K.K.; the design of each wafer is indicated in Fig. 1. Concerning the radiation hard material, three different silicon growth techniques are investigated. For the innermost part of the current CMS tracker a 320 μm thick floating zone (FZ) material is used, whereas the outer parts use a 500 μm thick floating zone material. Therefore this material serves as a reference and has also a high quality in terms of the high resistance values. The magnetic Czochralski (MCZ) wafer has a high oxygen concentration, and therefore is expected to be more radiation hard. The benefit of the epitaxial grown (Epi) silicon is the possibility to produce thin sensors. The variety covers thicknesses from 50 μm to 320 μm for n-in-p and p-in-n sensor types. For the n-in-p sensors, two different strip isolation technologies are tested. The sensor types named with letter P (p-stop) use a p^+ layer between the n^+ strips to intercept the electron accumulation layer, whereas sensor types labeled with the letter Y (p-spray) introduce a p doping on the full surface. The p-in-n sensors are indicated with the letter N. Wafers with a second metallization layer were also produced to investigate the radiation hardness and the noise behavior with directly connected electronics. The baby pitch adapter sensors are used for this purpose. Concerning the layout, the same wafer design is

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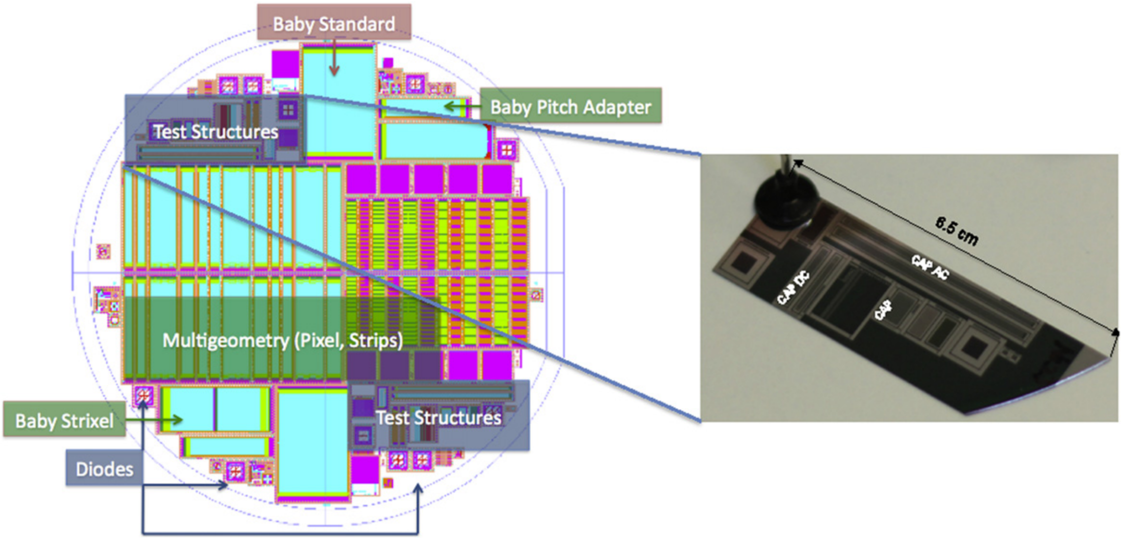

Fig. 1. Picture of the CMS upgrade wafer and halfmoon.

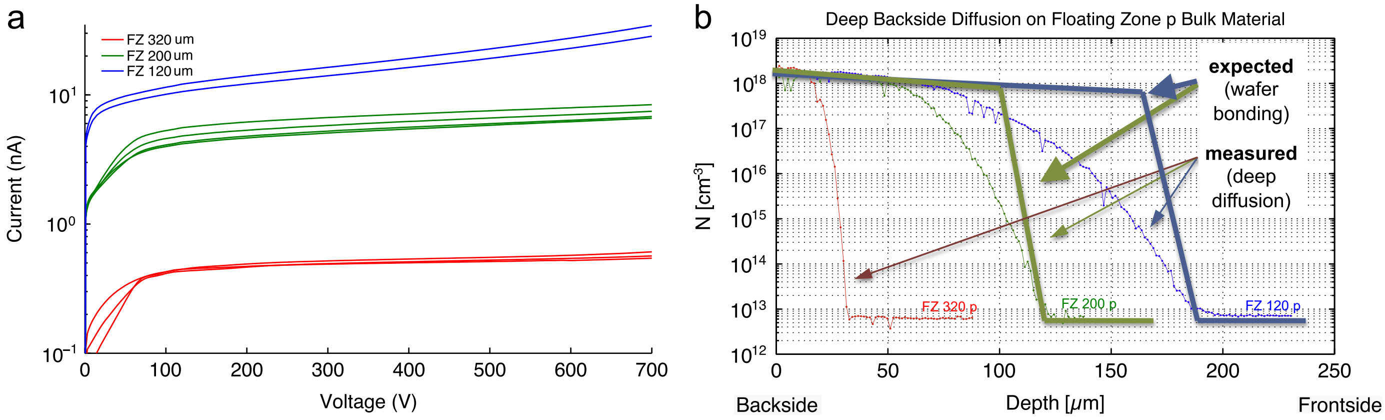

Fig. 2. (a) Dark current and (b) doping profile of floating zone diodes with three different thicknesses.

implemented on each wafer. There are standard baby sensors, which serve as a reference, and test structures for the determination of the process quality. Diodes are needed for material investigation. On the back of the diodes, the metal grid [1] is required for the Transient Current Techniques (TCT) [2] measurement. Short laser pulses induce signals in the diode to investigate for example the electric field or the trapping time. The main focus of the multigeometry pixel and strip structures are measurements leading to strip coupling, charge sharing and noise behavior. There are 12 different regions defined which use different strip pitches and different width-to-pitch ratios. One possible solution to cope with the higher track density would be the use of the so-called baby strixel sensors, where the words strip and pixel are combined. These strixel sensors contain segmented strips with a larger area compared to the standard strip structures. The physical size of the strixel sensor is planned to be $10 \times 10\,\text{cm}^2$.

In the following sections the results measured on the test structures [3] are presented. The set of different test structures is called "halfmoon" within the community. A picture of the standard CMS upgrade halfmoon is seen in Fig. 1. Ten different measurements can be performed with this halfmoon structure. The dark current of the detector is derived from the measurements on the diodes. The interstrip parameters are taken from test structures consisting of strips. For the interstrip capacitance measurement, the bias ring is connected to the strips with a polysilicon resistor. This structure is labeled with CAP AC. In contrast, the interstrip resistance is determined with the CAP DC structure. As a polysilicon resistance would distort the interstrip resistance measurement, the strips of this structure are isolated from the bias ring. The interstrip measurements are performed from the center strip to its two neighbors. The coupling capacitance and dielectric break down voltage are determined with the CAP structure where the strips are also isolated from the bias ring.

3. Results for non-irradiated test structures

To extract information on the process quality, different measurements on the halfmoon were performed. The measurements of non-irradiated structures are performed at 20 °C. The results of measurements concerning the other parts of the wafer can be found in Refs. [4,5].

3.1. Bulk dark current

The bulk dark current is measured on diodes. Fig. 2a shows several results for sensors of p type on floating zone material, where two samples of the thinnest and four samples of the thicker diodes have been measured. All types of the thinner floating zone materials showed an unexpected effect, as thinner