R&D on novel sensor routing and test structure development

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Abstract

The Central European Consortium designed and prototyped generic test structures (TS) in a R&D study to allow standard monitoring of the process quality of silicon sensors of any given vendor. Furthermore, some novel signal routing strategies for silicon sensors have been applied on the wafers to achieve an implementation of a pitch adapter directly in the sensor, either in the first metal layer or in a second additional metal routing layer. These improvements would allow to connect the readout chip directly to the sensor, omitting an additional pitch adapter. The on-sensor pitch adapter would be reflected by a substantial material budget saving which would be of special interest for the tracking detectors at the super-LHC.

After a first batch of improved TS was produced in 2007, a second batch of enhanced TS and additional sensors, with integrated pitch adapters, has been produced by the Institute of Electron Technology in Warsaw, Poland. Some improvements of the TS and the designs of the sensors will be shown. Afterwards a selection of measurements on TS and sensors will be discussed as well as a testbeam and its first results.

Key words: silicon strip sensor, test structures, quality assurance, integrated pitch adapter

1. Introduction

After the LHC upgrade, the CMS tracking system will have to cope with a much higher radiation level and readout channel occupancy due to an increasing number of emerging particles and resulting higher track densities. The central tracker will not only have to be replaced, but it also will need a new sensor technology. The number of pixel detectors will be increased, and for larger radii of the tracker short strips are foreseen. Using the short strips (strixels) would increase the number of readout channels and the material budget of the tracker. One possibility to reduce the costs could be to integrate the pitch adapter (PA) directly into the sensor, saving the material and the costs of the standard pitch adapter used up to now.

In summer 2009, the second batch of new TS and sensors with novel routing schemes was produced by the Institute of Electron Technology (ITE), in Warsaw, Poland. We are interested in the effects of the changes on the TS, compared to the measurements performed on the first batch produced by ITE in 2007, and we mainly want to evaluate the impact of the on-sensor PA on the sensor performance.

2. Test structures and their purpose

Based on the CMS standard set of test structures described in [1] we improved the TS already in 2007 (see [2] for details). The figure 1 shows the new arrangement of the further improved set of TS:

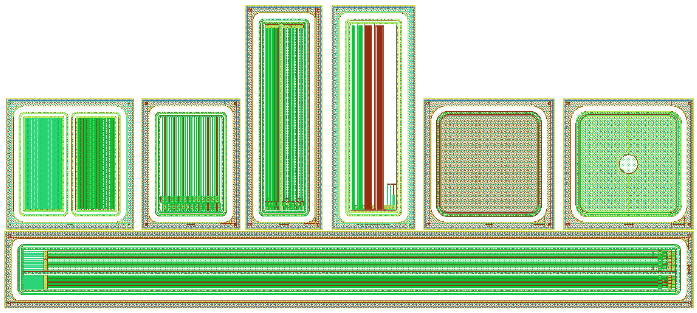

Figure 1: Picture of one set of test structures (from left to right): GCD, TS-CAP, CAP-TS-DC, Sheet, MOS, Diode, and the CAP-TS-AC on the bottom.

- The Gate Controlled Diode (GCD) is used to measure the surface current and the flat-band voltage. There are two GCD's, one with aluminium and one with polysilicon strips.
- The TS-CAP is used to measure the breakdown of the dielectric and the coupling capacitance C_{ac} giving information about the thickness of the thin readout oxide. As the signal is depending on the C_{ac}, high values are desired.
- The CAP-TS-DC is used to measure the interstrip resistance between two adjacent strips.
- The SHEET is a test structure to measure the resistances of the used materials. There are strips to measure the resistivity of the aluminium, of the p^+-implant, and of the

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polysilicon.

- The Metal Oxide Semiconductor (MOS) structure is used to measure the flatband voltage.
- The DIODE can be used to determine the depletion voltage of the sensor via a capacitance versus voltage (CV) measurement, and to measure the breakdown voltage in dependence of the design, via a current versus voltage (IV) measurement. The diode was improved, having a single guard ring with a metal overhang to reach a high breakdown voltage.
- The CAP-TS-AC structure is used to measure the interstrip capacitance C_{int}. The structure has been elongated to increase the absolute value of C_{int} and thus to facilitate the specific measurement.

3. Sensors with integrated pitch adapters

Three sets of TS, five sensors with different routing layouts, and four additional double metal test structures to measure the oxide thickness between the first and the second metal layer have been placed on one wafer, as can be seen in figure 2.

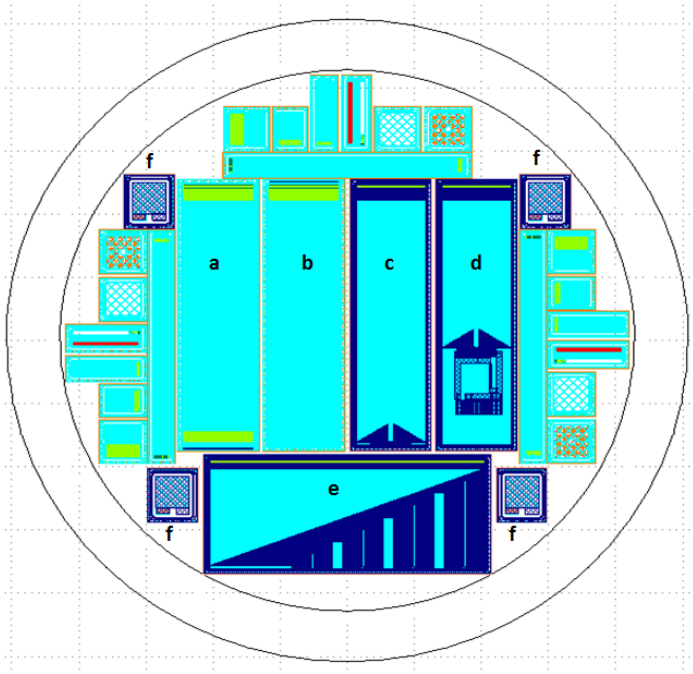

Figure 2: The wafer layout with the TS on the left, on the top and on the right, and five sensors with different routing strategies: a) standard sensor; b) sensor with integrated pitch adapter in the first metal layer; c) sensor with integrated pitch adapter in the second metal layer; d) sensor with direct to-chip bonding region; e) sensor with 512 short strips; and f) four double metal test structures.

All four central sensors have the same size. They have 128 strips with a pitch of 80 μm, implant strips of 20 μm width and aluminium readout strips with 5 μm metal overhang. The sensors differ in their sensor routing concepts (figure 2). While sensor a) is a **standard sensor** (STD) with a common strip design, sensor b) is a **sensor with an integrated pitch adapter in the first metal layer** (PAS). In figure 3a) one can see that the aluminium above the implant ends at the beginning of the pitch adapter routing. Sensor c) in figure 2 is a **sensor with an integrated pitch adapter in the second metal layer** (PAD). As the first layer is used only for the strip readout, a second layer becomes necessary to connect the strips to the bonding pads that are arranged to fit to the readout chip. The connection from the readout strips through the insulating oxide to the routing strips is done using so-called vias[1]. A section of the PAD can be seen in figure 3b).

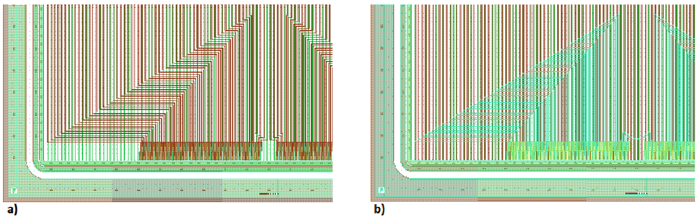

Figure 3: a) sensor with integrated pitch adapter in the first metal layer (PAS) and b) sensor with integrated pitch adapter in the second metal layer (PAD). For the PAS the aluminium above the implant ends where the routing to the bonding pads begins (bright region besides the bond pads), while for the PAD an additional routing layer is implemented in a second metal layer (continuous aluminum strips up to the end of the sensor).

Sensor d) in figure 2 is also a double metal sensor, but with an additional area to put the readout chip onto the sensor and to wire or bump bond it to the bonding pads. Sensor e) is a 512-strip sensor with short strips. The sensor comes in two versions. In one version it has a single metallization with the routing in this first metal layer, and in the other version the routing is done in a second metal layer. With the two versions of this sensor the differences in sensor parameters, like the signal-to-noise ratio caused by the second metal layer can be explicitly investigated.

4. Electrical characterization of TS and sensors

A cross check of the characterization measurements has been perfomed on two out of eight wafers at two of the involved institutes (Vienna and Karlsruhe). The results showed good agreement.

As can be seen in figure 4, the breakdown voltages of the diodes in the new design are significantly higher compared to the breakdown voltages of the diodes of the production run in 2007. While the breakdown voltage for the older diodes was at 200 V, the new diodes show a higher breakdown voltage and are stable up to and beyond 1000 V. All measurements have been done at 20 °C.

By measuring the coupling capacitance C_{ac}, the oxide thickness between the p^+-implant and the aluminium strip can be calculated. As the measured C_{ac} values are in the range of 34 pF to 37 pF, the thickness of the readout oxide is calculated to be about 700 nm. Originally for this production a thickness of 177 nm was specified by ITE, corresponding to a C_{ac} of 148 pF.

[1] aluminium connection

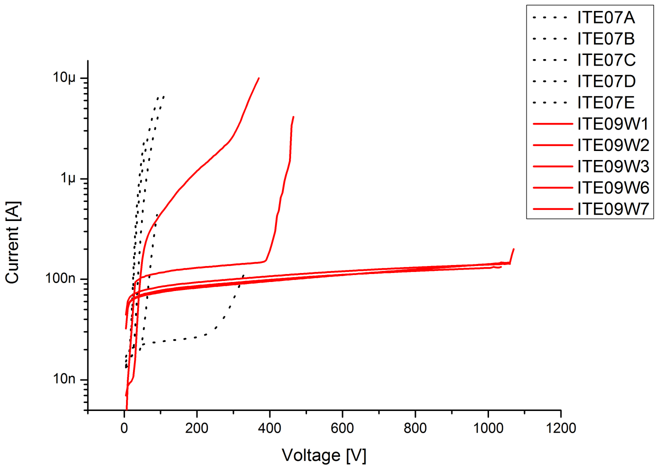

Figure 4: Comparison of the leakage current I_{leak} of the diodes produced by ITE Warsaw in 2007 (dashed lines) and 2009 (continuous lines). Design changes led to a significant increased breakdown voltage up to and beyond 1000 V. (T=20 °C)

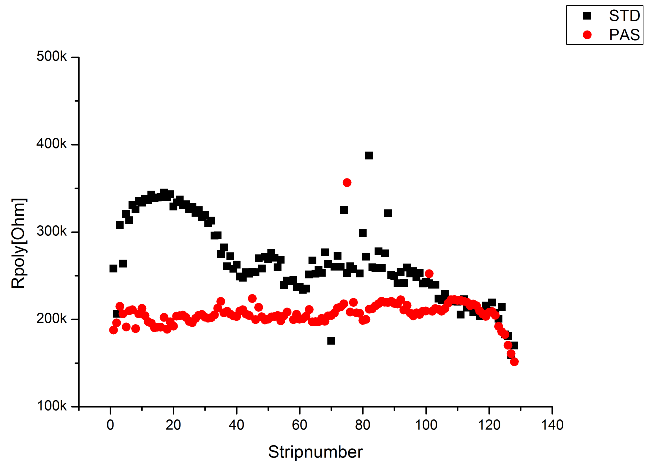

Figure 6: Bias resistors for the standard sensor (STD) and the sensor with integrated pitch adapter (PAS).

Since the signal depends on the C_{ac} small values lead to a lower signal [3].

The pinhole measurement, used to look for defect strips with undesired ohmic connections between the p$^+$-implant and the aluminium strip, measures the current over the readout oxide by applying a voltage over the dielectric. If the current exceeds 1 nA there is an ohmic contact, called a pinhole [3]. In figure 5 the pinholes for three sensors of Wafer 8 are shown.

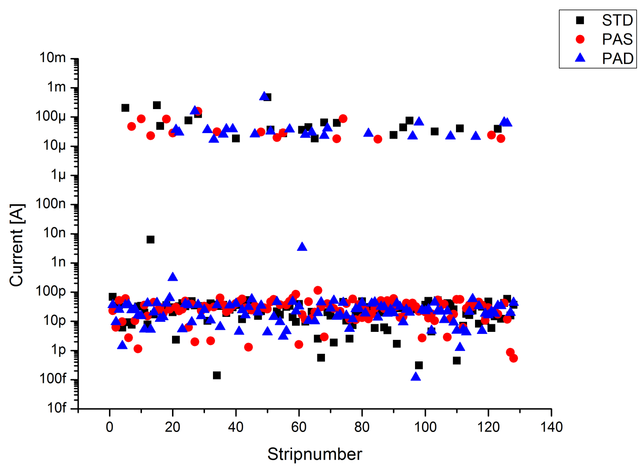

Figure 5: Three sensors of Wafer 8, all sensors have between 10 and 20 pinholes. Pinholes are strips with an ohmic contact between the aluminum strip and the p$^+$-implant. Defined as a current value of more than 1 nA.

As the bias resistors contribute to the thermal noise, high resistances in the order of a few MΩ are favoured [3]. Unfortunately the polysilicon resistors on the sensors yielded a value of only 200 - 400 kΩ. In figure 6 the values for the STD and the PAS sensors are shown.

The depletion voltages of the sensors, extracted from CV curves, have been measured to be around 25 V, giving a bulk resistivity of 12.5 kΩ.

The measurements on the additional double metal test structure allowed us to calculate the oxide thickness between the first and the second metal layer. The measured values are at around 1,4 nF which leads to a thickness of 600 nm, close to the specified value of 700 nm.

Although not all tested sensor parameters matched the specifications caused by problems during the wafer processing that led to a thicker readout oxide, an excessive number of pinholes and to low values of the bias resistors, the sensors were fully functional. They were perfectly suited for the foreseen R&D purpose, and they allowed the evaluation of the new routing schemes in a test beam.

5. Test beam and results

The test beam took place at CERN's north area in the area H6B of the SPS accelerator in August 2009. We received hadrons (Π^+ (55,67%), p (38,95%), and K^+ (5,38%)) with an energy of 120 GeV. The DUT sensors have been installed in the center of the EUDET Beam Telescope[4] to get track information. In total, eight modules have been built and one terabyte of data has been taken. We present the results from the analysis showing the signal-to-noise ratios of the sensors with an integrated pitch adapter in the first metal layer (PAS). The sensors with the routing in the second metal layer (PAD) were seriously affected by the accumulation of pinholes during bonding which was encouraged by the poor quality of the readout oxide (between readout implant and aluminium strip). Therefore the analysis of the PAD sensors remains inconclusive and is not presented here.

In figure 7 the hit regions are shown, and in figure 8 the corresponding signal-to-noise ratios for the two regions are plotted. The data taken with particles hitting a region with standard AC-coupled readout strips gives a signal-to-noise ratio of about 20. This is a reasonable value given the specifications of the sensor and the readout chain. Hitting the sensor in the region with the

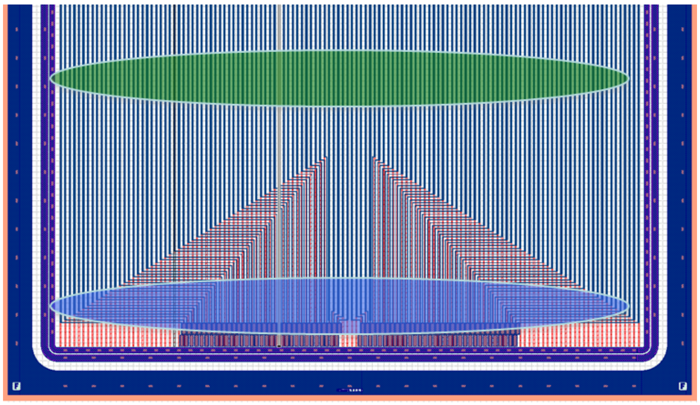

Figure 7: The PAS sensor was hit in two regions: the ellipse in the upper part of the picture indicates a region where strips are fully covered by the aluminium readout strip, which capacitively couples to the charge collected by the implanted strip below. The ellipse in the lower part indicates the region where the readout strips are missing as the aluminium layer is used to route the strips to the bonding pads.

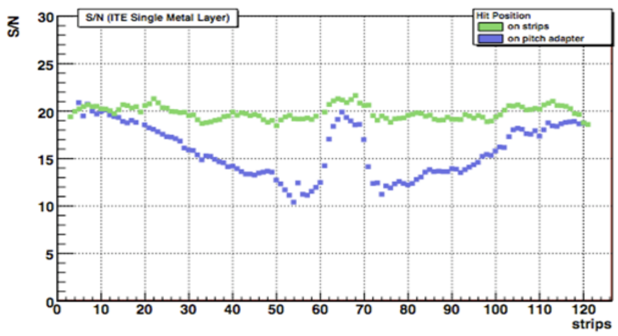

Figure 8: Signal-to-noise ratio for the region with standard readout strip (upper curve) and for the region with the routing to the bonding pads (lower curve) on the PAS.

routing shows a significantly lower signal-to-noise ratio with values as low as 10. With increasing length of the p^+ implant without an aluminium readout strip above, the signal-to-noise ratios decrease. This behaviour can be seen in the lower curve of figure 8, going from the strips at the outer edges to the central strips. In the centre, where the aluminium readout above the p^+ implant is not reduced, the signal-to-noise ratios reaches similar values as in the upper curve, corresponding to standard readout strips.

This signal loss is caused by the significantly higher resistivity of the p^+ implant compared to the aluminium readout strips. Signals generated by incident particles inside the routing area have to to travel along the high resistive implant until the capacitive coupling to the aluminium readout strip occurs. This additional resistance reduces the measured signal compared to areas where the capacitive coupling occurs and charge creation by the incident particle occur at the same location along the strip.

6. Conclusion

The new batch of wafers produced by ITE Warsaw, containing the latest improvements of the test structures and of the sensor designs, show a high breakdown voltage of the sensors and allow the extraction of all important sensor parameters. Several deficiencies in the manufacturing process could be identified and were discussed with the manufacturer. Modifications to the process should remedy these problems for a future run.
The standard sensors (STD) and the new sensors with integrated pitch adapters in the first metal layer (PAS) performed well in a first test beam measurement. The deficiencies in the manufacturing process had only a small impact on the general functionality of these sensors allowing first conclusions on the performance of integrated pitch adapters. For the sensors with the pitch adapter in the second metal layer, the poor quality of the readout oxide together with small flaws in the design encouraged the creation of pinholes during bonding. This has seriously compromised the functionality of the sensors, making any conclusion on the performance of a second metal layer routing unfeasible.
The analysis of the PAS sensor shows the expected behaviour of this device: if particles traverse the sensor in the standard readout strip region, the signal-to-noise ratios are comparable to a standard sensor. If particles hit the sensors within the pitch adapter region, the measured signal-to-noise ratios are reduced by a factor proportional to the length of the strip not covered by an aluminium readout strip. The main cause for this behaviour is the high resistivity of the implant along which the signal has to travel before capacitive coupling to the readout strip can occur.
A more detailed analysis of the PAS and the study of the other sensors of this batch are still in progress and may produce further results of interest for a future production run. A more comprehensive study of the sensors produced by ITE Warsaw will be published in [5].

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