Further improvement of the Telescope Chip performances

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Abstract

The Telescope Chip (TC, alias MIMOSA-26) equips the 6 planes of the EUDET beam telescope (BT) since 2009. The extra year of the project was used to investigate the added value of a new substrate, expected to extend the sensor lifetime and its adaptability to more demanding operating conditions, and to still improve its spatial resolution, due an enhanced signal-to-noise ratio. The study was performed along two consecutive steps. The first step consisted in re-fabricating the TC with the new, high resistivity, substrate. Because of its improved detection performances, this new version of the TC (called HRTC) was mounted on the BT in replacement of the former TC version. Next, a new variant of the IDC (Intermediate Digital Chip) was manufactured on the new substrate and assessed at the CERN-SPS. It features optimised pixel architectures in perspective of a next generation of sensors to be used, in particular, in the large area telescope planned within the FP-7 project AIDA.

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1 Introduction

The Telescope Chip (TC, alias MIMOSA-26) is already running in the EUDET Beam Telescope (BT) since 2009. Since the EUDET project was extended by one year, an opportunity was given to explore the added value of a new fabrication process featuring a high-resistivity epitaxial layer, expected to allow for improved detection performances. This process was in particular supposed to benefit to the sensor lifetime as well as to its adequacy to demanding operation conditions. Some improvement of the sensor spatial resolution seemed also possible.

This document starts with the most essential characteristics of the new process. It next addresses the test results of a replica of TC, manufactured with this process. Finally, the process potential was prototyped with a new version of the IDC (Intermediate Digital Chip), aiming for a still improved pixel architecture in perspective of the next generation of sensors, derived from TC, to be applied in various domains, including the forthcoming EU project AIDA, upcoming subatomic physics experiments as well as dosimeters and imaging devices.

2 Investigations on a new substrate

CMOS industry can satisfy a large majority of their customers with processes featuring a low resistivity (in the order of 10 Ω.cm) epitaxial layer. These processes are therefore the most accessible, and TC was manufactured in such a standard CMOS technology. Commercial processes based on a high resistivity epitaxial layer became only available recently. They triggered the fabrication of a new version of TC, called HRTC (for High Resistivity TC), expected to exhibit improved detection performances.

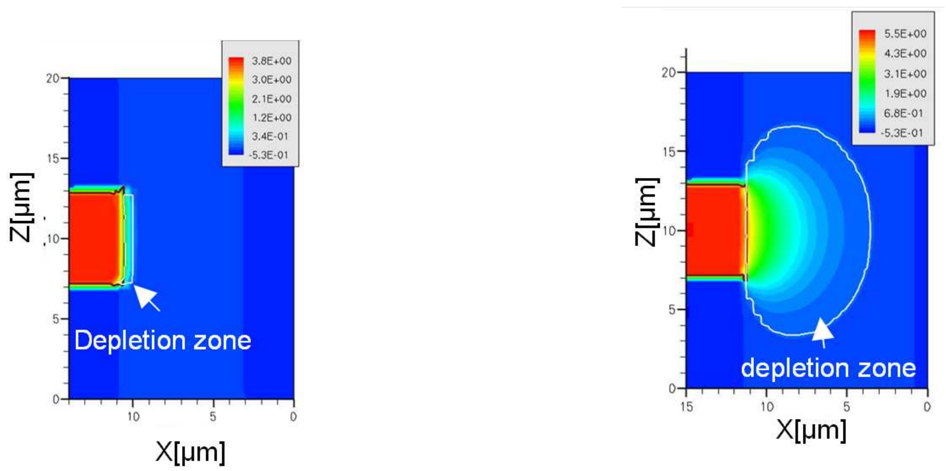

Figure 1: Results of ISE TCAD device simulations [1]: the sensing diode is represented in red, and the green area indicates the size of the depletion zone. The latter is minute in case of a low resistivity epitaxial layer (left), and gets significantly larger in case of a high resistivity layer (right).

A major difference between the two types of epitaxial layer concerns the depletion depth underneath the sensing diode. On standard, low resistivity, substrates, the depletion depth amounts to a fraction of a micrometer only (figure 1, left). Signal charges get therefore mainly collected through thermal diffusion. On a high resistivity (HR) substrate, this depletion depth may reach several micrometers (figure 1, right), with immediate benefits for the amplitude of the charge collected and for the signal-to-noise ratio (S/N), as shown in [1]. Consequently, the sensors may be better suited to demanding operating conditions (e.g. longer integration time, higher ambient temperature, higher radiation level), which originate degraded noise or charge collection performances. This advantage enlarges the domain of applications of the sensor and tends to extend its lifetime.

3 Performances of TC with a high resistivity epitaxial layer

The HRTC reproduces the layout of the TC and is manufactured in the same AMS 0.35 µm Opto process, but with a different epitaxial layer doping profile. The chip is composed of 1152 columns read out in parallel. Each column contains 576 square pixels featuring a pitch of 18.4 µm. The active area of the sensor amounts to ~ 21.2 x 10.6 mm^2. More details may be found in [2]. Unlike TC, HRTC is built upon a high resistivity epitaxial layer (400 Ω.cm resistivity). To investigate the improvement expected from the high resistivity substrate, the sensors were fabricated with three different epitaxial thicknesses: 10, 15 and 20 µm. This is to be compared to the 14 µm thick, low resistivity, epitaxial layer (~ 10 Ω.cm resistivity) of TC.

The detection performances of the three different variants of HRTC were first assessed with radioactive sources, and the measurements obtained were compared to those obtained with TC. The sources used were ^{55}Fe and ^{106}Ru. The measurements were performed with a clock frequency of 20 MHz (i.e. a quarter of the nominal value) and at a temperature of 20°C.

The sensor performance was first studied by computing the Charge Collection Efficiency (CCE), which was extracted from the reconstruction of clusters generated by the 5.9 keV X-Ray of the ^{55}Fe source (Table 1 – top). The values observed indicate that the HR epitaxial layer allows for a substantial enhancement of the CCE. The effect is most pronounced for the 10 and 15 µm thick epitaxial layers. It follows the expectations based on an increased depletion volume, which reduces the path of the signal charges and thus diminishes the recombination rate and drives the charges towards a smaller number of pixels than in case of low resistivity.

EPI layer	**Standard (~ 10 Ω.cm) 14 µm**			**High resistivity (~ 400 Ω.cm)**			
Charge Collection (^{55}Fe source)	Seed	2x2	3x3	EPI	seed	2x2	3x3
	~ 21 %	~ 54 %	~ 71 %	10 µn	~ 36 %	~ 85 %	~ 95 %
				15 µm	~ 31 %	~ 78 %	~ 91 %
				20 µm	~ 22 %	~ 57 %	~ 76 %
S/N at seed pixel (^{106}Ru source)	~ 20 (230 e^-/11.6 e^-)			10 µn	~ 35		
				15 µm	~ 41		
				20 µm	~ 36		

Table 1: Test results of TC and HRTC obtained with an X-Ray (^{55}Fe) and a β^- (^{106}Ru) source. The top of the table displays the measured CCE (in %) for the seed pixel and for 2x2 and 3x3 pixel clusters. The bottom provides the observed S/N (most probable value) of the seed pixels. The left bottom also shows the mean charge collected by seed pixels measured with TC and its average noise value. The relative uncertainties affecting the values displayed are typically in the order of 0.5-1%.

Consequently, the S/N delivered by HRTC was expected to be well above the value obtained with TC. The improvement was quantified with a ^{106}Ru source, which allows detecting β^- electrons of up the 3.5 MeV, and provides therefore a practical mean of assessing the sensor detection performances for nearly minimum ionising particles (m.i.p.). As shown in Table 1 (bottom), the S/N obtained improves the value observed with TC by up to 100 %, depending on the thickness of the HR epitaxy (the highest S/N value being provided by the 15 µm thick epitaxial layer).

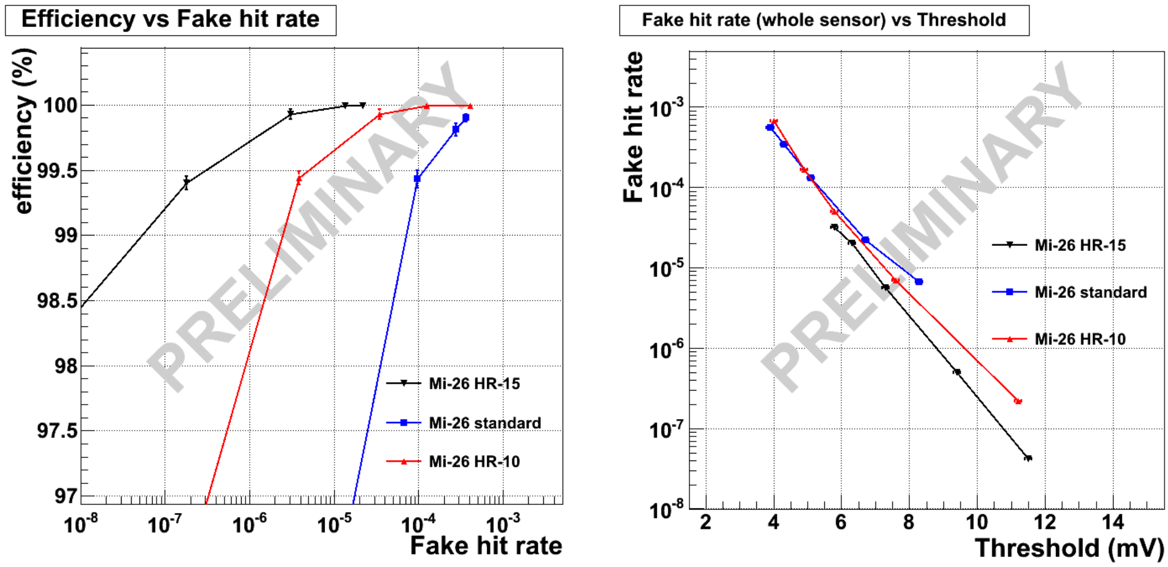

Figure 2: Preliminary beam test results for non-irradiated sensors with various epitaxial layers: efficiency versus fake hit rate (left) and average fake hit rate versus discriminator threshold (right).

Next, several sensors were qualified with a beam of ~ 120 GeV π^- at the CERN-SPS. The set-up consisted of a telescope made of two arms of two planes each, each plane being composed of one (standard) TC. In between the two arms, two HRTC were mounted as DUT (Device Under Test). The readout was realised at the nominal frequency of 80 MHz. HRTC versions featuring 10 and 15 µm thick epitaxial layers were studied.

Their m.i.p. detection efficiency, average fake hit rate and spatial resolution were determined for various values of the discriminator threshold. The fake hit rate is defined as the probability for one pixel in one event to deliver a noise fluctuation above the discriminator threshold. The study addressed the probability value averaged over all pixels of the sensor. Its measured values are shown on Figure 2 (right). The similarity of the fake rates observed with the three different epitaxial layer thicknesses coincides with the absence of difference between the three noise measurements. The variations of the detection efficiency and the fake hit rate with the discriminator threshold led to Figure 2 (left), which shows how both parameters are correlated. This distribution allows determining a working point, i.e. a threshold value high enough to maintain the fake rate at an affordable level (typically below 10^{-3}) and still not as high as to degrade the detection efficiency.

The measured single point resolution is displayed on Figure 3 as a function of discriminator threshold. One observes that the spatial resolution of HRTC is about 0.5 µm better than the one of TC. It amounts to 3.2/3.3 µm over a sizeable range of threshold values. The corresponding average number of pixels per hit is typically around 3.

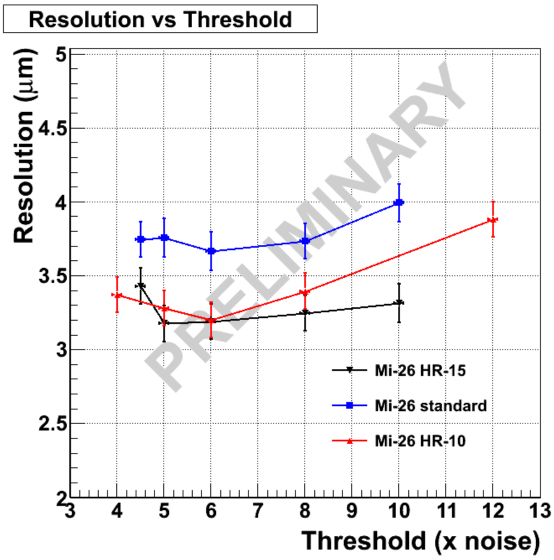

Figure 3: Preliminary beam test results for non-irradiated sensors featuring various epitaxial layers: spatial resolution versus discriminator threshold.

The study was repeated with sensors irradiated with neutrons beforehand. The fluence considered amounted to 1.10^{13} n_{eq}/cm^2, a value exceeding the expected integrated dose if running the BT over a decade at the CERN-SPS. The sensors were tested in the same operating conditions as the non-irradiated ones, except for the temperature, which was set to 0°C. Figure 4 shows the measured detection efficiency, fake hit rate and spatial resolution for various discriminator threshold values. One observes that the sensors exhibit a detection efficiency exceeding 99 % for a fake rate well below 10^{-3}. The performances of the HR-15 sensor are particularly high, with an efficiency above 99.9 % for a fake rate below 10^{-4}.

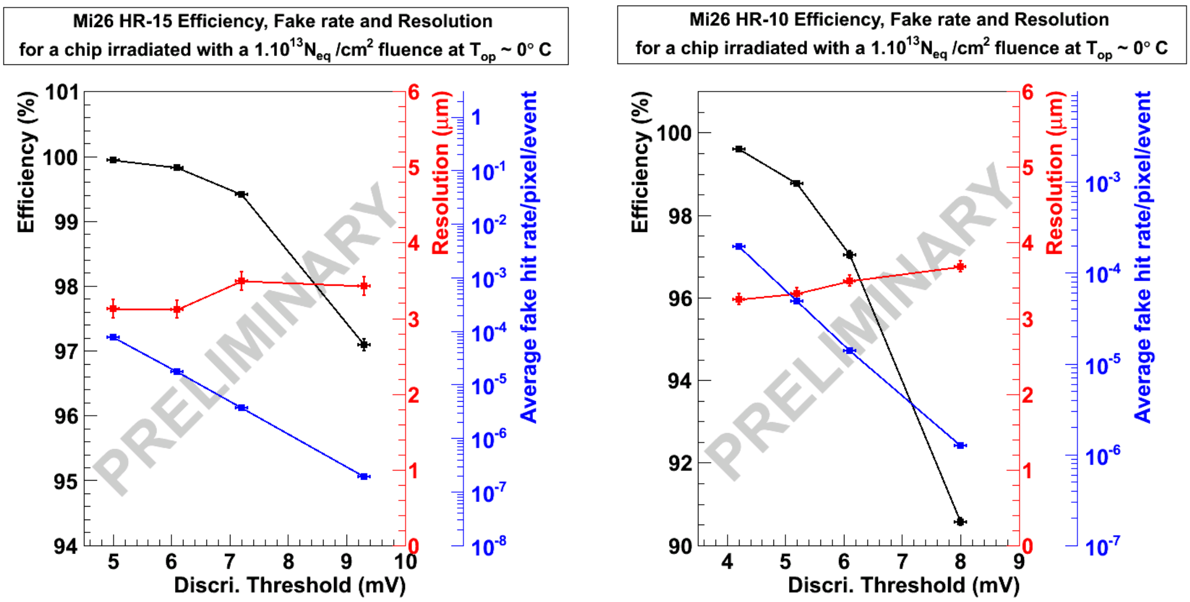

Figure 4: Preliminary beam test results of irradiated HRTCs. The measurements were performed at a temperature of ~ 0 °C. The sensors were exposed to a fluence of 1.10^{13} n_{eq}/cm^2 beforehand. The detection efficiency (in black), the fake hit rate (in blue) and the spatial resolution (in red) are displayed as functions of the discriminator threshold, for 10 µm (right) and 15 µm thick (left) epitaxial layers.

In summary, these results indicate that a spatial resolution around or below 3.5 µm may be reached with the HRTC while preserving an efficiency in excess of 99% and a fake hit rate below 10^{-3}/pixel/event over several years of operation. In such conditions, the telescope reaches a resolution better than 2 µm on the impact position at the DUT surface. It was thus decided to upgrade the EUDET BT by replacing the present TC sensors with High-Resistivity replicas.

4 A new IDC to complete this study

The development of a thin and granular sensor for the EUDET BT has opened new possibilities for various other applications, including a new BT generation with still improved performances and a large, multi-reticule, sensitive area for the FP-7 project AIDA. In perspective of the latter, a new version of the IDC was designed and fabricated. Called IDC-HR, it explored improved or modified versions of the TC pixel architecture. It was manufactured through an AMS 0.35 µm Opto engineering run featuring 4 epitaxial layer variants: one of them reproduced the previously used, 14 µm thick, low resistivity (~ 10 Ω.cm) epitaxy; the three others featured the already used high resistivity (~ 400 Ω.cm) layers of 10, 15 and 20 µm thickness.

IDC-HR allowed studying two different in-pixel amplification schemes: a Common Source (CS) amplifier similar to the one implemented in TC, and a CASCODE (CAS) alternative design with different optimisation schemes. 2 different pixel pitches were implemented in the sensor: 18.4 and 20.7 µm. IDC-HR was also designed to explore the possibility and effect of a higher bias voltage of the sensing diode, as well as to study elongated pixels (with dimensions of 18.4 µm x 36.8 µm and 18.4 µm x 73.8 µm). For details on IDC-HR operation, the reader is invited to consult the description of the IDC [3], which differs from the HR version essentially in terms of pixel designs implemented. This note concentrates on the pixel optimisation with a 15 µm thick, high resistivity, epitaxial layer and a 18.4 µm pitch.

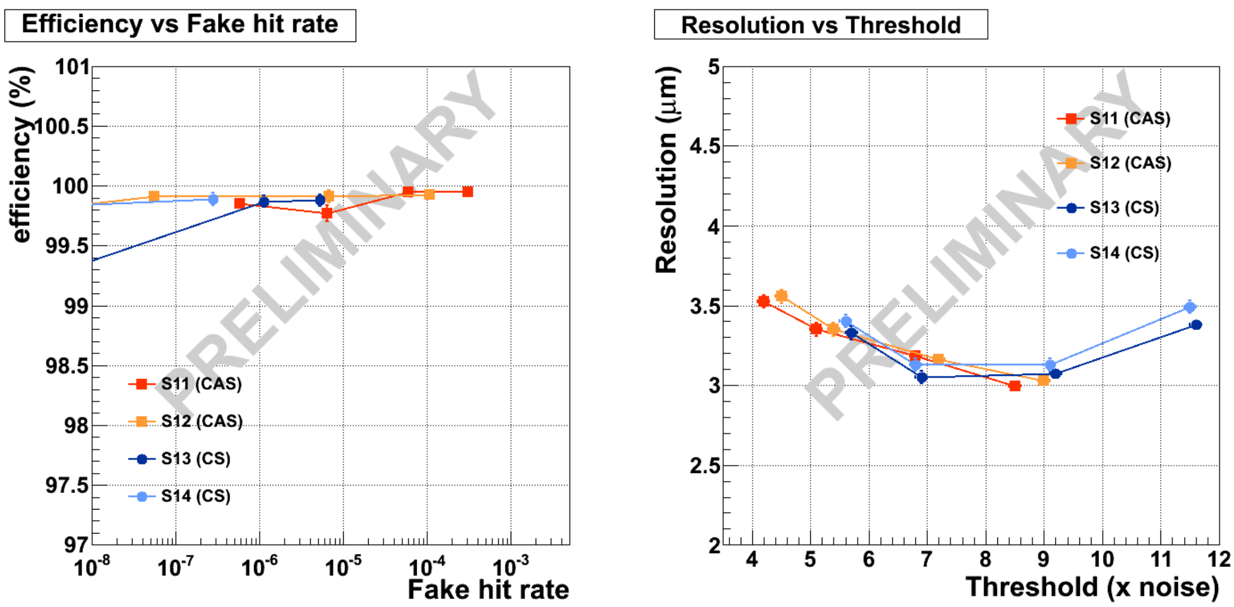

Figure 5: Beam test results of IDC-HR: efficiency versus fake hit rate (left) and spatial resolution versus discriminator threshold (right). The two blue curves stand for two common source amplifier variants, while the red curves correspond to two variants of a CASCODE amplifier.

The sensor was fabricated in Spring 2010. It was first characterized in the laboratory and next with a 120 GeV π^- beam at CERN-SPS (August and September 2010). Figure 5 shows the preliminary beam test results at an operating temperature of 20°C and a (nominal) clock frequency of 100 MHz. The measurements are shown for two variants of the common source amplifier and for two variants of the CASCODE amplifier. For all 4 variants, the detection efficiency remains around 99.8 %, or above, while the average fake hit rate is very low (e.g. less than 10^{-7}), which is still better than HRTC. This low fake rate would be particularly valuable in the case of a large area, multi-reticule, sensor, such as the one foreseen for the FP-7 project AIDA. The measured single point resolution is close to 3 µm for well chosen threshold values, improving slightly the value provided by the HRTC. The corresponding telescope resolution on the DUT surface is about 1.5 µm.

The analysis of the data delivered by the other pixel variants, e.g. elongated pixels, is still under way.

5 Conclusion

For the last year of the EUDET project, two new sensors were manufactured and characterised to investigate the potential benefits of a newly accessible fabrication process variant, featuring a high resistivity epitaxial layer.

One of the sensors, called HRTC, is a new version of the TC. Because of their twice higher S/N and improved spatial resolution, HRTC units will be mounted on the EUDET BT in replacement of the present TC sensors as soon as they have been thinned down to 50 µm. The benefits of this replacement are manifold. They first concern the BT lifetime (likely to extend beyond a decade) and its adequacy for demanding operating conditions (temperature, radiation level, etc.). They also translate into a resolution on impact positions on the DUT surface better than 2 µm.

The other sensor fabricated is a new version of the IDC, which was produced on high resistivity epitaxial layers and with new pixel designs. Its characterisation at the CERN-SPS showed still improved performances with respect to HRTC. The outcome of the study will in particular benefit to the forthcoming FP-7 project AIDA [4], for which a large area, multi-reticule, sensor ought to be fabricated in order to equip a BT. Finally, it should be emphasized that various other projects will be nourished with sensors derived from those developed for the EUDET BT [4].

Acknowledgement

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