Vertically Integrated CMOS Active Pixel Sensors for Tracking Applications in HEP Experiments

D. Passeri, *Member, IEEE*, L. Servoli, S. Meroli, D. Magalotti, P. Placidi, *Member, IEEE*, A. Marras

Abstract– **In this work we propose an innovative approach to particle tracking based on CMOS Active Pixel Sensors layers, monolithically integrated in an all-in-one chip featuring multiple, stacked, fully functional detector layers capable to provide momentum measurements (particle impact point and direction) within a single detector. This will results in a very low material detector, thus dramatically reducing multiple scattering issues. A first chip prototype has been fabricated within a multi-project run using a 130nm CMOS 3D Chartered/Tezzaron technology, featuring two layers bonded face-to-face. Tests have been carried out on full 3D structures, providing the functionalities of both tiers and their inter-communications. Actually, laser scans have been carried out using highly focussed spot size, obtaining coincidence responses of the two layers. X-rays sources have been used as well for sensor calibration purposes. Beam tests with 3MeV protons have been carried out at the INFN LABEC laboratories in Florence (Italy) to assess the suitability of the proposed approach for Minimum Ionizing Particle detection.**

I. INTRODUCTION

THE particle detectors designed to operate in the high luminosity scenarios planned for the future upgrade of the Large Hadron Collider (HL-LHC) in various experiments (LHCb, ALICE, ATLAS, CMS) will require better performance with respect to tracking systems currently in use. In particular, beside the increased resistance to radiation, the most significant issues to be addressed are: *i*) the reduction of the material budget, in order to improve the accuracy of the reconstruction of primary and secondary vertices; *ii*) the reduction of the size of the pixels and high operating speeds of the acquisition systems, in order to obtain an efficient and accurate reconstruction of the tracks produced by charged particles in environments where their spatial density and temporal frequency is very high.

In order to cope with the above mentioned issues, in this work we propose an innovative approach to particle tracking based on CMOS Active Pixel Sensors layers, monolithically integrated in an all-in-one chip featuring multiple, stacked, fully functional detector layers capable to provide momentum measurement (particle impact point and direction) within a single detector. This will results in a very low material detector, thus dramatically reducing multiple scattering issues.

II. THE TWO TIER 3D CMOS ACTIVE PIXEL SENSOR SYSTEM

A first chip prototype has been fabricated within a multi-project run using a 130nm CMOS 3D Chartered/Tezzaron technology [1], featuring two layers bonded face-to-face (Fig. 1). Several test structures have been integrated, namely single pixels, as well as different matrices, e.g. featuring 5×5 and 16×16 pixels. Each pixel is based on the standard 3 transistors (3T) architecture, featuring 10×10 micrometers, with different sensitive element (photodiode) layout, in particular, small and large sensitive area form factor (Fig. 2).

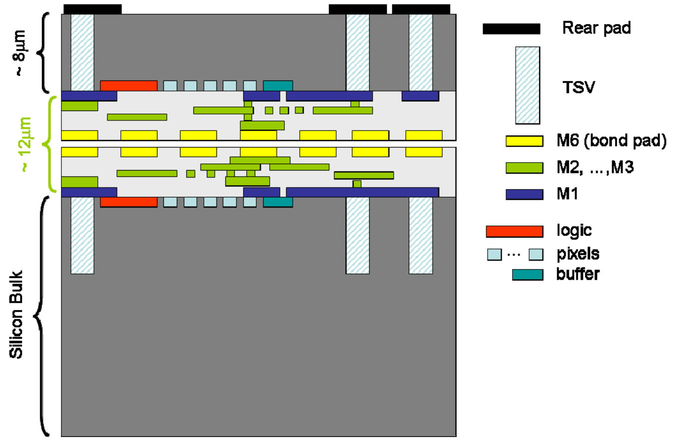

Fig. 1. Schematic cross-section of a front-to-front two chip bonding (thinned top tier). Both tiers feature few test structure, as well as fully-functional 16x16 pixel matrices with small and large photodiodes.

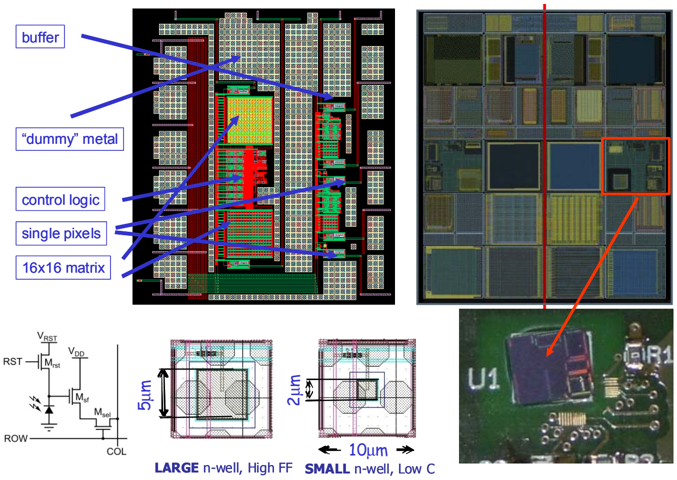

Fig. 2. The RAPS04 3D structures. The chip has been fabricated within the 3D-IC consortium [1] using a CMOS 3D Tezzaron/Chartered 130nm technology.

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D. Passeri and P.Placidi are with D.I.E.I., Università di Perugia, via Duranti 93, 06125 Perugia, Italy.

A. Marras is with Deutsches Elektronen-Synchrotron, Germany.

All authors but A. Marras are with Istituto Nazionale di Fisica Nucleare (I.N.F.N.), Sezione di Perugia, via Pascoli 1, 06100 Perugia, Italy.

III. ELECTRICAL AND FUNCTIONAL CHIP CHARACTERIZATION

A. Characterization with Laser (531nm and 780nm)

For electrical and functional characterization a suitable HW/SW read-out set-up has been devised and fabricated. In particular, an advanced optical workbench with IR, UV, and VISible laser heads with micro-focusing (spot size below 2μm) and micro-positioning (scan step of 0.21μm) capabilities has been used. It allows up to four sensors parallel read-out for track reconstruction and spatial resolution analysis, as well as 2D scans for surface mapping (Fig. 3).

In order to evaluate the different layout pixel options illustrated in Fig. 2, a scan of a subset of 3×3 pixels has been carried out, using a back-illumination configuration, e.g. illuminating the outer tier from the top. Thanks to the very fine steps and small spot dimensions, an accurate evaluation of the pixel output as a function of the spot position can be appreciated. Slightly higher responses of the small form factor pixel have been obtained, thanks to the lower photodiode capacitance resulting in higher charge to voltage conversion gain. On the other hand, higher fill factor pixels show a bigger efficiency (e.g. sensitive area extensions) (Fig. 4). These aspects should be carefully evaluated when looking at specific tracking requirements. Actually, significantly different responses for spots hitting the pixel sensitive area with respect to spots crossing in between pixels have been found: this is a potential warning for effective fill-factor / efficiency issues.

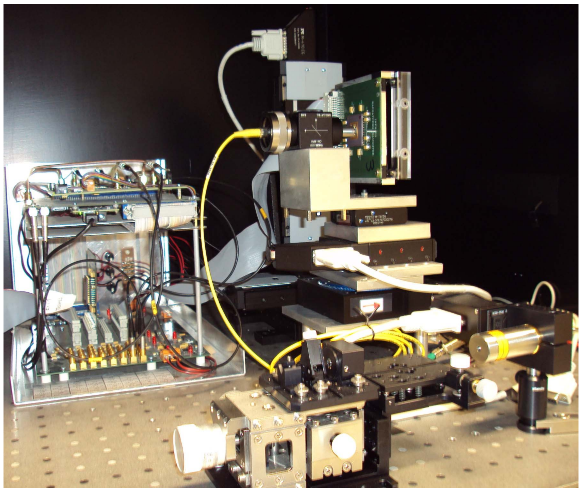

Fig. 3. The optical laser workbench.

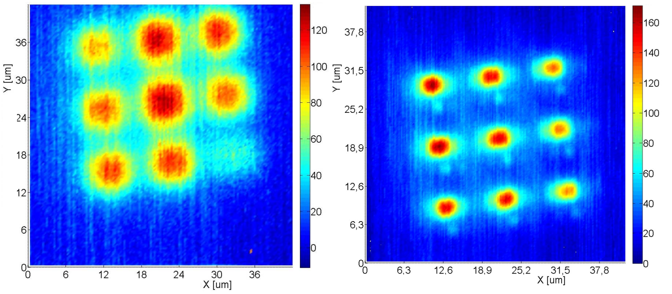

Fig. 4. Back-side illumination: scan of a subset of 3×3 pixels: large photodiodes (left-hand side) vs. small photodiodes (right-hand side). Regular response patterns have been obtained (no metal-shielding effects).

A clear evidence of coincidence responses between top and bottom tiers has been found. Synchronous read-out of both tiers can be carried out by simple reading in parallel top and bottom matrices, without need of coincidence elaboration (time-stamps verification) (Fig. 5).

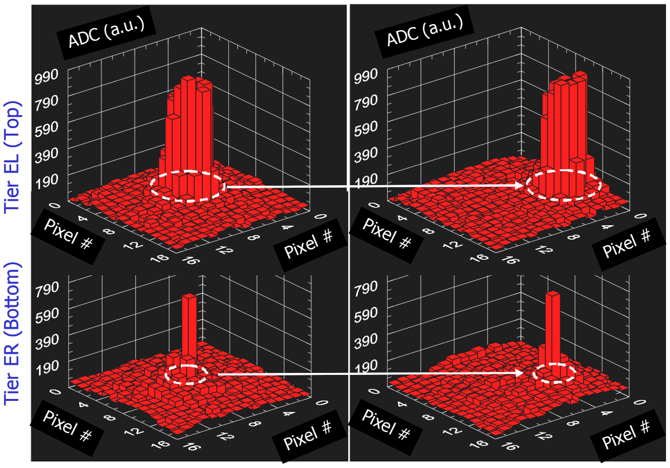

Fig. 5. Top (outer) and bottom (inner) tier responses (X-Y scan) with 780nm red laser (16x16 matrix): coincidence between outer and inner tier responses.

B. Characterization with X-rays (40kV / 90μA - Fe and Cu fluorescence)

An Amptex Mini-X X-rays source has been used for sensor calibration purposes with photons of different energies. In particular, fluorescence of Fe and Cu targets has been used. The peak positions on the cluster signal distributions of Figs. 6 and 7 correspond to almost complete charge collection; even if a significant tail to lower signal can be noticed due to non-complete charge collection. From the fitting Gaussian curve mean value the sensor calibration can be carried out. Actually, assuming for this position a complete charge collection, from the given energy of the photons and assuming 3.6*eV* energy value for e/h pair generation within silicon substrate, the number of collected electrons can be correlated with the ADC counts, allowing an estimation of the conversion gain of around 22e/h pairs per ADC for the outer tier and 25e/h pairs per ADC for the inner tier. Eventually, after calibration, the overall (spatial and temporal) measured noise was around 41e [3]. A good linearity of the sensor response has been found at different photon energies.

C. Characterization with 3 MeV proton beam

In order to evaluate the suitability of the two layer monolithic active pixel sensor system to reconstruct particle tracks, a test with 3*MeV* energy proton beam has been carried out at the INFN LABEC laboratories in Florence, Italy. The set-up is illustrated in Fig. 8; the photon energy is sufficient to cross both outer and inner pixel layer, thus allowing the evaluation of the correlated responses.

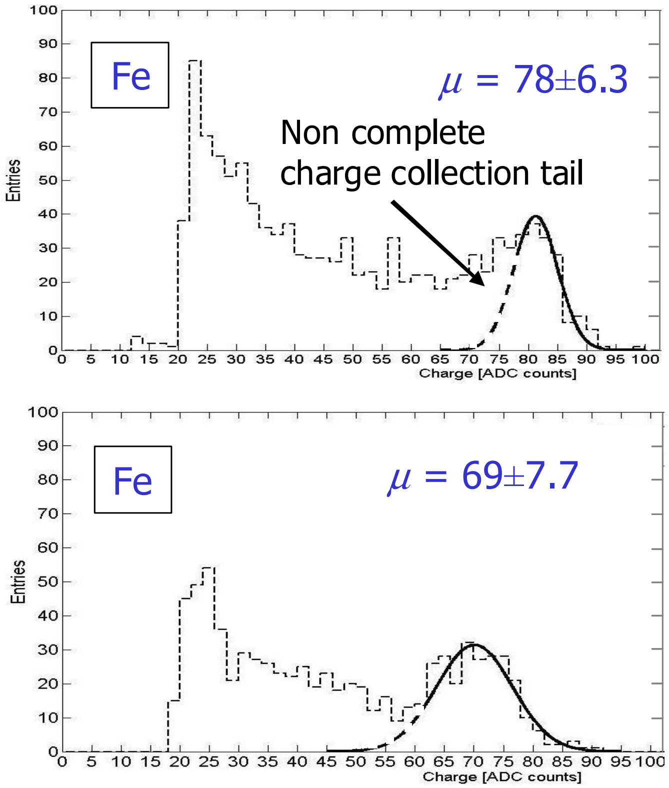

Fig. 6. Cluster signal distribution: 16x16 outer (top) and inner (bottom) tier matrix responses to X-rays produced with a Fe target in fluorescence mode.

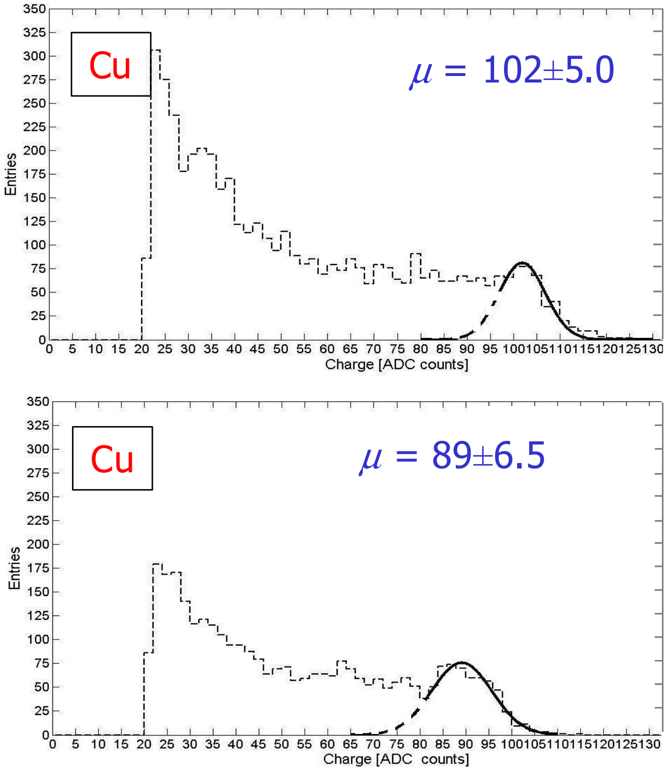

Fig. 7. Cluster signal distribution: 16x16 outer (top) and inner (bottom) tier matrix responses to X-rays produced with a Cu target in fluorescence mode.

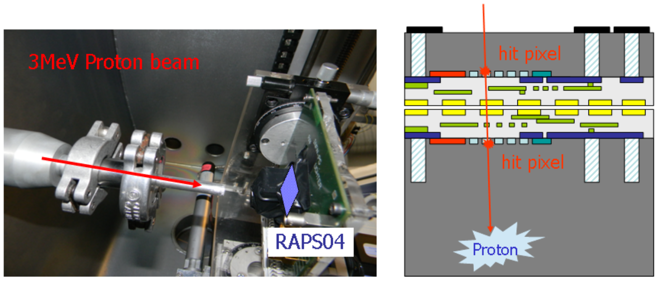

Fig. 8. Test beam set-up at the INFN LABEC laboratories (Florence, Italy).

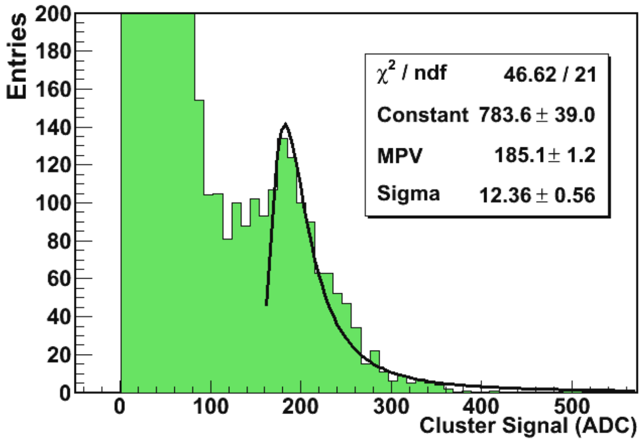

Fig. 8. Cluster signal distribution: 16x16 large matrix responses to 3 MeV protons – small form factor photodiode.

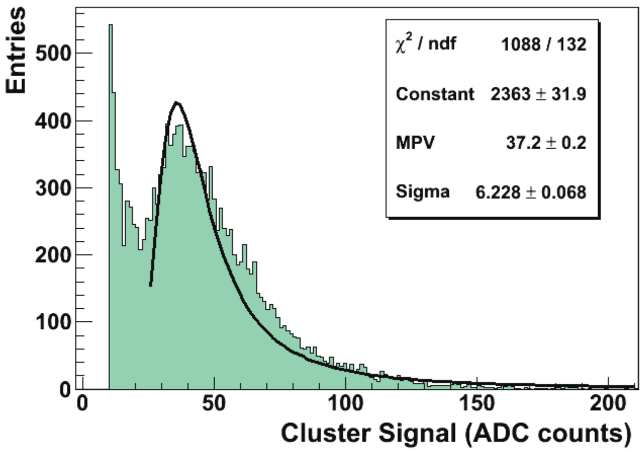

Fig. 9. Cluster signal distribution: 16x16 large matrix responses to 3 MeV protons – large form factor photodiode.

The signal distributions for both small and large photodiode devices are reported in Figs. 9 and 10, respectively. The superimposed Landau fittings allow the estimation of the most probable value in terms of ADC counts. Thanks to the previously calibrations, we can estimate the effective collected charge, which results in an effective charge collection region thickness of the order of few micrometers.

A typical coincidence response to an orthogonal beam is reported in Fig. 10. The outer layer cluster is typically made by one pixel, whereas more pixels are involved in the inner layer cluster.

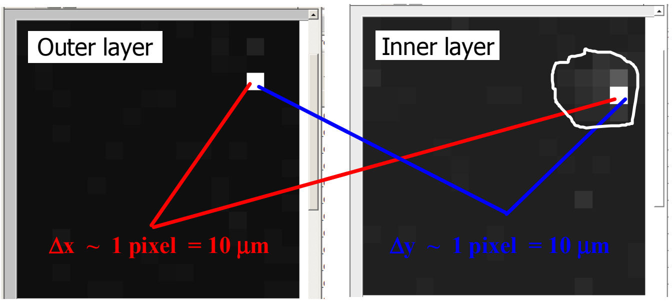

Fig. 10. 16x16 large matrix coincidence response of outer and inner tiers to a 3 MeV proton beam (tilt = 0°).

From these data, the inner and outer layer misalignment has been measured using difference of coordinate method. A 10.8µm displacement (1.08 pixel units) has been found with a sigma of about 1.4µm for both coordinates. This has been confirmed by means of a chip Computed Tomography carried out ad DESY, Hamburg, where the misalignments of the PAD region is clearly visible, in both coordinates [3].

As an example, in Fig. 11 are reported the residual (i.e. differences) distributions of the row pixel coordinates between outer and inner tier. The peaks at 0, 1 and 2 represent the cases when mono-hit clusters have been obtained in both tiers, whereas from the Gaussian fit of the standard (i.e. non-mono pixel clusters) occurrences the above mentioned parameters can be inferred.

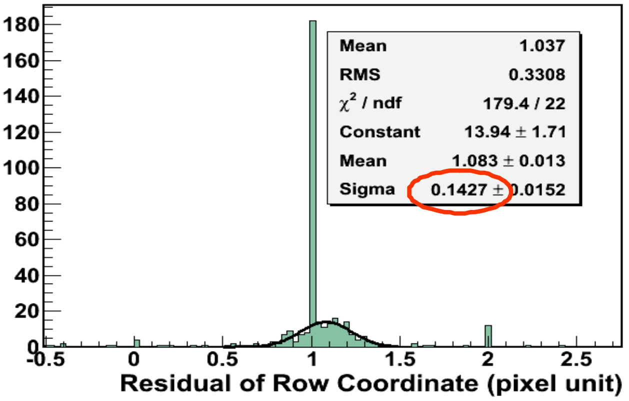

Fig. 11. Residual distributions of the row pixel coordinates between outer and inner tier.

These results confirm the capability of the 3D monolithic two tiers device to evaluate the particle track incidence angle within few degrees, allowing the particle momentum evaluation, as foreseen in a previous simulation work which allowed the estimation of the geometrical design parameters, namely pixel pitch and distance between the two pixel layers [2].

IV. CONCLUSIONS

The first functional characterization of 3D monolithically stacked Active Pixel Sensors layers fabricated in Chartered/ Tezzaron 130nm 3D technology for particle tracking purposes has been presented.

Good communications between bottom and top tiers have been found; actually, both tiers are fully functional. Different test structures and matrix structures (5x5, 16x16, small vs. large photodiode) have been characterized with focused laser. Noise analysis and X-rays calibrations with Fe and Cu fluorescence have been carried out. Coincidence responses between bottom and top matrices have been obtained with laser stimuli as well.

Charged particle characterization with 3 Me*V* proton beam to estimate charge collection region thickness and tracking capabilities has been carried out, assessing the suitability of the 3D monolithic two tiers device to evaluate the particle track incidence angle within few degrees, allowing the particle momentum evaluation.

REFERENCES

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