TALK RD-2-2: New developments for silicon detectors

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The success of future particle physics experiments will rely on vertex detectors of unprecedented performances. This observation has led to several new developements in Si detector technologies, aiming for very high granularity, very modest material budget, good to high radiation hardness and fast read-out time. A review of the on-going developements is provided, emphasising those aiming for a future e^+e^- Linear Collider (LC).

1. Motivations for R&D on Si detectors

The need for High Energy Physics experiments to aim for ever increasing reaction energies, in order to cross new kinematical thresholds and access new phenomena, is at the origin of a sizeable effort of R&D for a new generation of Si pixel detectors. This is mainly to equip future vertex detectors operating in an environnement characterised by a large number of jets (typically > 10), a significant fraction of them containing b or c quarks or τ leptons. An example is provided by the reaction: $e^+e^- \rightarrow HA \rightarrow t\bar{t}t\bar{t} \rightarrow b\bar{b}b\bar{b}W^+W^-W^+W^-$, which may lead to at least 12 jets, 4 of them coming from b quarks and - eventually - 4 from c quarks. Moreover, gluon radiation tends to increase the number of jets and of b and c quarks.

Such extreme experimental conditions call for a vertex detector with unprecedented performances. The importance of the latter is further enhanced by the need to characterise (new) phenomena and particles. This ability is mandatory to disentangle various possible explanations for new observations and pin down the dynamics they express (e.g. electroweak breaking mechanism, supersymmetry, new gauge interactions, low scale quantum gravity).

Future vertex detectors must therefore allow reconstructing the flavour of each vertex in a "poly-jet" environnement with very high efficiency and purity (for charm quarks in particular). Pixels are mandatory in most of these cases, where it is necessary to assign each track to its vertex origin, to reconstruct the vertex mass, energy and electric charge as well as to establish the link between vertices (e.g. between tertiary and secondary ones), to help the reconstruction of energy flow, to identify the nature of electrons in jets (e.g. photon conversions or prompt electrons), a.s.o.

Experiments will therefore require very granular, ultra-light and poly-layer vertex detectors, installed very close to the interaction region. Among existing technologies, Charged Coupled Devices (CCD) offer performances which are closest to those ambitionned. They are however not fully satisfactory, as shown below.

The smallness of the cross-sections related to the processes of interest make very high luminosity collisions mandatory. This translates into harsh radiation conditions which degrade the detector performances, and into high background, which leads to high occupancy. CCDs are therefore not applicable in cases where the read-out speed or the radiation tolerance demanded are high and where only Hybrid Pixel Sensors (HPS) may be used. However, the latter are substantially less granular and thin than CCDs. This situation originated a wide panel of R&D activities, which aim to combine specific advantages of CCDs with those of HPSs, mainly in perspective of a Future e^+e^- Linear Collider. Another class of developments aims for more futuristic objectives (e.g. Super-LHC), which require winning

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one or two additionnal orders of magnitude in read-out speed and radiation tolerance.

2. R&D on Charged Coupled Devices

CCDs are mainly developed by the LCFI collaboration [1] in perspective of a LC. This technology was retained for the baseline of the vertex detector considered in the Technical Design Report of the TESLA collider [2].

2.1. Principle of operation

The signal is generated in a typicaly 20 μm thick, partially depleted, epitaxial layer. The signal electrons are collected through diffusion and drift, the latter occuring in the depleted part of the layer. Fig.1 illustrates the charge collection in a typical device consisting of a lightly doped epitaxial p-layer on a heavily doped p^+ substrate, covered with a $\sim$ 1 μm thick n^+ layer. The partial depletion of the n^+/p region creates a potential minimum for electron storage just above the n^+/p edge. The charge collected is clocked out through the sensor material.

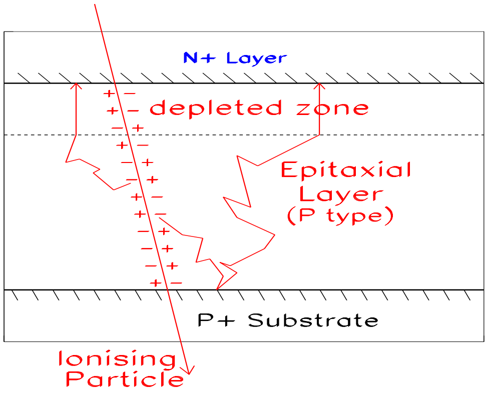

Figure 1: Schematic charge collection in a CCD.

CCDs were used very successfuly for the vertex detector of the SLD experiment. Made of about 307 million pixels, the detector was read out at a frequency of 5 MHz, translating into a (serial) frame read-out time of $\sim$ 200 ms. Based on a 20 μm pitch, on layers representing 0.4 % radiation length only, and on a small beam pipe radius, it provided an unprecedented impact parameter resolution of $\sigma = 8 \oplus 33/p \cdot sin^{3/2}\theta$ μm. These performances need however substantial improvement to exploit the physics at a LC.

2.2. R&D objectives and achievements

The LC running conditions call for a much shorter frame read-out time and a significantly lighter material budget. Moreover, the radiation tolerance of the CCDs for the foreseen radiation levels needs to be assessed. The exact performance goals are not the same for all LC projects. For TESLA, which has the most demanding running conditions, the first layer of the detector, which has the highest occupancy, needs to be read out in less than 50 μs, making a clock frequency of at least 50 MHz mandatory. The material budget of each of the 5 layers (with radii ranging from 15 to 60 mm) of the detector should be kept below 0.1 % radiation length. The impact parameter resolution should therefore be better than $\sigma = 5 \oplus 10/p \cdot sin^{3/2}\theta$ μm. The detector should stand a few 100 kRads ionising radiation and fluences exceeding 10^{10} n$\cdot$cm^{-2}.

Several steps are being made to achieve these goals. The first column parallel CCD was designed, due for delivery in October. 50 MHz column parallel operation may already be possible with this prototype. The first column parallel read-out chip is in advanced design, and should be back from fabrication on a similar timescale. Successful operation of a commercial CCD was achieved, clocked at 50 MHz with a driving voltage of 3 V. This device will also allow radiation tests. Further prototyping aims in particular for rather high resistivity Si, allowing a larger depleted volume, and for low voltage two-phase clocking.

Trials have been made to achieve an unsupported ladder system, where the latter were thinned down to about 60 μm and hold by springs at both ends. Up-to-now, these trials were semi-successful. While longitudinal stabilisation was satisfactory, the processed Si tends to have a transverse curvature which is difficult to control sufficiently well by the spring tension. Alternative solutions consisting of semi-supported options (e.g. Si/Be) are presently under study, which should yield better overall stability.

3. R&D on Hybrid Pixel Sensors

This pixel technology is best suited to LHC experiments, because of its proven 25 ns time stamping and sparse data scan capabilities and of its high hadron radiation tolerance. It does however not provide sufficient spatial resolution for the LC physics goals. The R&D activity is therefore mainly aiming for more granular and thinner devices. For the long term, effort is also made to further improve the HPS radiation tolerance in order to stand running conditions such as those foreseen at a very high luminosity LHC.

Substantially better granularity was already obtained by a Como-Cracow-Milano-Warsaw collaboration [3], which designed test structures exploiting the concept of interleaved (i.e. floating) pixels. Tests performed with one of them featuring 60/100 μm implant width/pitch and 200 μm read-out pitch showed that the charge sensing by interleaved pixels works efficiently, translating into an average single point resolution of ~ 6.5 μm, i.e. ~ 4 times better than the binary resolution associated to the implant pitch. New tests structures, having ~ 25 μm implant pitch, are being fabricated, which are expected to provide a single point resolution better than 3 μm.

4. Monolithic Active Pixel Sensors

The developement of these sensors (called MAPS) for charged particle tracking was initiated by an IReS-LEPSI (Strasbourg) collaboration in 1999. This novel technology allows to integrate signal processing (amplification, discrimination, etc.) in the detector substrate, which may be thinned down to a few tens of μm.

4.1. Principle of operation

The principle of detection is similar to that used in visible light CMOS cameras. The signal delivered by a charged particle is generated in a low resistivity, p- type, epitaxial layer of 5 - 15 μm thickness (see fig.2). The electrons diffuse thermally and are collected by regularly implanted n wells, where the signal gets converted into an electrical pulse. Since the lightly doped epitaxial layer is embedded between two heavily doped media (i.e. p wells and substrate), electrons reaching the boundary regions get reflected by the potential barrier due to the doping profile.

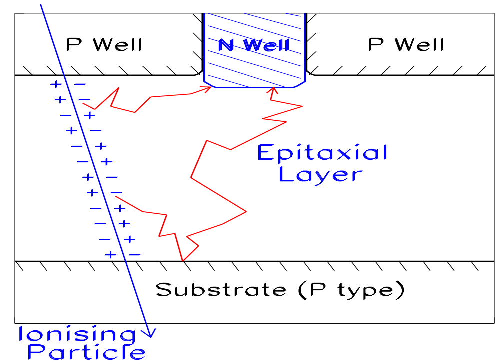

Figure 2: Schematic charge collection in a MAPS.

4.2. Present status [4]

The first prototypes, made of small arrays of a few thousands of pixels, demonstrated the viability of the technology and its high tracking performances (e.g. > 99 % detection efficiency, single point resolution of 1.5 μm, double track resolution below 30 μm). Moreover, a prototype manufactured in a process without epitaxy, but based on a low doping substrate, exhibited a detection efficiency close to 100%, and a single point resolution of ~ 4 μm. It was also shown that the sensors could stand fluences of 10^{12} to 10^{13} $\mathrm{n{\cdot}cm^{-2}}$ without significant performance drop.

Important steps were achieved recently: the first real scale prototype was fabricated. Made of arrays of 10^6 pixels (17x17 μm^2 wide), it reproduced the tracking performances of the small prototypes rather well (e.g. > 99 % detection efficiency, single point resolution of 1.7 μm). Moreover, the average gain dispersion over the sensor surface was of the order of a few per-mill only.

Next R&D steps include the design of microcircuits providing integrated amplification, noise suppression and signal discrimination in a column parallel architecture aiming to meet the LC readout speed requirements. A first test structure of this kind was fabricated and is being tested.

5. DEPleted Field Effect Transistors

DEPFET (i.e. DEPleted Field Effect Transistor) pixel sensors offer performances which make them particularly attractive for X-ray imaging. Their application to charge particle tracking started recently, promoted by a MPI(Münich)-Bonn collaboration.

5.1. Principle of operation

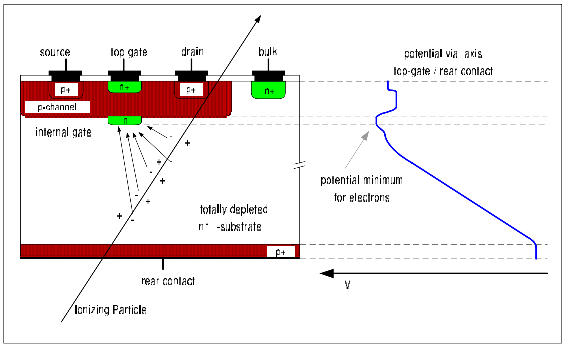

Figure 3: DEPFET basic operation principle.

The signal collection is illustrated on fig.3. A MOS or junction field effect transistor is integrated in a high resistivity, fully depleted, n-type substrate. By means of sidewards depletion and additional n-implants below the transistor, the signal electrons get collected by the n-implant underneath the transistor channel, for which it acts as an internal gate. The signal holes drift towards the rear contact of the sensor. The detection of a charged particle exploits the modulation in the transistor current induced by the change in the internal gate potential.

5.2. Present status [5]

A 64x64 (50 x 50 μm^2) pixel prototype was fabricated in 2000 for biomedical imaging and tested. A noise of 40 e^- was observed, as well as a single point resolution of $\sim$ 10 μm, the frame read-out time being $\sim$ 1 ms. The first read-out chip achieving zero suppression was fabricated recently in 0.25 μm TSMC technology. It is currently tested.

The next step of the developement will consist of a sizeable array of 30 x 30 μm^2 pixels, read-out with a row clock frequency of 50 MHz, and thinned down to $\sim$ 50 μm.

6. Other developments

Several other R&D activities are carried on, which aim for the long-term, and are therefore not described in this short review. This is the case for 3-D detectors, defect engineered Si, cryogenic detectors, Si-on-Insulator, amorphous Si, etc., for which more information can be found in [6].

7. Summary

Major future high energy physics projects will require pixel vertex detectors with unprecedented performances, allowing to tag with high efficiency and purity, b and c quarks as well as τ jets, in high jet multiplicity final states. Existing technologies (CCD, HPS) don't fulfil these requirements at a satisfactory level, a fact which originated various research lines, either to improve their performances or to explore new technologies (MAPS, DEPFET, SoI, 3-D, etc.). Substantial effort is also made to improve the radiation tolerance of Si against bulk damage (defect-engineering, cryogenic detectors, amorphous silicon, etc.), a crucial issue for future Hadron Colliders.

Given the importance of the material budget for the impact parameter resolution at the LC, the technology best suited to its physics goals (CCD, HPS, MAPS, DEPFET, ...) may not emerge before several years, since a quite detailed vertex detector design is needed for such a choice.

REFERENCES

1. C.J.S.Damerell (for the LCFI collaboration), *A CCD based Vertex Detector for TESLA*, preprint LC-DET-2001-023;
2. Part III of the TESLA Technical Design Report, DESY 2001-011, March 2001;
3. M.Caccia et al., *Characterisation of Hybrid Pixel Detectors with capacitive charge division*, contribution to the Linear Collider Workshop 2000, FNAL, October 24-28, 2000;
4. Y.Gornushkin et al., proceedings of the 6th Conference on Position Sensitive Detectors, Leicester, September 9-13, 2002;
5. P.Fischer at al., *A DEPFET based pixel vertex detector for the detector at TESLA*, preprint LC-DET-2002-004;
6. F.Gianotti et al., *Physics potential and experimental challenges of the LHC luminosity upgrade*, preprint hep-ph/0204087.