CAPACITIVELY COUPLED ACTIVE PIXEL SENSORS WITH ANALOG READOUT FOR FUTURE e^+e^- COLLIDERS*

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The physics programme of a future high energy e^+e^- linear collider requires very accurate three-dimensional measurements of particle positions close to the interaction point. Silicon Active Pixel Sensors are an attractive technology for a Vertex Tracker if their single point resolution can be improved further than the performances envisaged for the generation of detectors being developed for the LHC. Capacitively coupled Active Pixel Sensors with an analog readout electronics should bring the solution. The design and production of the first prototypes of these novel detectors as well as the electronics concept are presented.

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1. Introduction

With the completion of the SLC and LEP experiments, the next step in experimentation with e^+e^- colliders at high energies will be at a linear collider. Expected to be built and commissioned by the end of the first decade of the new millennium, the e^+e^- linear collider will complement the physics reach of the LHC hadron collider at CERN in the study of the mechanism of electro-weak symmetry breaking and in the search for new physics beyond the Standard Model. Running at centre-of-mass energies $\sqrt{s}$ ranging from the Z^0 pole to about 1 TeV with high luminosities, the linear collider has the potential of delivering large data samples well suited for precision measurements and particle searches. These studies set stringent requirements on the efficiency and purity in identifying the flavour of hadronic jets, since short-living b and c quarks are the main signatures of many of the processes of interests. Therefore high accuracy in reconstructing the trajectories of charged particles close to their production point is necessary to ensure efficient jet flavour tagging based on the topological reconstruction of decay vertices.

If a Higgs boson exists at masses 100 GeV/c^2 $< M_H <$ 150 GeV/c^2 as predicted by the electro-weak fits it will be important to carry out precision measurements as a proof of discovery and to identify its Standard Model or Supersymmetric nature [1]. This will require to measure with high accuracy its decay rate to $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, gg and WW^* pairs and possibly to detect deviations from the Standard Model predictions. The study of top-quark decays at energies around the $t\bar{t}$ threshold and the measurement of the Higgs-top Yukawa couplings require efficient tagging of b-jets due to the dominant $t \to Wb$ transition. If Supersymmetry is realised in Nature, the study of its rich Higgs sector will require b-tagging to isolate the signal for the A^0 decay and again b or c-tagging for the search of the charged Higgs $H^\pm$ according to its mass. Finally jet flavour tagging will be important in the study of the scalar quark sector while τ identification may be relevant to investigate the expected phenomenology of Gauge Mediated Supersymmetry Breaking (GMSB) models.

2. The Linear Collider Vertex Tracker

In order to meet the aims of this physics programme, it is necessary to design a performant Vertex Tracker continuing the developments started with the construction of the Vertex detectors for the LEP and SLC experiments and presently continued to match the LHC requirements. A useful figure of merit for the track reconstruction accuracy is the resolution σ_d in the impact parameter d, defined as the point of closest approach of the extrapolated particle trajectory to the beam collision point.

At typical linear collider centre-of-mass energies, the mean decay distance of a b hadron from $H^0 \to b\bar{b}$ is about 1.0 cm and the corresponding impact parameter is 150 μm. This is smaller for charm particles, scaling with their lifetime, and b-jets from top decays, due to the higher jet multiplicity and thus lower boost. Therefore, a resolution of 10 $\mu\mathrm{m} \bigoplus \frac{30\ \mu\mathrm{m}GeV/c}{p\sin^{3/2}\theta}$, or better, has to be obtained for efficient jet flavour tagging. In a simple model with two measured points having resolution σ_{point}, located at radii R_{in} and R_{out}, the impact parameter resolution σ_d is given by:

$$\sigma_d = \sqrt{\sigma^2_{\mathrm{asympt}} + \sigma^2_{\mathrm{ms}}}; \qquad \sigma_{\mathrm{asympt}} = \sqrt{(n+1)^2 + n^2}\sigma_{\mathrm{point}}$$

where $n = \frac{R_{\mathrm{in}}}{R_{\mathrm{out}} - R_{\mathrm{in}}}$. The impact parameter resolution, in absence of multiple scattering contributions, for a given single point resolution of the detector, depends on the radius of the first point of measurement. The multiple scattering contribution σ_{ms} is given by $\sigma_{\mathrm{ms}} = \frac{\sqrt{\sum_i R_i^2 \theta_{0,i}^2}}{p\sin^{3/2}\theta}$, where i runs over the material surfaces up to and including the first measured point and θ_0 is the multiple scattering angle for normal incidence particles. This makes desirable to install the first layer of detectors at the minimum radius allowed by the backgrounds generated by the colliding beams.

The expected backgrounds at the interaction region of a linear collider are mostly due to particles pairs produced in the electromagnetic interactions of the electrons and positrons of the colliding bunches. These represent an irreducible source of spurious particle hits, which interfere with the reconstruction of the particles from the main physics processes of interest. The number of particles from pairs intercepting a surface located at a given radius r depends on the intrinsic p_t acquired by the particle at its production and on its subsequent deflection arising from the electromagnetic interaction with the opposite beam. As a result, particles are confined spiralling in an envelope defined by the maximum angle of deflection and by the strength of the solenoidal magnetic field. This defines the inward bound for the first detector layer and its maximum length.

An additional background source that needs to be taken into account in the choice of the detector technology is due to the neutrons produced by the dump of both particles from pairs and of beamstrahlung photons. The computation of the neutron flux at the interaction region requires careful modelling of their production and transport in the accelerator tunnel and in the detector and is subject to significant uncertainties. Estimated fluxes have been of the order of a few times 10^9 n cm^{-2} year^{-1}.

At the radius of the innermost layer of 1.2 cm to 2.2 cm, the anticipated hit density, due to the particles from both pairs and hadronic jets, exclude the use of the silicon strip detectors adopted by the LEP experiments thus requiring smaller sensitive cells. There are two types of silicon detectors, already used in experiments in high energy physics, both providing the performances required for the Vertex Tracker in terms of single point resolution and pixel size. These are the Charge Coupled Devices (CCD) and the Active Pixel Sensors (APS). CCD detectors have been successfully used in the vertex detector of the SLD experiment at the SLC collider at SLAC. Their application in the vertex tracker at a high energy linear collider has been already proposed [2]. CCD detectors have ideal characteristics in terms of single point resolution and multiple scattering contribution. However they presently lack the required readout speed to cope with the bunch structure of the proposed TESLA collider based on superconducting RF cavities and are potentially sensitive to neutron damage. An alternative design based on the APS pixel detectors has been also proposed [3].

The use of APS pixel detectors at collider experiments has been pioneered in the upgraded Vertex Tracker of the DELPHI experiment at LEP [4]. Such detectors are presently included in the trackers of the ATLAS, CMS and ALICE experiments at the LHC. Compared to CCD sensors, APS detectors have the advantages of allowing fast readout, reducing the occupancies, and being tolerant to neutron fluxes well in excess to those expected at the linear collider. On the other hand, improvements in the single point resolution and in the thickness of each detector layer need to be made to meet the requirements of efficient jet flavour tagging and discrimination of c from b jets.

3. Design considerations for the Capacitively Coupled Active Pixel Sensors

Active Pixel Sensors currently used in high energy physics experiments consist of a matrix of detector cells bump bonded with the corresponding matrix of readout electronics cells. The minimum size of the detector cell is limited by the space required for the single cell of the readout electronics. In the case of detectors designed for the ATLAS and CMS Vertex Trackers cell sizes are 300×50 μm and 150×150 μm, respectively. Their further minimisation looks difficult. Such cells are too big to obtain the required space point resolution for the Vertex Tracker at a future e^+e^- linear collider as described in the previous Section.

One should be able to achieve the required resolution by applying the concept of capacitively coupled detection elements to the Active Pixel Sensors. This concept has been used with great success in silicon strip detectors for many years [5]. For example, strip detectors with a readout pitch four times bigger than their strip pitch and with three interleaved strips capacitively coupled to the readout strips give the point resolution only slightly worse than the detectors with the same strip pitch and all the strips being read out. The only difficulty in the construction of such detectors is a proper evaluation of different capacitances (to the readout electronics, to the detector backplane and to the neighbouring strips) to avoid significant loss of the particle signal. As the single cell capacitance for the APS detectors is much smaller than for the strip detectors, their construction could be more difficult. It allows, however, to overcome the basic difficulty i.e. the building of a detector with sufficiently small detector cells to achieve the required measurement precision and keeping at the same time enough space for the readout electronics.

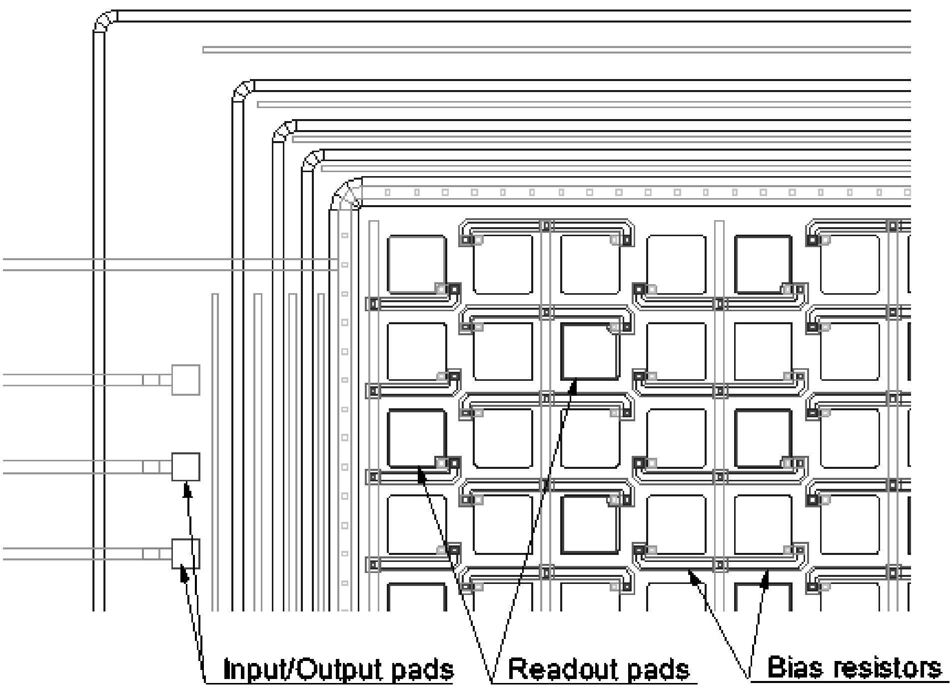

Fig. 1. Layout of the corner of one of the prototype detector structures.

During 1998 we had been working on the design and production of the first prototypes of the capacitively coupled APS detectors. A small part of one of the proposed structures is shown in figure 1. Every fourth pixel in each row and every second pixel in each column is the readout pixel. Each single pixel is biased through a bias line and a polisilicon resistor. The whole detector structure is surrounded by a series of guard-rings to enable the detector to work at high voltage (necessary to deplete detectors partially degraded by the radiation). The input and output pads for the whole detector are also provided (on the left side of the structure).

Altogether 17 different types of detector structures were designed. They differ by pixel sizes (50×50, 100×100, 50×100, 100×200 μm^2), readout pitches (200 μm or 300 μm in both dimensions), numbers of interleaved pixels (0, 1 or 3) and total sizes (one or four electronics chips to be bump bonded). They should give us a better understanding of these novel detectors and of their further optimisation for the next production run with a final size of pixels (25×25 μm^2).

4. Production of the prototype detectors

The first 360 prototype detector structures were produced during the fall of 1998 [1]. Ten wafers of 4-inch diameter, high resistivity (4–8 kΩcm) n-type silicon from Wacker were used for that. Each wafer contained 36 detector structures of 17 different types as mentioned in the previous Section. In addition, ten low resistivity wafers were processed serving for tests, training and as a reference sample. In particular, high temperature technological processes were monitored by performing the production tests on these additional wafers.

The following technological sequence was employed. A standard cleaning (as for an advanced MOS technology) was performed before each high temperature technological step. First, all wafers were oxidized (using HCl gettering) to form a 700 nm thick silicon dioxide layer. Next, the phosphorus glass deposition from $POCl_3$ source was performed, followed by the drive-in process in oxidizing ambient. The diffusion of phosphorus formed a highly dopped n-type layer on the backside of the wafers to decrease resistance and get good ohmic contact with the backside metal grid.

Next, the pixel and guard-ring windows were defined by photolitography applying the wet etching technique. The boron diffusion from solid source had been carried followed by the drive-in processes. The resulting main detector junctions were 0.7 μm deep and had a resistance of U/I=15Ω. Then, the coupling capacitor for the detector readout was produced by forming the 200 nm thick high quality SiO_2 layer at 1000°C. This step was carefully monitored to achieve extremely low density of mobile ion charge.

To fabricate bias resistors, the 500 nm thick polisilicon layer was deposited and implanted with boron. A special high temperature annealing was optimised to obtain the required sheet resistance of 250 k$\Omega/\Box$ The resistors pattern was defined by photolitography. To ensure a good quality of the metal connections, the surface was planarised by means of BPSG (Boron-Phosphorus-Silicon Glass) chemical vapour deposition (CVD) followed by

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the high temperature annealing. Coating of the resistors was defined by photolitography applying plasma and wet etching techniques. The next mask defined contact windows to the resistors. To decrease contact resistance the boron implantation was used.

The planarisation of the pattern was achieved by annealing wafers in different ambients. This process requires further optimisation. Next photolitography defined contacts to p^+ regions. They were produced by the wet etching process. The metal connections were fabricated by sputtering of a 1.2 μm thick Al-Si-Cu layer followed by photolitography and plasma etching. The backside metalisation grid was made by evaporation of Al and then by wet etching. Finally all the wafers were sintered in hydrogen ambient during at 450°C during 20 minutes.

5. First results of measurements

Initial electrostatic measurements of some selected structures were done as post-production checks in the Institute of Electron Technology in Warsaw in January 1999. The detectors were then delivered to other participating laboratories in February this year. Now the systematic measurements of all detector structures are being performed. They show that the detectors are functional, but the relatively low yield of the good structures shows the need for a careful check of the production steps. Good structures have very nice electrostatic characteristics. This is illustrated in figure 2 where the leakage current and the capacitance ($1/C^2$) results as functions of the applied voltage are shown. The leakage current is very low. The full depletion of the detector is achieved at low voltage. The measured capacitance of the fully depleted detector is as expected. The full summary of the electrostatic measurements will be given elsewhere [6].

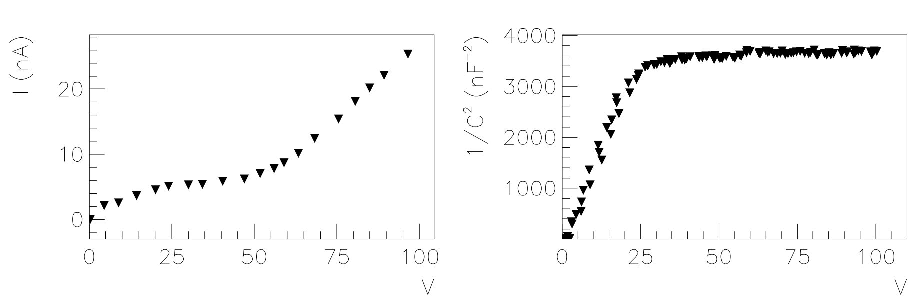

Fig. 2. I-V (left plot) and C-V (right plot) characteristics of a good detector (number 18 on wafer 5).

6. Requirements for the readout electronics

At present only some initial ideas concerning the readout electronics for our detectors can be given. The detailed requirements like those related to the noise matching or signal level depend directly on the detector parameters currently being measured. Some other requirements are driven by the experimental conditions which are under study as well. Ideas presented below are, therefore, based on the general rules governing the front-end systems for silicon strip and pixel detectors designed in the CMOS technology. It should be stressed, however, that the requirement of having the analog readout electronics for APS detectors is rather unusual. Nowadays, most of the circuits associated with the pixel detectors exploit the ideas of the fully binary readout or of the events counting methods. The expected small signal on some pixels, the intrinsic noise and the capacitive charge sharing make the analog readout a challenge.

It is proposed to use a standard low noise and low power topology consisting of an integrating preamplifier followed by a CR-RC type shaping filter in the amplifying stage. Both parts will be based on the folded cascode architecture with a PMOS transistor, chosen for its lower 1/f noise coefficient, at the input. These elements of the analog chain, a circuit containing the store capacitance and the small part of the system controlling the readout process are designed for each individual readout pixel. Thus they will occupy space under the pixel and its capacitively coupled neighbours. This electronics cell will be directly connected to a single detector readout cell by means of a bump bond.

We plan to use the readout system based on a two dimensional sparse data scan method, which has been successfully applied to the pixel detectors of the DELPHI Silicon Tracker [4]. It will be adapted to the new conditions of the capacitively coupled pixels so that not only the most activated pixel will be read out but also a certain number of the neighbouring readout pixels. The sparse data scan requires a definition of the threshold signal for each pixel. When a pixel signal exceeds the threshold, the associated logic will cause reading out of the main pixel and of the requested neighbours. Apart from these analog signals a digital position code of the main pixel will be kept for further use.

The threshold values and other system parameters like bias current and voltage values will be programmed by means of a slow control circuit. For this circuit we propose the digital serial interface (I2C) with an appropriate number of internal 8 bit long registers and a block of the bias generator with current and voltage mode Digital Analog Convertors. This control part can be placed in the free space between output pads and pixels.

The exact design of the individual chips, of their control systems, of data transmission as well as the choice of the fabrication technology need further work.

7. Conclusions

Active Pixel Sensors with interleaved pixels capacitively coupled to the readout pixels can give a single point resolution good enough for the Vertex Tracker at a future e^+e^- linear collider. First prototypes of these novel detectors have been designed and produced. Initial tests show that there is no obvious design fault but that the production technology could be improved. Basic ideas of the analog readout electronics for these detectors exist and dedicated work on the design will start soon.

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