High Resolution Hybrid Pixel Sensors for the e^+e^- TESLA Linear Collider Vertex Tracker

M. Battaglia, R. Orava, K. Tammi, K. Österberg

Department of Physics and Helsinki Institute of Physics,
P.O. Box 9, FIN–00014 University of Helsinki, Finland

W. Kucewicz

Department of Electronics, University of Mining and Metallurgy,
al. Mickiewicza 30, PL–30055 Krakow, Poland

A. Zalewska

High Energy Physics Laboratory, Institute of Nuclear Physics,
ul. Kawiory 26a, PL–30055 Krakow, Poland

M. Caccia, R. Campagnolo, C. Meroni

Dipartimento di Fisica, Universita' di Milano and I.N.F.N.,
Via Celoria 16, I–20133 Milano, Italy

P. Grabiec, B. Jaroszewicz, J. Marczewski

Institute of Electron Technology,
al. Lotnikov 32/46, PL–02468 Warszawa, Poland

In order to fully exploit the physics potential of a future high energy e^+e^- linear collider, a Vertex Tracker, providing high resolution track reconstruction, is required. Hybrid Silicon pixel sensors are an attractive option, for the sensor technology, due to their read-out speed and radiation hardness, favoured in the high rate environment of the TESLA e^+e^- linear collider design, but have been so far limited by the achievable single point space resolution. In this paper, a conceptual design of the TESLA Vertex Tracker, based on a novel layout of hybrid pixel sensors with interleaved cells to improve their spatial resolution, is presented.

Key words: pixel; vertex detector; linear collider

1 The requirements of the linear collider physics programme

The next generation of high energy e^+e^- experiments, following the LEP and SLC programs, will be at a linear collider, operating at centre-of-mass energies ranging from the Z^0 pole up to about 1 TeV. Expected to be commissioned by the end of the first decade of the new millennium, the linear collider will complement the physics reach of the Tevatron and LHC hadron colliders in the study of the mechanism of electro-weak symmetry breaking and in the search for new physics beyond the Standard Model. Both precision measurements and particle searches set stringent requirements on the efficiency and purity of the flavour identification of hadronic jets since final states including short-lived b and c-quarks and τ leptons are expected to be the main signatures. High accuracy in the reconstruction of the charged particle trajectories close to their production point is required in order to reconstruct the topologies of the secondary vertices in the decay chain of short-lived heavy flavour particles.

If a Higgs boson exists with mass below 150 GeV/c^2, as indicated by the fit to the present electro-weak data (1), it will be essential to carry out precision measurements of its couplings to different fermion species as a proof of the mass generation mechanism and to identify its Standard Model or Supersymmetric nature (2). This can be achieved by accurate determinations of its decay rate to $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, W^+W^- and gluon pairs to detect possible deviations from the Standard Model predictions (3). Since the rates for the Higgs decay modes into lighter fermions $h^0 \rightarrow c\bar{c}$, $\tau^+\tau^-$ or into gluon pairs are expected to be only about 10% or less of that for the dominant $h^0 \rightarrow b\bar{b}$ process, the extraction and measurement of the signals of these decay modes requires suppression of the $b\bar{b}$ contribution by a factor of twenty or better while preserving a good efficiency.

The measurement of the top Yukawa coupling (4) as well as the top-quark mass measurement will require efficient b-tagging to reduce combinatorial background in the reconstruction of the six and eight jet final states. If Supersymmetry is realized in nature, the study of its rich Higgs sector will also require an efficient identification of b-jets and τ leptons to isolate the signals for the decays of the heavier A^0, H^0 and $H^\pm$ bosons from the severe combinatorial backgrounds in the complex multi-jet hadronic final states. Due to the expected large b-jet multiplicity, highly efficient tagging is required to preserve a sizeable statistics of the signal events. Finally, both b and c-tagging will be important in the study of the quark scalar partners, while τ identification may be instrumental in isolating signals from Gauge Mediated Supersymmetry Breaking (5).

A set of curves representative of the performance of a jet flavour tagging algorithm at the linear collider are given in Figure 1 under two different as-
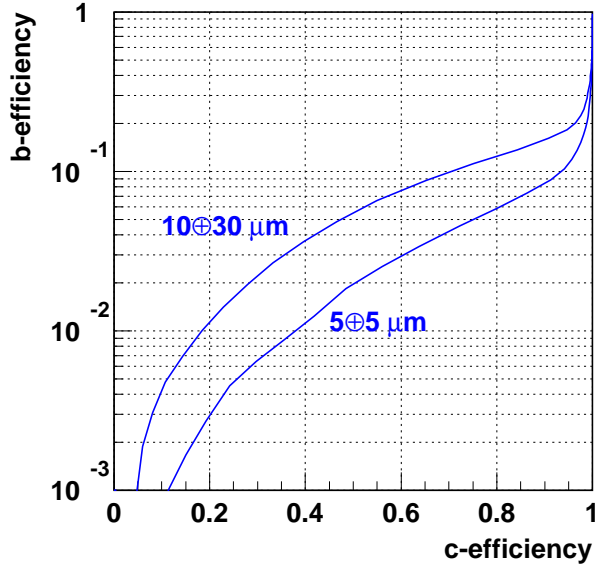
Fig. 1. The *b*-quark background efficiency as a function of the *c*-quark signal efficiency for a *c*-tag algorithm based on topological vertexing and impact parameters, developed on the basis of the experience from the SLC and LEP experiments, (6). The two curves show the expected performance for two different assumptions on the track impact parameter resolution.

sumptions for the track impact parameter resolution. The requirement of efficient *c* identification with a rejection factor against *b*-jets of more than ten, highlights the need of track impact parameter resolution $\sigma_{I.P.}$ better than $10~\mu m \oplus \frac{30~\mu m~\text{GeV}/c}{\text{p}~\sin^{3/2}\theta}$ in both projections. It is important to minimise the multiple scattering contribution to the impact parameter resolution. In fact, b/c discrimination is obtained mostly by probing the difference in charged decay multiplicities and invariant masses of the B and D hadrons. This requires to identify the majority of charged decay products that have typical momenta of a few GeV/c in multi-jet events. A precise determination of the track perigee parameters close to their production point also assists in the track reconstruction and improves the momentum resolution. The addition of the Vertex Tracker space points with 7 μm resolution to those from a TPC main tracker improves the estimated momentum resolution σ_p/p^2 from $1.5 \times 10^{-4}~(\text{GeV}/c)^{-1}$ to $0.6 \times 10^{-4}~(\text{GeV}/c)^{-1}$ for charged particles of large momentum. The design of the linear collider Vertex Tracker and the choice of the sensor technology are driven by these requirements, to be achieved within the constraints set by the accelerator induced backgrounds at the interaction region and by the characteristics of the physics events. In the next section these constraints are discussed with specific reference to the TESLA linear collider project, while section 3 presents the conceptual design proposed for the Vertex Tracker. The silicon pixel sensor technology, developed to overcome the hybrid pixel sensor limitations in terms of single point space resolution, is discussed in details in section 4.

3

2 The experimental conditions at the TESLA interaction region

Several concepts have been developed for the acceleration, preservation of low emittance and final focusing of electron and positron beams at energies in excess of 200 GeV/beam (7). The TESLA project (8) has proposed to use superconducting accelerating structures, operating at L-band frequency that delivers very long beam pulses ($\sim$ 900 μs) accelerating up to 4500 bunches per pulse. This scheme allows a large bunch spacing (190-340 ns) making it possible to resolve single bunch crossings (BX) and also to perform fast bunch-to-bunch feedback needed to stabilize the beam trajectory within a single pulse, thus preserving the nominal luminosity of 3-5 $\times 10^{34}$ cm^{-2} s^{-1}. The large luminosity of each individual bunch-crossing (2.2×10^{-3} nb^{-1} BX^{-1}) and the large number of bunches in a single pulse imply a high rate of background events that need to be minimised by identifying the bunch corresponding to the physics event of interest.

A primary source of background at the linear collider interaction region is the incoherent pair production in the electromagnetic interactions of the colliding beams. These particles are confined by the solenoidal magnetic field, spiralling in an envelope defined by the field strength, B, and their intrinsic transverse momentum acquired at production and the subsequent deflection in the electric field of the opposite beam. The pairs represent an irreducible source of spurious particle hits, which interferes with the reconstruction of the particles from the physics processes of interest. The maximum radius and longitudinal position of crossing of the envelope of deflected pairs defines both the inward bound for the first sensor layer and its maximum length. At 1.2 cm radial distance from the TESLA colliding beams, with a magnetic field $B = 3$ T, the hit pair density is expected to be $\simeq 0.2$ hit mm^{-2} BX^{-1} with $\pm$ 5 cm available in the longitudinal coordinate to fit the first sensitive layer of the detector. An additional background source that needs to be taken into account in the choice of the sensor technology is the flux of neutrons photo-produced at the dump of electrons from pairs and radiative Bhabha scattering and of beamstrahlung photons. The computation of this neutron flux at the interaction region relies on the modelling of their production and transport in the accelerator tunnel and in the detector and is subject to significant uncertainties. Estimated fluxes are of the order of a few 10^9 n (1 MeV) cm^{-2} year^{-1} (9; 10), where the anticipated neutron flux has been normalised in terms of equivalent 1 MeV neutrons assuming NIEL scaling. Finally the large $e^+e^- \rightarrow \gamma\gamma$ cross-section requires single bunch identification and high resolution on the longitudinal position of production of forward charged particles in order to suppress to a few % the rate of two photon background overlap with physics events.

In addition to these background sources, the occupancy from the charged particles inside dense jets in multi-parton hadronic final states has to be con-

4

sidered. A study of $t\bar{t}$ and $h^0 Z^0$ events at $\sqrt{s} = 500$ GeV showed that at 3.0 cm from the interaction point, about 20 % (10 %) of the particles in the jet have at least one additional hit from another particle of the same jet within a 150 μm distance in the $R - \Phi$ ($R - z$) plane, which corresponds to the typical two-track separation capability of a microstrip detector. Therefore, sensors with small sensitive cells have to be used in order to avoid a large number of merged hits and ambiguities in the pattern recognition.

In summary, the linear collider Vertex Tracker must be able to provide a track impact parameter resolution better than $10 \ \mu m \oplus \frac{30 \ \mu m \ GeV/c}{\mathrm{p} \ \sin^{3/2} \theta}$ in both the $R - \Phi$ and $R - z$ projections for jet flavour identification, identify single bunch crossings separated by about 200 ns to reduce pair and $\gamma\gamma$ backgrounds and have sensitive cells of $150 \times 150 \ \mu m^2$ or less to keep the occupancy from pairs and hadronic jets below 1%. There are two types of such silicon sensors, already used at collider experiments, that have the potential to satisfy these specifications in terms of sensitive cell size: the Charged Coupled Devices (CCD) and hybrid pixels sensors. The CCD sensors have successfully been used for the SLD Vertex Detector at the SLC collider at SLAC (11) while hybrid pixel sensors, pioneered by the WA-97 experiment at CERN (12), have been adopted at LEP in the upgraded DELPHI Silicon Tracker (13). These have been further developed for the ALICE (14), ATLAS (15) and CMS (16) experiments to meet the experimental conditions of the LHC collider. CCD detectors have been already proposed for the linear collider Vertex Tracker (17). While CCD's have ideal characteristics in terms of spatial resolution and detector thickness, they presently lack the required read-out speed necessary to cope with the TESLA bunch timing and are possibly sensitive to neutron damage at fluxes of the order of that expected at the linear collider. An intense R&D program is presently underway to overcome these limitations (18). The use of hybrid pixel sensors for the linear collider Vertex Tracker was also proposed a few years ago and a first conceptual design of the detector was defined (19). Compared to the CCD's, hybrid pixel sensors have the advantage of allowing fast time stamping and sparse data scan read-out, thereby reducing the occupancies due to backgrounds, and of being tolerant to neutron fluxes well beyond those expected at the linear collider. Both these characteristics have been demonstrated for their application in the LHC experiments. On the other hand, there are areas of R&D that are specific to the linear collider, namely the improvement of the pixel sensor spatial resolution and the reduction of its total thickness.

3 The TESLA Vertex Detector design

The proposed layout of the TESLA Vertex Detector (19) based on hybrid pixel sensors is shown in fig. 2 and consists of a three-layer cylindrical detector surrounding the beam-pipe complemented by forward crowns and disks extending

the polar acceptance to small angles. This geometry follows solutions adopted for the DELPHI Silicon Tracker. The first detector layer, closest to the in-
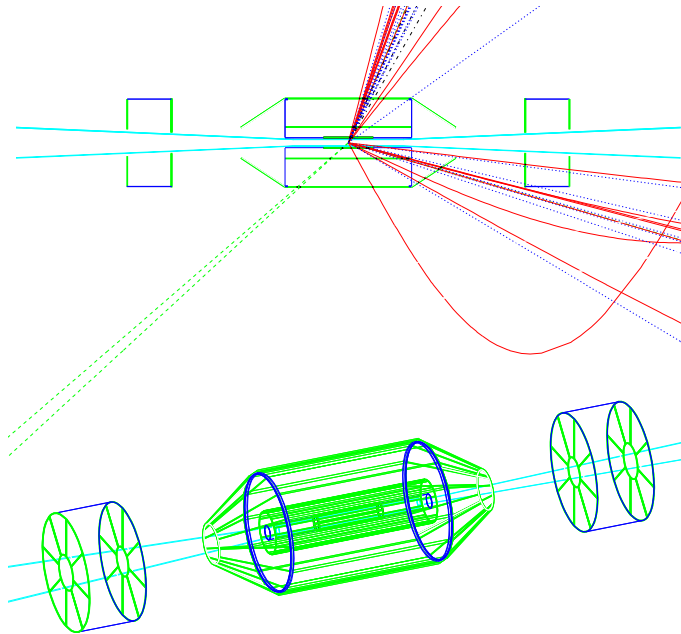

Fig. 2. The proposed layout of the Vertex Tracker with a simulated $e^+e^- \to h^0 Z^0 \to b\bar{b}\mu^+\mu^-$ event overlayed. The three layered barrel section is complemented by a crown and two disks of detectors to ensure accurate tracking in the forward region.

teraction region, is located at a radius of 1.2 cm and has a length of 10 cm. The two additional barrel layers are located at 3.5 cm and 10 cm respectively and have a polar acceptance down to $|\cos\theta| = 0.82$. At lower angles, additional space points are obtained by extending the barrel section by a forward crown and two disks of detectors providing three hits down to $|\cos\theta| = 0.995$. The transition from the barrel cylindrical to the forward conical and planar geometries optimises the angle of incidence of the particles onto the detector modules in terms of achievable single point resolution and multiple scattering. This tracker can be assembled by two independent half-shells, allowing its installation and removal with the beam-pipe in place. Overlaps of neighbouring detector modules will provide an useful mean of veryfing the relative detector alignment using particle tracks from dedicated calibration runs taken at Z^0 centre-of-mass energy. The geometry optimisation and the study of the physics performances of the Tracker design has been performed with a GEANT based simulation of the detector, accounting for benchmark physics processes with enhanced forward production cross-section, such as $e^+e^- \to H^0\nu\bar{\nu}$, pair and $\gamma\gamma$ backgrounds, local pattern recognition and detector inefficiencies. The impact parameter resolution has been obtained by a Kalman filter track fit to the associated hits in the Vertex Tracker and in the TPC. In order to achieve a resolution for the impact parameter reconstruction better than 7 μm for tracks
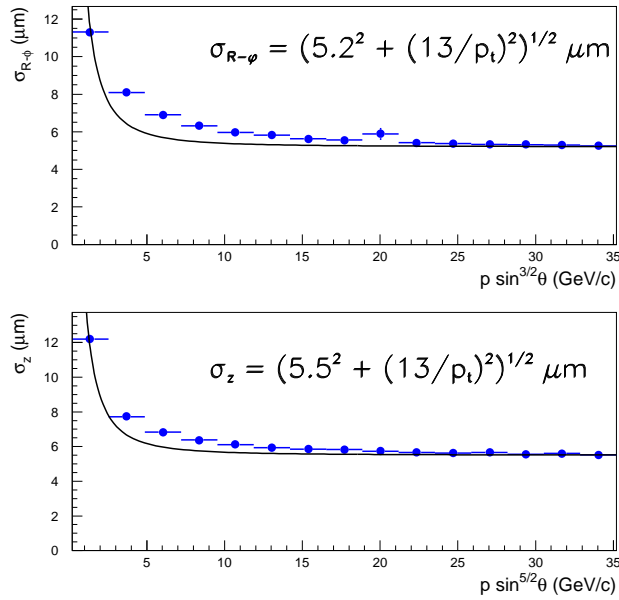
Fig. 3. The expected impact parameter resolution $\sigma_{I.P.}$ in the $R - \phi$ (upper plot) and $R - z$ (lower plot) projections as a function of the particle momentum for the proposed Vertex Tracker assuming a single point resolution of 7 μm corresponding to that obtained for microstrip sensors with 25 μm strip pitch and 50 μm read-out pitch. The curve overlayed to each plot shows the result of a fit to the function $\sigma_1 \oplus \frac{\sigma_2}{p \ \sin^{3/2(5/2)} \theta}$. The departure of the points from the predictions of these parametrisations in the region from 2.0 GeV/c to 10 GeV/c is due to the effect of multiple scattering between the Vertex Tracker and the TPC.

at large momenta, a detector space point accuracy of better than 10 μm must be obtained. The requirement on the multiple scattering contribution to the track extrapolation resolution, lower than 30 μm/p_t, and the need to minimise the amount of material in front of the calorimeters and to ensure the optimal track matching with the main tracking system, set a constraint on the material budget of the Vertex Tracker to less than 3 % of a radiation length (X_0). These requirements can be fulfilled by adopting 200 μm thick detectors and back-thinning of the read-out chip to 50 μm, corresponding to 0.3 % X_0 of a radiation length, and a light support structure. The present concept for the mechanical structure envisages the use of diamond-coated carbon fiber detector support layers acting also as heat pipes to extract the heat dissipated by the read-out electronics uniformly distributed over the whole active surface of the detector. Assuming a power dissipation of 60 μW/channel, the total heat flux is 450 W, corresponding to 1500 W/m^2, for a read-out pitch of 200 μm. Preliminary results from a finite element analysis show that pipes circulating liquid coolant must be placed every 5 cm along the longitudinal coordinate except for the innermost layer where they can be placed only at the detector ends to minimise the amount of material. Signals will be routed along the

7

beam pipe and the end-cap disks to the repeater electronics installed between the Vertex Tracker and the forward mask protecting the Vertex Tracker from direct and backscattered radiation from the accelerator. The material budget for the proposed design is shown in Figure 4.
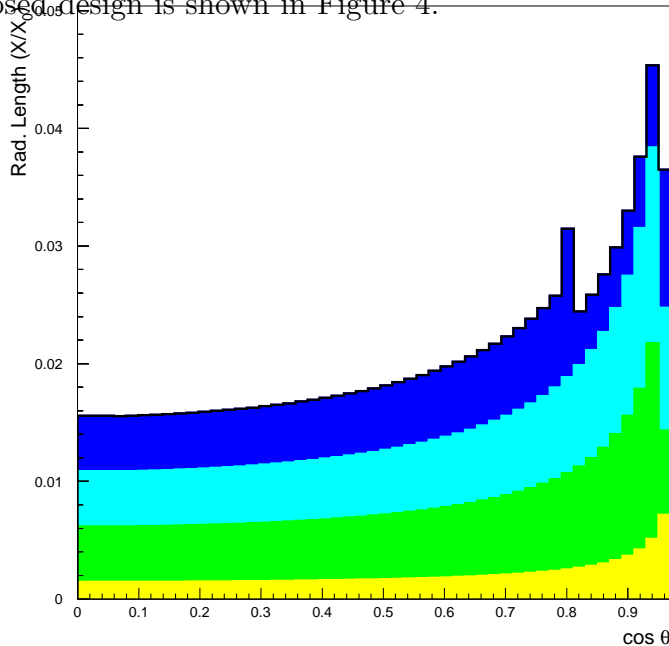

Fig. 4. The material budget given in units of radiation length as a function of $|\cos\theta|$. The contributions of a 0.5 mm Be beam-pipe and of the three detector layers with cables and support structure have been included.

4 Hybrid pixel sensors with interleaved pixels

The desired impact parameter resolution defined in section 1 requires a single point precision in the Vertex Detector better than 10 μm. This can be accomplished sampling the diffusion of the charge carriers generated along the particle path and assuming an analog read-out to interpolate the signals of neighbouring cells. In such a case, the expected resolution is $\sigma = a_{cf} \frac{pitch}{S/N}$, where $a_{cf} \approx 2$ is a centroid finding constant and S/N defines the performance of the front-end electronics in terms of signal amplitude normalised to the noise. Given that the charge diffusion is ~ 8 μm in 300 μm thick silicon, its efficient sampling and signal interpolation requires a pitch of not more than 25 μm. This has been successfully proven to work in one-dimensional microstrip sensors (20). In pixel devices the ultimate read-out pitch is constrained by the front-end electronics, to be integrated in a cell matching the sensor pattern. At present, the most advanced read-out electronics have a minimum cell dimension of 50×300 μm^2 not suitable for an efficient charge sampling. The trend of the VLSI development and recent studies (21) on intrinsic radiation

8

hardness of deep sub-micron CMOS technology certainly allows to envisage of a sizeable reduction in the cell dimensions on a linear collider timescale but sensor designs without such basic limitations are definitely worth being explored.

A possible way out is to exploit the capacitive coupling of neighbouring pixels and to have a read-out pitch n times larger than the implant pitch (22). The proposed sensor layout is shown in Figure 5 for n=4. In this configuration, the charge carriers created underneath an interleaved pixel will induce a signal on the read-out nodes, capacitively coupled to the interleaved pixel. In a simplified model, where the sensor is reduced to a capacitive network, the ratio of the signal amplitudes on the read-out nodes at the left- and right-hand side of the interleaved pixel in both dimensions will be correlated to the particle position and the resolution is expected to be better than (implant pitch)/$\sqrt{12}$ for an implant pitch of 25 μm or smaller. The ratio between the inter-pixel capacitance and the pixel capacitance to backplane will play a crucial role, as it defines the signal amplitude reduction at the output nodes and therefore the sustainable number of interleaved pixels. Calculations with such capacitive network models (23) show that resolutions similar to those achieved by reading out all pixels are obtainable if the signal amplitude loss to the backplane is small. Recent tests on a microstrip sensor, with 200 μm read-out pitch, have achieved a 10 μm resolution with three interleaved strip layout (24). Similar results are expected in a pixel sensor, taking into account both the lower noise because of the intrinsically smaller load capacitance and the charge sharing in two dimensions. Reducing the read-out density, without compromising the achievable space resolution, is also beneficial to limit the power dissipation and the overall costs. In order to verify the feasibility of this scheme, a prototype set of sensors with interleaved pixels and different choices of implant and read-out pitch have been designed, produced and tested. These test structures have been designed in 1998 and delivered in January 1999. Ten high resistivity wafers were processed [1] together with an equal number of low resistivity wafers for process control. A detailed description of the processing can be found in ref. (25). A bias grid surrounding the pixel cells allows the polarisation of both the interleaved and read-out pixels and each p^+ pixel implant is connected to the metal bias line by polysilicon resistors. This is to ensure a similar potential for all pixels and hence a uniform charge collection. A metal layer is deposited on top of the pixels to be bump-bonded to a VLSI cell. The backplane has a meshed metal layer to allow the use of an infrared diode for charge collection studies. Structures with the number of interleaved pixels ranging between 0 and 3 were fitted on a 4" wafer, assuming a VLSI cell size of 200×200 or 300×300 μm^2. All of the structures on six undiced wafers were visually inspected and characteristic I–V and C–V curves were measured up to 250 V. The I–V and 1/C^2–V curves obtained for a good structure are shown

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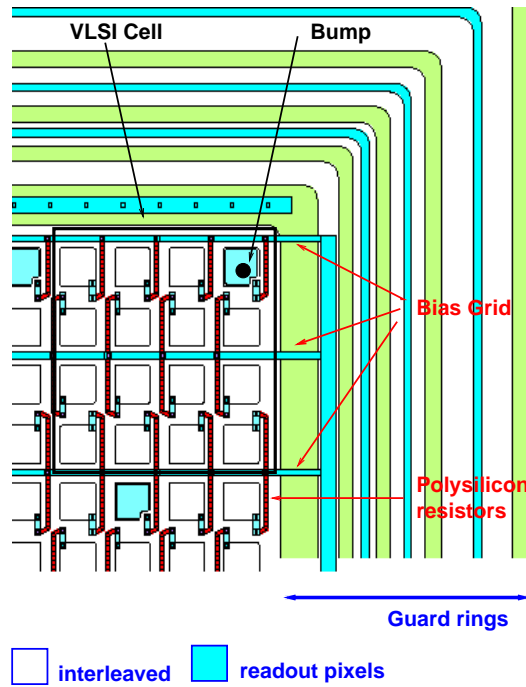[1] at the Institute of Electron Technology, Warszawa, Poland

Fig. 5. Layout of the upper corner of pixel detector test structure, with 50 μm implant and 200 μm read-out pitch.

in fig. 6. Two wafers have extremely good characteristics, with a mean current of $\sim$ 50 nA/cm^2 and about 50% of good structures. The test structures have not shown any design fault even if processing and layout optimisation has to be considered. A more detailed summary of the measurements can be found in ref. (26). On a short term, measurements of the inter-pixel and backplane capacitances are planned, completing the electrostatics characterisation of these sensors. A charge collection study will follow, relying on a low noise analog
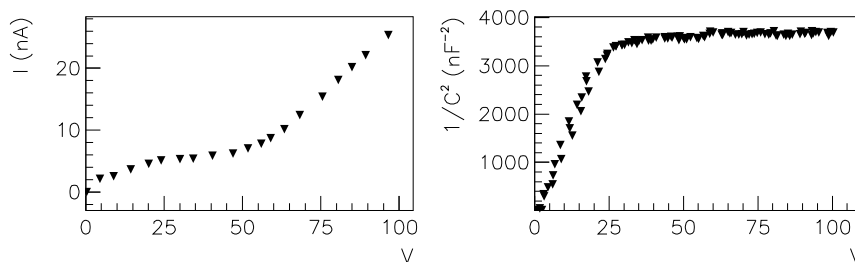

Fig. 6. I–V and 1/C^2–V curves for a good sensor structure

chip designed for microstrip sensor read-out and shining an infrared light spot on the meshed backplane. These measurements will be a proof of principle of

the proposed device and define the guidelines for further iterations, aiming at a 25 μm pitch.

The device thickness is a particularly relevant issue for the application of hybrid pixel sensors at the linear collider. The minimal thickness is set by the combination of the sensor noise performance and the limit of back-thinning technology for a bump-bonded assembly. Industrial standards guarantee back-thinning down to 50 μm for the electronics and procedures to obtain thin sensors are currently being tested (27). The small load capacitance of the pixel cells should guarantee an extremely good S/N. Scaling what has been obtained for the microstrip sensors, the desired resolutions should be obtained with a 200 μm thick sensor.

5 Conclusion

Hybrid pixel sensors are an attractive option for a linear collider Vertex Tracker owing to their fast read-out and radiation hardness, well suited to the high repetition rate of the TESLA design. The main present limitations of this option are the achievable single point space resolution and sensor thickness. To overcome these limitations, pixel sensor design with interleaved cells is proposed. Test structures with different configurations of interleaved cells have been designed and produced and the results of their first electrostatic characterisation are discussed. The conceptual design of a Vertex Tracker based on these detectors has been developed and its performances have been evaluated, using a detailed simulation accounting for the relevant background processes, and the preliminary results have been presented.

Acknowledgements

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