Measurement of the spatial resolution of double-sided double-metal AC-coupled silicon microstrips detectors

R. Brenner, R. Harr ¹, A. Rudge, D. Santos ², J. Straver and P. Weilhammer

CERN, Geneva, Switzerland

A. Czermak, S. Gadomski and M. Turala

Institute of Nuclear Physics, Crakow, Poland

V. Bonvicini, W. Kuczewicz ³, S. Masciocchi and G. Vegni

INFN and University of Milan, Italy

A. Peisert

INFN, Padova, Italy

J. Ardelan, A. Hriioho, K. Troung and F. Couchot

LAL, Orsay, France


LEPSI, Strasbourg, France

A. Smith

University of Liverpool, UK

R. Apsimon, P. Seller and M. Tyndel

Rutherford Appleton Laboratory, Didcot, Chilton, UK

M. Aalste, I. Hietanen, J. Lindgren, K. Osterberg, R. Orava, C. Ronnqvist, T. Tuuva

and M. Voutilainen

SEFT, Helsinki, Finland

The design and first results from double-sided silicon microstrip detectors designed for use in the DELPHI experiment at LEP are presented. The detectors are AC-coupled on both the n- and p-side. A novel readout scheme using a second metal layer has been implemented, allowing the readout of both coordinates on the same edge of the detector. The detectors have been tested in a high energy beam at the CERN SPS. Results on spatial resolution, pulse-height correlation and charge division are presented. The spatial resolution of the n-side has been measured as a function of the beam particle incident angle from 0 to 60°.

1. Introduction

Silicon strip detectors are today strongly demanded as precise vertex detectors in high energy physics experiments. Single-sided detectors, with p strips on n
doped silicon have been used in high energy experiments for more than ten years [1]. At this time only one experiment (ALEPH at LEP) has used double-sided detectors [2], but in recent years many efforts have been put into the development of these detectors (see for example [3–5]). Double-sided detectors are also serious candidates as high resolution vertex detectors for the future colliders LHC and SSC [6,7].

The main technological problem encountered in the development of double-sided detectors is to create resistively separated strips on the n-side. Fixed positively charges are always present in the oxide at the Si–SiO₂ interface. These charges cause an accumulation layer of electrons to form on the silicon side of the interface. In the n-doped bulk silicon, this layer acts as a low resistance conduction path. As a consequence the signal spreads between several strips and the position information is lost.

One way to overcome this problem is to add additional “p-stop” implants between n⁺ strips. This is the solution adopted by the ALEPH experiment, and laboratory as well as beam test measurements have proven its effectiveness [2,3].

A few years ago we started developing a new kind of double-sided detector [8]. In order to ensure the ohmic separation between n⁺ strips we make use of the MOS structure naturally available in AC-coupled detectors. The aluminium electrode of the MOS coupling capacitors is made larger than the underlying n⁺ strips. The potential difference existing between the silicon and the metal electrode serves to control the free carrier silicon charge density below that part of the electrode that extends beyond the n⁺ strips. Thus the interstrip resistance can be voltage-controlled [9,10]. The field plate solution allows to keep the design of the n-side as close as possible to that of the p-side. Moreover, due to the absence of additional strips between the n⁺ strips, a reduced readout pitch can be designed and thus better spatial resolutions can be achieved.

At collider experiments another practical problem occurs. Strips on the two sides of the detectors end up on two orthogonal edges. In a barrel geometry the readout of Z strips is thus quite clumsy [2]. Mounting the electronics just by the end of the Z strips means adding material in front of the other detectors, thus increasing multiple scattering in the central region of the spectrometer. In our prototypes, we have integrated the fanout on the detector, using a second metal layer. In this way, the readout of both sides is made on the same edge.

2. Design

The design of the double-metal detectors (see fig. 1) follows from that of the AC-coupled single-sided det-
tectors successfully used by the DELPHI collaboration [11]. The main parameters of the two prototypes we tested are shown in Table 1. They were manufactured by S.I. (Oslo, Norway) and V.T.T. (Helsinki, Finland). MOS capacitors for AC-coupling are integrated on the detector itself. Each strip is individually biased via a polysilicon resistance connected to an aluminium bias bus. On the n-side, the ohmic separation is obtained by field shaping [8]. The first metal layer lines play the double role of field shaping electrodes and of metal plate of the MOS coupling capacitors. They are larger than the underlying n+ strips. In order to avoid resistive coupling of the n+ strips to the guard ring, at one edge of the strip the field electrode ends with a ring under the short metal lines connecting the bias resistors and the n+ strips. At the other edge it is longer than the n+ strips. Strips on the second metal layer are orthogonal to the strips in the first metal layer. On one edge they end in four rows of bonding pads. Each line of the first metal layer is connected to a line on the second metal layer. The two metal layers are separated by a thick insulator layer. Since in DELPHI, as well as in other collider experiments, the geometry is such that there are more z strips than rφ ones, we have tested different multiplexing schemes (see ref. [12] for more details).

3. Electrical measurements

The main electrical parameters of our detectors have been measured in the laboratory prior to the beam tests. Table 2 summarizes the results.

The coupling capacitance has been measured with the quasistatic CV method. The polysilicon resistors and the resistance between adjacent strips on the n-side were measured by applying a high voltage to the diffusion strips on the n-side, and keeping the diffusion lines on the p-side and the readout lines on both sides at ground potential. The values quoted in Table 2 were measured when detectors were fully depleted. Fig. 2 shows the variation of the interstrip resistance with the applied voltage measured on the VTT detector.

The capacitance of a single strip to the adjacent lines was measured in the same conditions on the n-side. This capacitance is a convolution of a direct capacitance between diffusion lines and the capacitance of the metal lines in the two layers. The first term decreases rapidly with the distance between strips [13], while the second has a long range. A simple model which allows calculation of this contribution is proposed in reference [12]. In this model the double metal layer makes each strip couple to all the others, no matter what is the distance between them. This effect can be seen by measuring the capacitance of one strip to its neighbours connected together. Fig. 3 (from ref. [13]) shows this capacitance as a function of the number of adjacent strips measured on the VTT detector.

<table>
<thead>
<tr>
<th>Detector parameters</th>
<th>VTT</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polysilicon resistance [MΩ]</td>
<td>10</td>
<td>5.5</td>
</tr>
<tr>
<td>Coupling capacitance [pF/cm]</td>
<td>10.5</td>
<td>5.9</td>
</tr>
<tr>
<td>Interstrip resistance [GΩ]</td>
<td>&gt; 1</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>n-side</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polysilicon resistance [MΩ]</td>
<td>26</td>
<td>9</td>
</tr>
<tr>
<td>Coupling capacitance [pF/cm]</td>
<td>19.5</td>
<td>20</td>
</tr>
<tr>
<td>Interstrip resistance [GΩ]</td>
<td>&gt; 0.4</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>Detector leakage current [μA]</td>
<td>0.3</td>
<td>7.5</td>
</tr>
<tr>
<td>Guard ring leakage current [μA]</td>
<td>0.01</td>
<td>350</td>
</tr>
<tr>
<td>Depletion voltage [V]</td>
<td>60</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 2. Interstrip resistance on the n-side of the VTT detector measured as a function of the bias voltage.

Fig. 3. Capacitance of one strip with respect to the neighbours as a function of the number of neighbours (figure appeared in ref. [13]).
4. Beam test setup

Tests were performed in the West Area at the SPS, CERN. During most of the data taking period, we used a pion beam with a momentum of 70 GeV/c. At this energy and for our setup, the multiple scattering is not negligible. This point is taken into account in the off-line analysis (see section 5).

Reference detectors are of the same type as the ones used in the DELPHI Microvertex. They are single-sided, AC-coupled microstrip detectors, with integrated capacitors. Their size is $32 \times 60$ mm, $1280$ $p^+$ strips at a pitch of $25 \mu m$ are diffused on the detector. Each strip is individually biased via an integrated polysilicon resistance connected to a common metal bias bus line. Readout is done every second strip. The reference detectors are equipped with NMOS Microplex chips [14]. There are eight reference detectors, four ($x$ detectors) measure points in the $xz$ plane and four ($y$ detectors) measure points in the orthogonal $yz$ plane (fig. 4).

The double-sided detectors under test are equipped with CMOS MX6 VLSI readout circuits [12].

Each silicon detector is mounted on a precisely machined mechanical support which acts also as the heat sink. The supports are mounted on an optical bench that is installed on a marble table. The double-sided detector is mounted on a pivoting support. This support can rotate around a vertical axis by $\pm 180^\circ$.

Multiplexed differential analog signals coming from the silicon detectors are fed into CAMAC [15] and VME [16] Sirocco units. A total of six Sirocco units were used.

The trigger is provided by a set of upstream and downstream scintillators mounted on the optical bench. Data acquisition software [16] runs on a VME/OS9 system. Raw data are written to Exabyte cassettes, each event accounting for 16 KB.

5. Off-line analysis

For each event and for each channel, the pulse-height and the noise are calculated off-line. Digital filtering techniques are used for a continuous update of pedestal and noise [17]; common mode shift of the base line is calculated for each event. The techniques of cluster reconstruction and the algorithms for calculating the position of the clusters are described below.

A weighted least-squares fit to a straight line is used to reconstruct tracks in both projections $xz$ and $yz$ separately. Only tracks defined by the whole set of the eight reference detectors are accepted. A $\chi^2$ cut de-

<table>
<thead>
<tr>
<th>Angle [degrees]</th>
<th>Cluster finding algorithm</th>
<th>Position finding algorithm</th>
<th>$\sigma_{F\text{T}}$ [\mu m]</th>
<th>Error on impact point [\mu m]</th>
<th>Spatial resolution [\mu m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N</td>
<td>ETA</td>
<td>$7.1 \pm 0.3$</td>
<td>$6.0 \pm 0.3$</td>
<td>$3.8 \pm 0.6$</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>ETA</td>
<td>$6.9 \pm 0.3$</td>
<td>$6.1 \pm 0.3$</td>
<td>$3.2 \pm 0.9$</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>ETA</td>
<td>$7.1 \pm 0.3$</td>
<td>$6.1 \pm 0.3$</td>
<td>$3.6 \pm 0.6$</td>
</tr>
<tr>
<td>20</td>
<td>N</td>
<td>ETA</td>
<td>$7.3 \pm 0.3$</td>
<td>$6.1 \pm 0.3$</td>
<td>$3.7 \pm 0.6$</td>
</tr>
<tr>
<td>30</td>
<td>N</td>
<td>ETA</td>
<td>$7.2 \pm 0.3$</td>
<td>$6.2 \pm 0.3$</td>
<td>$3.7 \pm 0.6$</td>
</tr>
<tr>
<td>40</td>
<td>N</td>
<td>ETA</td>
<td>$7.5 \pm 0.2$</td>
<td>$6.0 \pm 0.3$</td>
<td>$4.5 \pm 0.6$</td>
</tr>
<tr>
<td>50</td>
<td>N</td>
<td>ETA</td>
<td>$8.1 \pm 0.3$</td>
<td>$6.2 \pm 0.3$</td>
<td>$5.2 \pm 0.4$</td>
</tr>
</tbody>
</table>
5.1. Signal spread for inclined tracks

The details of the data analysis depend on the geometry of the tracks (fig. 5). In our setup, n-side strips are vertical, while p-side strips are horizontal. This means the n-side measures a point in the yz projection while the p-side gives a point in the xz projection. Two angles are needed to define the inclination of the tracks in space: we can choose the angles that the track forms with the normal to the detector surface in the two projections xz and yz. We call them $\theta_x$ and $\theta_y$, respectively. In our setup $\theta_x$ is always zero and we can only vary $\theta_y$. In the following we will indicate $\theta_y$ as $\theta$. It is also important to consider the projection of the path of the particles in the silicon onto the two planes xz and yz. In our geometry the first one is always zero, while the second one, that we call sagitta, is given by

$$\text{sagitta} = \text{thickness} \times \tan \theta.$$  \hspace{1cm} (1)

For sufficiently large angles $\theta$, the signal spreads over several strips where the mean number $N_{cl}$ of strips per cluster is roughly given by

$$N_{cl} = \frac{\text{sagitta}}{\text{pitch}} = \frac{\text{thickness}}{\text{pitch}} \times \tan \theta.$$  \hspace{1cm} (2)

The length of the path of the particle in silicon is proportional to $1/\cos(\theta)$. Since the most probable energy loss is roughly proportional to the length of this path [19], we can write

$$S(\theta) = \frac{S(0)}{\cos \theta},$$

where $S(\theta)$ is the cluster signal measured at an angle $\theta$.

Taking into account eqs. (2) and (3), we can say that for sufficiently large $\theta$, the average signal collected by one strip (on the n-side only, in our geometry) is given by

$$S_{\theta} = \frac{S(\theta)}{N_{cl}} = \frac{S(0)}{N_{cl}} \frac{\text{pitch}}{\text{thickness}} \frac{1}{\sin \theta},$$

Neglecting Landau as well as noise fluctuations, we observe that the signal on one strip is exactly $S_{\theta}$ on all the strip in the cluster but the first ("tail") and the last ("head") one.

5.2. Cluster finding algorithms

On the basis of the previous considerations we have considered two algorithms for cluster reconstruction. The two algorithms differ on how the selection of the strips in the cluster is done.

<table>
<thead>
<tr>
<th>Angle [degrees]</th>
<th>Cluster finding algorithm</th>
<th>Position finding algorithm</th>
<th>$\sigma_{F1IT}$ [$\mu$m]</th>
<th>Error on impact point [$\mu$m]</th>
<th>Spatial resolution [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N</td>
<td>ETA</td>
<td>8.8 ± 0.4</td>
<td>5.8 ± 0.2</td>
<td>6.6 ± 0.6</td>
</tr>
<tr>
<td>5</td>
<td>N</td>
<td>LIN</td>
<td>8.6 ± 1.0</td>
<td>5.8 ± 0.3</td>
<td>6.3 ± 1.4</td>
</tr>
<tr>
<td>10</td>
<td>N</td>
<td>LIN</td>
<td>8.5 ± 0.3</td>
<td>6.1 ± 0.3</td>
<td>5.9 ± 0.5</td>
</tr>
<tr>
<td>20</td>
<td>I</td>
<td>AHT</td>
<td>10.3 ± 0.8</td>
<td>6.4 ± 0.3</td>
<td>8.1 ± 1.0</td>
</tr>
<tr>
<td>30</td>
<td>I</td>
<td>AHT</td>
<td>14.9 ± 0.9</td>
<td>7.3 ± 0.4</td>
<td>13.0 ± 1.1</td>
</tr>
<tr>
<td>40</td>
<td>I</td>
<td>AHT</td>
<td>16.8 ± 0.9</td>
<td>7.8 ± 0.4</td>
<td>14.9 ± 1.0</td>
</tr>
<tr>
<td>50</td>
<td>I</td>
<td>AHT</td>
<td>20.9 ± 0.5</td>
<td>9.9 ± 0.5</td>
<td>18.4 ± 1.2</td>
</tr>
</tbody>
</table>

V. SI MICROSTRIP
In the first method ("normal" cluster finding algorithm), we look first for a strip (the "central" strip) which has a signal-over-noise ratio S/N higher than a given threshold $T_1$, and then we add in the cluster all the neighbouring strips for which is $S/N > T_2$.

In the second method ("inclined track" cluster finding algorithm), we include in the cluster all the strip with $S/N > T'_1$, and then we add also the strips next to the two edge strips if their $S/N$ is higher than $T'_2$.

Once we have defined a cluster, it must pass the following controls.
(a) The signal-over-noise ratio for the cluster must be higher than $T_1^{cl}$.
(b) The signal of the cluster must be higher than $T_2^{cl}$ and lower than $T_3^{cl}$ ADC counts.
(c) The number of strips in the cluster must be higher than $T_4^{cl}$ and lower than $T_5^{cl}$.

5.3. Position finding algorithms

For computing the impact point position of the particle passing through the detector, several algorithms can be used. The choice depends on the detector parameters (pitch, bias voltage, thickness) and on the geometry of the track. For non-inclined tracks, most of the charge is collected by two strips in a non-linear way [20]: a nonlinear interpolating algorithm can be used [21,22]. This algorithm ("eta" algorithm) is based on the variable $\eta$ defined as

$$\eta = \frac{PH_R}{PH_R + PH_L},$$

where $PH_R$ ($PH_L$) is the pulse-height on the strip on the right (left). The experimental distribution of this variable measured for non-inclined tracks is shown in fig. 6.

For an angle $\theta$ such that the sagitta is smaller than the pitch, the charge spreads over two strips in an almost linear way. The position is assumed to be directly proportional to the variable $\eta$ ("linear" algorithm).

For inclined tracks, the first approach is to use the geometrical mean of the positions of the "head" and of "tail" strips of the cluster. The position is then given by ("digital head-tail" algorithm)

$$X_{DHT} = \frac{x_h + x_t}{2}.$$  

From geometrical considerations (fig. 7), the impact point position is given by

$$X_{IMP} = \frac{x_h + x_t}{2} + \frac{p_h - p_t}{2} = X_{DHT} + \frac{p_h - p_t}{2}.$$  

The energy loss is roughly proportional to the path of the particle in silicon, so we can write ("analog head-tail" algorithm)

$$X_{AHT} = \frac{x_h + x_t}{2} + \omega,$$  

where

$$\omega = \frac{(S_h - S_t)}{2S_\theta}$$

and $S_h$ and $S_t$ are the pulse-heights measured on the head and on the tail strip of the cluster, respectively.

Since Landau fluctuations are more likely to push the energy loss towards values higher than the most probable one, we can hope to have a better position definition if we define $\omega$ as

$$\omega = \frac{\min(S_h, S_\theta) - \min(S_t, S_\theta)}{2S_\theta}. $$  

\[\text{Fig. 6. Distribution of the $\eta$ variable for non-inclined tracks. (a) VTT detector p-side; (b) VTT detector n-side; (c) SI detector p-side; (d) SI detector n-side.}\]

\[\text{Fig. 7. Reconstructed impact point and position finding algorithm for inclined tracks.}\]
6. Beam test results

Data have been taking at eight different angles $\theta$ (0, 5, 10, 20, 30, 40, 50 and 60°) with the VTT detector and at 4 different angles (0, 20, 40 and 60°) with the SI detector. In this paper we will present results from a subset of these runs since data analysis is not yet finished. Due to the lack of time, we could not do an optimal choice of the analysis parameters. Because of the low statistics, only results on n-side regions with a pitch of 50 and 35 $\mu$m for the VTT and SI prototypes respectively are considered.

6.1. Landau distribution, noise, Landau correlation, charge division, efficiency

Fig. 8 shows the pulse-height distributions for our prototypes and for non inclined tracks ($\theta = 0°$). The differences in S/N ratios are due to the different design of the detectors. Efficiency has been measured for non-inclined tracks and found consistent with 100% on both sides and for both prototypes.

Correlation of the pulse-heights measured on the two sides of a double-sided detector is important in order to reduce ambiguities in the case of multi-hit events. For all the different runs we analysed, we did not find any significant difference between the pulse-heights measured on the two sides. Fig. 9 shows the

![Fig. 8. Pulse-height distributions for non-inclined tracks. (a) VTT detector p-side; (b) VTT detector n-side; (c) SI detector p-side; (d) SI detector n-side. Signal-over-noise ratios S/N are also indicated.](image)

![Fig. 9. Landau correlation measured at two different track angle with the VTT detector. (a) $\theta = 0°$; (b) $\theta = 50°$. Each point in the plots represents one event.](image)
The pulse-height correlation for data taken at two different angles for the VTT detector. The distribution of the charge between the strips in the cluster has been studied (fig. 6). For small angle $\theta$, we consider the distribution of the variable $\eta$. On the n-side of both SI and VTT detectors, the readout is done at every strip and the distribution of the variable $\eta$ shows the characteristic two-peaks structure. On the p-side, where the readout is done every second strip, this distribution has a three-peaks structure, where the central peak is the mark of the intermediate strip. In this case, the charge division between the two readout strips is almost linear.

For larger angles, we expect the pulse-height distribution of all the strips in the cluster but head and the tail to have the Landau shape. This is confirmed by the experimental data (fig. 10). The position of the peak is found to be consistent with that of the distribution shown in fig. 8b.

### 6.2. Spatial resolution

The results on the spatial resolution are shown in tables 3 to 6 and fig. 11. The resolution on the p-side remains almost constant with the angle $\theta$ (table 3) the $\eta$-algorithm is used at each angle. For the n-side different algorithms are used (table 4). For sufficiently high angle, the analog head–tail with $\omega$ defined by eq. (10) gives the best results (table 5). Resolution of 18.4 $\mu$m has been obtained for 50° tracks. A minimum in the spatial resolution seems to appear at around 5–10° but the errors on these points are quite large due to statistics. Increasing the angle the spatial resolution worsens but is better than 20 $\mu$m at 50°.

### 7. Conclusions

We have designed and successfully tested a double-sided detector with field plate ohmic separation and on-chip fan-out, processed on a second metal layer on the n-side. One of the prototype features 35 $\mu$m pitch on the n-side, that is the smallest pitch ever tried for n$^+$ strips on n substrate.

Spatial resolution has been measured in a high energy beam. For non-inclined tracks, we have mea-

<table>
<thead>
<tr>
<th>Angle</th>
<th>AHT (no min)</th>
<th>DHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>16.2 ± 1.3</td>
<td>18.0 ± 1.1</td>
</tr>
<tr>
<td>50</td>
<td>20.6 ± 1.4</td>
<td>19.9 ± 1.3</td>
</tr>
</tbody>
</table>

Table 6

Position resolution for the SI detector and non-inclined tracks. See table 3 for explanation of abbreviations

<table>
<thead>
<tr>
<th>Detector</th>
<th>Cluster finding algorithm</th>
<th>Position finding algorithm</th>
<th>$\sigma_{\text{VTT}}$ [$\mu$m]</th>
<th>Error on impact point [$\mu$m]</th>
<th>Spatial resolution [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI p-side</td>
<td>N</td>
<td>ETA</td>
<td>6.4 ± 0.1</td>
<td>5.7 ± 0.3</td>
<td>2.9 ± 0.6</td>
</tr>
<tr>
<td>SI n-side</td>
<td>N</td>
<td>ETA</td>
<td>8.6 ± 0.1</td>
<td>5.6 ± 0.3</td>
<td>6.5 ± 0.3</td>
</tr>
</tbody>
</table>
Fig. 11. Summary of the beam test measurements (see also table 3 to 6). As explained in the text, the angle $\theta$ has a different meaning if we consider the p- or the n-side because of the geometry of our setup.

measured a spatial resolution of 2.9 $\mu$m on the p-side. To our knowledge this is the best result ever obtained with 50 $\mu$m readout pitch detectors, and this shows the importance of an intermediate strip for charge interpolation. On the n-side we measured 6.5 $\mu$m.

We also measured the spatial resolution as a function of the angle of inclination of the tracks on the n-side. At 50° we obtained a resolution of 18.4 $\mu$m.

These results prove the effectiveness of our design. Double-sided detectors with double-metal fan-out are being currently processed and will be used by the DELPHI experiment.

Acknowledgements

We would like to thank B.S. Avset and L. Evensen from S.I. and K. Leinonen and S. Eranen from V.T.T. for their close collaboration.

References

[16] C. Colledani et al., CRN-LEPSI note, to be published.