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DOUBLE-SIDED Si STRIP SENSORS FOR LEP VERTEX DETECTORS

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ABSTRACT

Technology aspects in the production of double-sided Si strip sensors which arise from the physics requirements in Vertex Detector systems in the four big LEP experiments are discussed. Some recent experimental results relating to the spatial resolution, which can be obtained with these sensors, are presented for a variety of technologies which have recently been developed.

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1. INTRODUCTION

Lifetimes of heavy flavour particles composed of c- and b-quarks, and also of the τ -lepton, which all have been discovered in the '70s, are in the range of some fractions of up to a few picoseconds. Direct observation of decays of such exotic particles and the measurement of the lifetimes of individual particles is clearly of great interest in understanding the detailed interplay between hadronic and weak interaction phenomena. In this context, a big effort has been put into studies of the production and subsequent decay of heavy particles, both in photo-production and hadro-production at high energy accelerators like the CERN SPS and the Fermilab Tevatron. The direct observation of these particles became even more important in the large experiments built for high energy e^+e^- colliders operating at energies around the Z^0 mass. The coupling of the Z^0 to quark-antiquark pairs being roughly of equal strength for light and heavy quarks, makes charmed and beauty particles very abundant in these collisions.

It was recognised early on that high granularity Si sensors are an ideal tool for these studies. Existing planar technology used in microelectronics fabrication could be employed [1] to produce Si strip sensors which give the required spatial resolution of a few μm . Consequently at SLC [2] and at LEP [3,4,5,6] the big experiments have developed Si sensors and integrated front-end readout electronics, which allowed the construction of very efficient Si Vertex Detectors capable of reconstructing decay vertices with the required precision. This technology made it possible to distinguish very efficiently heavy flavour particles and τ -leptons from interaction products emerging from the primary vertex (Fig. 1).

In this article, the physics requirements on such sensors in the context of the LEP experimental environment will be discussed, an overview of the more current technologies for sensor production will be given and some experimental results on the performance of such sensors will be presented.

2. PHYSICS REQUIREMENTS ON SENSORS

The main goal in the use of Si strip sensors in High Energy Physics Experiments over the last decade - be it in fixed target geometries or in collider experiments - has been the fast, high precision measurement of space points of high energy particles emerging from an interaction point in order to determine primary and secondary vertices with the best possible precision. The inherent spatial resolution of Si strip sensors allows in this way to uniquely identify exclusive decays of heavy flavour particles (charm and beauty) and also tau leptons with lifetimes of typically

0.1 to 1.5 psec. Figure 2 shows an example of a double b-decay measured in the DELPHI experiment using Si sensors.

In order to separate such decay vertices in complicated event topologies, the transverse measurement error projected back to the primary vertex has to be smaller than 30 micrometers for the shortest lifetimes. From Fig. 3 one can see that (in the case of no magnetic field) the extrapolation error σ_e at the primary vertex of a track measured at two measuring stations x_1 and x_2

$$\sigma_e^2 = (\alpha + 1)^2 \sigma_1^2 + \alpha^2 \sigma_2^2 \quad (1)$$

with $x_1 = \alpha d$ and $x_2 = (\alpha+1) \cdot d$. α is a characteristic multiplication factor expressing the extrapolation distance in multiples of the distance of the two measuring stations. In the case of a collider geometry the smallest possible value of α is obtained by mounting the first measuring station as close as possible to the beam pipe and the distance d between the two measuring stations is usually limited by the radial space available for the detector. Taking in expression (1) e.g. $x_1 = 5$ cm and $x_2 = 10$ cm and the spatial resolution of the sensors $\sigma_i = 10$ μ m, σ_e becomes 22 μ m. This example demonstrates that a spatial resolution of a single sensor of the order of 10 μ m is necessary to resolve heavy flavour decays efficiently with this type of geometry.

The impact parameter of a track is defined as the smallest distance between the track and the primary vertex. Including multiple scattering effects in the beam pipe and in the sensors including mechanical support structures, one arrives at a formula for the impact parameter precision

$$\sigma_{ip}^2 = \sigma_e^2 + \frac{\sigma_{ms}^2}{p^2} \quad (2)$$

In the case of the DELPHI micro-vertex detector with a Be beam pipe at the radius of 5.3 cm and wall thickness of 1.45 mm and the equivalent of 310 μ m of Si for each sensor layer including support structures (Fig. 4) one finds experimentally $\sigma_{ms} = 69$ μ m [3]. Figure 5 shows the experimental impact parameter error. The measured curve implies that multiple scattering puts a lower limit for a sensible point resolution of about 5 μ m for typical LEP geometries unless one is able to reduce the amount of material in the sensitive region.

The spatial resolution of a Si strip sensor is dependent on the particular way it is used. In the case of hit information only, the spatial resolution of the sensor is related to the strip pitch p by

$$\sigma = \frac{p}{\sqrt{12}} \quad (3)$$

In the case of analogue readout the resolution is depending on several parameters. The most important are the electronic noise, the strip pitch, readout pitch and the biasing voltage, which determines the lateral diffusion of charges. The lateral charge diffusion (an example of a measured charge distribution is shown in Fig. 6 [7]) distributes the charge created by the traversing particle on more than one strip (Fig. 7). Using non-linear charge interpolation algorithms [8,9] one obtains optimal resolution limited finally only by noise and the physical processes of charge deposition. The spatial resolution in this case is roughly

$$\sigma = \beta \frac{N}{S} \cdot p_s \quad (4)$$

S/N is the signal over noise ratio and p_s is the strip pitch. β is a proportionality constant with values empirically around 4 to 10.

At this point it may be useful to recall the important sensor parameters which influence the noise performance of the front-end electronics [10]: (i) the capacitance of the readout strip to ground or virtual ground of the neighbour strips; (ii) the leakage current (shot noise) and (iii) the sensor bias resistor. The capacitance (i) is the determining factor for the serial noise and (ii) and (iii) give the main contributions to the parallel noise.

The above considerations lead to certain implications on the technology for Si strip sensors for use in LEP experiments for vertex detection:

- Co-ordinates should be measured with a precision of 5 - 10 μm . Given the minimal practical readout pitch of 50 μm , this requirement necessitates analogue readout and the use of intermediate strips (usually one strip) for capacitive charge coupling to the readout strips. Furthermore, to exploit fully the charge sharing between strips to be used in centre of gravity determination of the co-ordinate, the sensor design should aim for lowest possible noise in the readout electronics which requires small interstrip capacitance, low leakage current and as high as possible bias resistors. The bias resistor should however not exceed values which lead to variations of the voltage drop across

neighbouring strips due to the leakage current to avoid co-ordinate distortions due to lateral electric field gradients.

- Multiple scattering should be kept as small as possible to maintain good impact parameter resolution also for particles with low momenta. This requires to reduce sensor thickness to a practical minimum limited by mechanical robustness both in processing (4-inch wafers can be processed with sufficiently high yield down to 200 - 300 μm thickness) and in mounting. Supports in the sensitive area have to be massless and the electronics should be mounted outside the sensitive volume. For a measurement of both the $r\phi$ - and z -co-ordinate double-sided readout on one sensor plate with the readout electronics on both sides of the sensor, mounted outside the sensitive volume, is essential.

Before discussing in the next paragraph recent technical developments in Si strip sensors for LEP experiments it is worth mentioning that this technology has already produced a variety of important physics results based on the analysis of data from existing Si-vertex detectors in 3 of the 4 LEP experiments [11].

3. STRIP SENSOR TECHNOLOGIES IN THE 4 LEP EXPERIMENTS

At present all 4 experiments installed at the LEP collider have Si vertex detectors in operation. In this paragraph a description of the basic strip sensor technologies employed in the different vertex detectors will be presented and new developments within upgrade projects for these vertex detectors will be briefly discussed.

An overview of the different technologies chosen will be presented before discussing the choices made in the 4 experiments.

3.1 Current strip sensor technologies

All sensors used in LEP experiments are produced using variations and different recipes in planar technology. Sensors making use of Schottky barriers will not be included in this discussion. It seems adequate to discuss separately properties and technical problems occurring on the junction side, which is simpler and usually used for single-sided readout sensors, and on the ohmic contact side, which poses relatively difficult problems and is important in the case of double-sided readout sensors.

3.1.1 *The Junction Side*

Recent technical developments on single-sided readout sensors with strips on the pn junction side mainly concern different coupling schemes of the junction strip to the electronics and different biasing schemes. The inevitably existing positive interface charges located in the Si-SiO₂ interface create an electron accumulation layer which separates ohmically neighbouring strips and strips from guard-ring structures. The interstrip resistance is usually between several 100 MΩ and GΩ. However, attention has to be paid to avoid negative surface charge-up, which can deplete and even invert the Si-SiO₂ surface leading to interstrip shorts between neighbouring p⁺n junctions.

3.1.1.1 *The Coupling of Strips to the Readout Electronics*

Si strip sensors were originally read out with hybrid amplifiers connected to the metallised strip diodes via externally mounted capacitors with separate external resistors for each diode. With the advent of fully integrated readout electronics [10, 12-15] different coupling schemes were introduced. Coupling capacitors were integrated on the sensor itself using a 100 - 200 nm thick thermal SiO₂ as insulator between junction and metal readout strip [16]. Typical values of the coupling capacitances for, e.g., 7 μm wide strips are 12 - 15 pF/cm, sufficiently high in comparison with the strip to backplane capacitance and the interstrip capacitance that are in the order of 0.2 and 1 - 1.5 pF/cm, respectively. More recently, technologies have been developed which combine Si-oxide and Si-nitride layers as insulator for the coupling capacitors. Si-nitride offers higher coupling capacitance at the same thickness. In both technologies, the occurrence of pinholes in the insulator still poses some problems, which is less severe on the pn-junction side, where one can usually adjust the voltage difference between pn-junction and metal strip to a minimum. This allows to still have a well functioning strip as long as the leakage current on the particular strip is in the region of nanoamps.

Another method to achieve the capacitive coupling of junction strip and pre-amplifier has been developed [17] by the Pisa group in collaboration with CSEM Neuchâtel. A separate capacitor chip on a glass substrate with identical pitch as on the sensor is placed between readout chip and sensor and connected by wire bonding to the sensor and the readout chip. The advantage of this method is an improved yield by selecting capacitor chips with zero pinholes, but one has to cope with twice the number of external connections.

It is possible to have dc coupling into the electronics, which can be achieved when leakage currents are low enough so that they do not affect the working point of the integrator too much through a voltage drop over the feedback resistor. For higher leakage currents, the leakage current flowing into the preamplifier can, e.g., be compensated for by a current source at the input of the integrator.

3.1.1.2 Biasing Schemes

Originally, sensors with integrated coupling capacitors were also designed with integrated bias resistors [18,16]. These resistors are produced in a lithographic step where suitably low doped deposited polysilicon is shaped into fine strips, often in a mander pattern to minimise the occupied area. The polysilicon strips are contacted on one side to the pn-junction strip and on the other side to a common bias line. Sheet resistance values from below 1 k/ to about 100 k/ can be produced. This allows values of up to 50 M for a single resistor. Whereas the uniformity of such resistors across one wafer can be quite easily maintained within a few percent, it often varies between different wafers by several ten percent. Low sheet resistance can be made more reproducibly than high sheet resistance.

Another biasing scheme consists of "reach through" [19] and FOXFET p+n+p+ structures [20]. A p+ implanted line orthogonal to and at a small distance (5 - 10 m) from one end of all the p+ strips is used to bias the sensor (Fig. 8). When a bias voltage is applied between backplane and the bias strip, the potential (U_{strip}) on the floating p+ strips will follow the backplane potential until a thermionic emission of holes over a small potential barrier (Fig. 9) of the forward biased p+n junction (the bias bar) will keep the potential difference between the two p+n junctions at an approximately constant value. This potential difference is again U_{strip} since in all applications the bias bar is held at ground potential. Raising the voltage further will then deplete the bulk underneath the strips. In reality, the strip voltage is rising slowly with the backplane voltage due to potentials from fixed oxide charges (Fig. 10). A variation of this biasing method employs a gate electrode on top of the field oxide between biasing bar and p+ strips (FOXFET). A voltage applied to this gate allows control of the voltage drop between bias bar and p+ strips (Fig. 11).

The actual value of the bias resistance for this device is usually called dynamic resistance and is $R_d = \frac{\partial U_{\text{strip}}}{\partial I}$ with I being the total current flowing through the device. The working point of the reach through device is defined by the condition that the hole current from the thermionic emission cancels the leakage current of holes flowing in the opposite direction. The effective bias resistance is

therefore the dynamic resistance at $I = 0$ across the reach through structure. An example of the I-V characteristics of a FOXFET biasing structure (produced by CSEM Neuchâtel) is shown in Fig. 12. In a simplified model of the I-V characteristics of a reach through structure [23], one obtains $R_d \sim \frac{1}{I}$ with I being the leakage current on one strip (Fig. 13). The experimental result in Fig. 13 follows a distribution between $\frac{1}{I}$ and $\frac{1}{I^2}$.

In Fig. 14 the measured dynamic resistance of two different FOXFET structures is plotted versus the gate voltage. The low leakage current device has a resistance of several hundred $M\Omega$ and drops rapidly to about 250 $k\Omega$ between -1 V to -4 V on the gate where the FET channel becomes conductive (the field oxide has 200 nm thickness for this device). The high leakage current device has a constant dynamic resistance of 10 to 20 $M\Omega$ over the whole measured voltage range (the device has a field oxide of about 1 μm). This measurement shows that an acceptable resistance can be reached with these biasing devices over a wide range of leakage currents. In particular under LEP experimental conditions, where long shaping times (a few μsec) in the readout electronics are feasible and therefore very low serial noise can be achieved, FOXFET biasing offers an advantage over passive resistors, since the very high dynamic resistance does not introduce potential variations across the strips, since ΔV_{RT} (reach through voltage drop) is only slightly dependent on I_{ST} [23]. Values of bias resistors above 50 $M\Omega$ make parallel noise from the bias resistor completely negligible [10].

3.1.2 The Ohmic Side

A number of manufacturers can produce single-sided pn junction strip sensors, employing almost any combination of technologies described in section 3.1.1. Double-sided strip sensors have been made since nearly 10 years, but many technology variants are at present still being developed. There are naturally more complications in producing a n^+ -strip Si sensor with equal performance to a pn junction strip sensor. Some of the reasons for these complications are (i) the presence of the electron accumulation layer on the Si-SiO₂ interface (Fig. 15), requiring additional technology steps to separate neighbouring strips ohmically, (ii) the high potential of the n^+ strips necessary for biasing the sensor and (iii) in particular in the case of LEP type (and in general collider type) vertex detectors the desire to route n-side strips parallel to the p-side strips for readout in order to place the readout electronics outside the sensitive area of the sensor for minimal multiple scattering.

3.1.2.1 *The n⁺ Strip Coupling*

As on the p-side, it is in general considered to be convenient to have capacitive coupling between the n⁺ strips and the readout electronics. Again both sensor integrated coupling capacitors, using either about 200 nm SiO₂ or a double layer of SiO₂ and Si₃N₄ with total thickness of 200 - 300 nm as an insulator between the n⁺ contact and the metal strip, or external coupling capacitor chips have been used [17,24]. The development of good oxide - nitride technology is in particular important on the n-side, since in most applications the bias voltage is applied on the n-side, and one would like to have the full bias voltage to be brought to ground across the insulator. The resulting high field strength (several MV/cm) introduces a risk of creating punch-through connections between n⁺ strip and metal strip, which upset both on the sensor and in the electronics wide regions around the broken-down strip. The usual breakdown voltage of good oxide insulators is around 4-8 MV/cm [21]. It has been shown that a double layer of grown oxide and deposited nitride has better yield for producing strips without process-induced pinholes and very good resistance against punchthrough. The disadvantage of a nitride layer is the introduction of another interface which can have high positive interface charge density, which induces high surface leakage currents.

3.1.2.2 *The Ohmic Separation*

In order to obtain high ohmic resistance between the neighbouring n⁺ strips and n⁺ strips and a guard-ring, which is usually laid out around the sensitive area of the n-side strips, two different methods are used. One solution is to surround the n⁺ strips by regions with a p⁺ implant [19], which breaks the conductive accumulation layer path between n⁺ strips (Fig. 15a). Another possibility is to use gate-like electrodes on the surface of the field oxide to create a field depletion in the bulk underneath by applying an appropriate voltage (negative w.r.t. the bulk) on these electrodes, usually called field plates (Fig. 15 b,c). A convenient way to achieve field depletion is to extend the metal readout strips sideways beyond the n⁺ strip (Fig. 15c). It has also been tried to use field plates consisting of metal strips positioned between the readout strips and all of them connected together with lines running across the sensor on the top and on the bottom of the sensor (Fig. 15b). Proper biasing of these strips, which is automatically achieved in the scheme (Fig. 15c) by connecting the metal strips to the gate of the readout amplifier, which is operated at 1 to 2 volts, and with the n⁺ strips at positive bias voltage, separates ohmically the n⁺ strips [24]. Interstrip resistances of several hundred MΩ have been achieved with field plate voltages above 5 V (Fig. 16).

Using field plates, special care has to be taken to isolate the n^+ strip at the position where it is contacted to the polysilicon resistor. Two effective technologies can be employed: (i) by shaping the high resistive polysilicon, which is used by some manufacturers for MOS structures between metal and oxide, in a window frame around the contact hole (this method is used, e.g., by CSEM, Neuchâtel and VTT, Helsinki) (Fig. 17) or (ii) extending the metal in window frame shape around the contact hole (done by S.I., Oslo) (Fig. 18). The latter method requires a double metal technology in order to connect the n^+ strip to the polysilicon resistor above the field plate by a metal two line.

3.1.2.3 *Biasing Schemes*

Besides polysilicon resistors, which are frequently used, an alternative biasing method making use of the ohmic resistance of the electron accumulation layer has been developed [17,19]. This method can be suitably implemented in the p-stop ohmic separation technology by shaping the p-stops such that they form narrow accumulation channels between the end of the n^+ strip and a n^+ biasing line. The bias resistance can be tuned by a suitable choice of the width and length of the accumulation layer channels.

Very recently, a new scheme to bias the n^+ strips via an n^+nn^+ type structure has been introduced [25]. The n^+ strips are capacitively coupled to metal readout lines by 200 nm SiO_2 , 18 nm wide p^+ implant strips are placed between n^+ strips. The biasing of the n^+ strips is achieved by a n^+ bias bar at one end of the sensor with a n-gate on top of the oxide which overlaps both n and p strips and the n^+ bias bar. The biasing condition can be controlled by applying a negative voltage on the n gate. The p strips are biased by a p^+ bias bar on the other end of the sensor with a p-gate which overlaps the p^+ bias bar and the p^+ strips but not the n^+ strips (Fig. 19a). In this scheme, the p^+ strip biasing is achieved through a FET structure working in enhancement mode whereas the n^+ strip biasing occurs through depletion of the n bulk under the gate. The source voltage versus source current characteristic for the n biasing field plate device is shown in Fig. 19b. It turns out to be similar to the I-V characteristics of a p^+np^+ FOXFET device. This implies that the field plate biasing structure has similar dynamic resistance to the reach through structure.

3.1.2.4 *Routing of Readout Lines*

Over the last three years a great effort has been put into a development of double-sided strip sensors with the n-side readout lines running parallel to the p-side strips in order to be able to place the readout electronics at the end of sensor

modules. The motivation for this technique comes from the fact that the application of these sensors in microvertex detectors requires minimal mass in the sensitive volume of the detector in order to reduce multiple scattering. This is especially important for future B-factories where the momenta of the decay products from heavy flavour particles are very small. But it affects the physics potential also quite considerably in the case of LEP and hadron collider vertex detectors.

Two avenues have been explored in this development : (i) integration of a second crossed layer of metal lines on the sensor, and (ii) external thin substrates on which these lines are printed.

(i) Integrated Double Metal Readout

This method uses an insulator which is deposited on the first metal layer of strips. Contact holes are etched through the insulator to electrically connect first metal layer strips to second metal layer strips (Fig. 20). Complications arise from the necessary thickness of the insulation layer which should be thicker than $2\text{ }\mu\text{m}$ to keep capacitive coupling of one strip to all the others at a low level. This is important both from the point of view of signal loss and increased noise in the readout electronics. So far two materials have been used, polyimide and deposited oxides. With polyimide one can reach $5\text{ }\mu\text{m}$ thickness in one processing step. SiO_2 layers up to $2.5\text{ }\mu\text{m}$ thickness in one step and $5\text{ }\mu\text{m}$ thickness in a two step procedure have been achieved, thus reaching sufficient decoupling between the two metal grids. An example of a technology combining ohmic separation on the n-side by field depletion and double metal routing is given in Fig. 17.

In the case where the same readout pitch on both n- and p-side is required and the length over width ratio of the sensor is greater than one, a multiplexing of several n-side strips to one metal 2 readout strip can be introduced. In many cases, this is an additional advantage when the resulting ambiguities can be resolved from external tracking information, thus reducing the number of electronic readout channels.

(ii) Rerouting on External Substrates

Two technologies have been developed to route the z-strips to the p-side end of the sensor on external substrates, one by the OPAL collaboration and one by the L3 collaboration :

- (a) A glass plate of 200 μm thickness carries diagonal lines. The lines are made of sputtered gold, 1 μm thick and 20 μm wide with a 40 μm pitch. Junction strip sensors are placed on the substrate and the z-strips of the sensor are connected via wire bonding to the diagonal strips on the glass plate. In this way the z strips of several sensors are multiplexed on one readout strip which can be connected to the readout chip at the p-side end of the sensor (Fig. 21).
- (b) A 50 μm thick kapton foil is used as substrate. 15 μm wide copper lines are produced by e-beam lithography in an L-shape. The z strips are connected to the short side of the L by wire bonding. The bond pads are Ni/Au plated.

The advantage of sensor external routing of strips is clearly a less complicated sensor design and higher sensor yield. It has, however, the drawback of introducing more material in the sensitive volume and of complicating connectivity in a similar fashion to the case of non-integrated coupling capacitor chips.

3.2 Use of technologies in the four LEP microvertex detectors

At present all the four big experiments installed at LEP have Si strip microvertex detectors in operation. The ALEPH and DELPHI collaborations have proposed Si microvertex detectors in the early stages of the elaboration of the proposals. Whereas the DELPHI experiment opted for a two-layer detector with $r\phi$ readout only, which was upgraded after the first year to a three-layer $r\phi$ only configuration, the ALEPH experiment pioneered from the start double side $r\phi, z$ readout sensors. OPAL followed at a later date to add a microvertex detector, first a $r\phi$ co-ordinate two-layer detector and since 1993 a two-layer $r\phi, z$ readout detector. In this version, the $r\phi$ and the z co-ordinates are measured with single-sided pn junction sensors mounted back to back. L3 installed a two-layer $r\phi, z$ readout detector with double-sided sensors and external z-strip routing for the first time in 1992. Some features of the layout of the four installed vertex detectors, the basic properties of the Si sensors used and the specific technologies employed in the different sensors together with their manufacturers are listed in Table 1.

The L3 experiment is at present in the running-in phase of their detector to obtain a first evaluation of its physics potential. The other three experiments, having had longer running experience with a Si vertex detector and corresponding feedback, have upgrade proposal already presented and/or approved or are considering upgrade possibilities for the future. The major issues considered are optimised

double-sided readout sensors involving combinations of the most promising technologies, lowest possible material in the sensitive volume of the detector and improved noise performance of the front-end electronics. One further development is to try to improve the radiation hardness of the readout electronics. Except in the L3 experiment, where the front-end chip has been produced in a radiation hard CMOS bulk process, the readout chips of the other experiments are at present made in conventional CMOS bulk process.

4. EXPERIMENTAL RESULTS

A large number of experimental results has recently been obtained on spatial resolution using sensors made in different technologies. A few results, which indicate the potential of the different methods, will be shown.

The L3 collaboration has performed beam tests with half modules of two sensors mounted on kapton films. The readout chip used is the SVXZH developed at LBL [26]. Figure 22 shows pulse height distributions on $r\phi$ and z-side of the sensor. The resulting spatial resolution is shown in Fig. 23 yielding $\sigma_{r\phi} = 7.0 \mu\text{m}$ and $\sigma_z = 14.7 \mu\text{m}$.

The DELPHI collaboration has performed beam tests with double-sided sensors with double-metal readout, with devices produced by S.I. Oslo [27] and VTT, Helsinki [28]. Two detectors produced by S.I. Oslo with $50 \mu\text{m}$ readout pitch on the p-side, and $42.5 \mu\text{m}$ and $85 \mu\text{m}$ pitch respectively on the n-side, have been tested. The detectors were joined by daisy-chaining into a half-module of dimension $120 \times 32 \text{ mm}^2$ in such a way that the p-side of one detector was daisy-chained to the n-side of the other and vice versa. This is done to achieve about equal stray capacitance on both sides of the module. The results were promising with signal to noise ratios on both sides around 25/1 and a spatial resolution measured between $\sigma = 5.5 \mu\text{m}$ to $7 \mu\text{m}$ (on the n-side of the detector with $85 \mu\text{m}$ pitch) [29]. The signal is the cluster pulse-height and the noise is the average noise of one strip. These detectors were cooled during data taking to reduce excessive shot noise. For readout the MX6 chip [14] was used. Figure 24 shows signal, noise and signal/noise values obtained with 10 different sensors produced by VTT, Helsinki of dimensions $77 \times 19 \text{ mm}^2$. Signal/noise values on the p-side (squares) are distributed around an average of 30 and on the n-side (circles) around an average of 16. The readout chip was the MX6. Figure 25 shows the spatial resolution measured at different angles of the incident beam w.r.t. a vertical plane coinciding with the strips and for different strip pitch on the n-side for one of the VTT detectors (the n-side of the VTT detector has two differ-

ent regions, one with 50 μm pitch, the other with 100 μm). This detector had a signal to noise ratio of about 30/1 on the p-side and 12/1 on the n-side. On the p-side the resolution is $\sigma = 5 \mu\text{m}$ at 0° incident angle, on the n-side $\sigma = 10 \mu\text{m}$ for the region of the sensor with 50 μm readout pitch and $\sigma = 23 \mu\text{m}$ for the 100 μm readout pitch.

Finally the signal over noise distribution for the sensors developed with FOXFET type biasing structures on p- and n-side of the sensor ($60 \times 32 \text{ mm}^2$) [25] are shown in Fig. 26. The MX7 chip [30], which was used for the readout, is directly mounted on the z strip side of the sensor. Very good S/N ratios with values around 38 on both sides have been obtained. The high values of S/N obtained indicate that the high dynamic resistance of the biasing structures on these sensors play an essential role in the good performance.

In Table 2 selective results on spatial resolution of sensors and sensor modules developed in the different LEP experiments are summarised. Radiation lengths quoted are estimated values for one layer traversed at an angle of 90° .

5. SUMMARY

The technology of high spatial resolution Si strip sensors has evolved significantly over the past 15 years. The stringent physics requirements on sensors to be used in the LEP environment have advanced the technology specifically for double-sided readout sensors. Whereas high quality single-sided pn junction strip sensors with spatial resolution better than 5 μm rms can now reliably be produced in large quantities, the technology of double-sided sensors is still evolving and it can be expected that optimal solutions for a variety of applications will be established within the next two years. Particularly challenging is the technology of sensors with double metal readout promising the best physics results in hadron and e^+e^- collider experiments and even more so in B-factory vertex detectors.

Two out of the four LEP experiments (ALEPH and L3) use at present double-sided sensors for $r\phi, z$ co-ordinate measurements, the OPAL experiment employs back-to-back mounted single-sided sensors for $r\phi, z$ measurements.

The DELPHI experiment has $r\phi$ single-sided sensors only. Both OPAL and DELPHI intend to go to fully double-sided sensor-equipped vertex detectors in the future.

It can be expected that all four LEP experiments will have double-sided sensors installed based on established technologies for fully exploiting the physics

potential of LEP200 from 1995 onwards. It is now well recognised that Si vertex detectors will play an essential role in the discovery potential of each of these experiments.

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REFERENCES

- [1] J. Kemmer, Nucl. Instrum. Methods 176 (1980) 449.
- [2] C. Adolphsen et al., Nucl. Instrum. Methods A313 (1992) 63;
C.J.S. Damerell et al., Nucl. Instrum. Methods A288 (1990) 236;
C.J.S. Damerell, this Conference.
- [3] N. Bingefors et al., Nucl. Instrum. Methods A328 (1993) 447.
- [4] G. Batignani et al., Conference Record of the 1991 IEEE Nuclear Science Symposium, November 1991, Santa Fe, New Mexico, USA, Vol.1, p.438;
J. Wear, *"Real Life Experience with the ALEPH Silicon Vertex Detector"*, The FERMILAB Meeting DPF 92, C. Albright, P. Kasper, R. Raja, J. Yoh editors, World Scientific, Singapore, 1993, Vol.2, p.1740. .
- [5] P.P. Allport et al., Nucl. Instrum. Methods A324 (1993) 34.
- [6] L3 Collaboration, *"Proposal for a Silicon Microstrip Detector for L3"*, CERN, LEPC 91-5, LEPCP4-Add.1, April 1991.
- [7] J. Straver et al., *"A Si Strip Detector with Spatial Resolution of 1 μm "*, to be submitted to Nuclear Instruments and Methods.
- [8] R. Turchetta, *"Developpment de Detecteurs Silicium Double Face à Resolution Spatiale Elevée et Lecture Projective"*, CRN/HE 91-07, Ph.D. Thesis N. d'ordre 1019, April 29th, 1991, Strasbourg.
- [9] E. Belau et al., Nucl. Instrum. Methods 214 (1983) 253.
- [10] E. Nygård et al., Nucl. Instrum. Methods A301 (1991) 506.
- [11] P.S. Drell, *"Weak Decays, Rare Decays, Mixing, and CP Violation"*, Review Talk, Proceedings of the XXVI International Conference on High Energy Physics, Vol.1, page 3, Aug. 1992, Dallas, Texas.
- [12] J.T. Walker et al., Nucl. Instrum. Methods 226 (1984) 200.
- [13] W. Buttler et al., Nucl. Instrum. Methods A273 (1988) 778.
- [14] J.C. Stanton, IEEE Trans. Nucl. Sci. 36, No.1, (1987) 124.

- [15] O. Toker et al., "*VIKING, A CMOS Low Noise Monolithic 128 Channel Frontend for Si Strip Readout*", submitted to Nuclear Instruments and Methods.
- [16] M. Caccia et al., Nucl. Instrum. Methods A260 (1987) 124.
- [17] G. Batignani et al., Nucl. Instrum. Methods 310 (1991) 160.
- [18] L. Evensen et al., Proc. of 4th Int. Conf. on Solid State Sensors and Actuators, Tokyo, Japan, p. 271, June 1987.
- [19] P. Holl et al., IEEE, NS 36, (1989) 251;
- [20] P.P. Allport et al., Nucl. Instrum. Methods A310 (1991) 155;
I. Hietanen et al., Nucl. Instrum. Methods 301 (1991) 116.
- [21] A. Peisert, "*Silicon Microstrip Detectors Instrumentation in High Energy Physics*", ed. F. Sauli, World Scientific Publishing Co., Singapore, 1992.
- [22] M. Laakso, Ph.D. Thesis, "*Radiation Detection Techniques for High Energy Physics and Industrial Applications*", Report Series, Hu-SEFT RD 193-01, University of Helsinki, Finland.
- [23] M. Laakso et al., Nucl. Instrum. Methods A326 (1993) 214.
- [24] B.S. Avset et al., IEEE Trans. Nucl. Sci. Vol. 37, No.3, (1990) 1153.
- [25] P.P. Allport, Nuclear Physics B (Proc. Suppl.) 32 (1993) 208.
- [26] The SVXZH chip is a further development of the SVX chip, see : S.A. Kleinfelder et al., IEEE Trans. Nucl. Sci. NS 35 (1989) 171.
- [27] M. Neese et al., "DS-641 Double-Sided Si Microstrip Sensor"; paper presented at the 7th International Conference on Solid State Sensors and Actuators, Yokohama, Japan, June 1993.
- [28] K. Leinonen, "*Fabrication of Radiation Detectors on High Purity Silicon*", Licentiate Thesis, Helsinki, 1991.
- [29] The author is grateful to the members of the DEPHI μ -vertex group who permitted the use of these results prior to publication.
- [30] MX7 is a modified version of the MX3 chip [14] produced in 1.5 μ m MIETEC technology.

Table 1

Si Sensor Characteristics and Some Properties of Vertex Detectors
Installed in the 4 LEP Experiments

DETECTOR	ALEPH	L3	OPAL	DELPHI
Total detector surface [m ²]	0.252 (×2)	0.255 (×2)	0.149 (×2)	0.4105
# of readout channels	73728	73728	32000	73728
# of layers	2	2	2	3
layer 1	6.5	6.1	6.1	6.3
layer 2	11.5	7.8	7.5	9.0
layer 3	-	-	-	11.0
angle coverage cos θ <				
layer 1	0.85	0.92	0.83	0.86
layer 2	0.65	0.88	0.77	0.80
layer 3	-	-	-	0.73
# of ladders	24	24	25	72
layer 1	9	12	11	24
layer 2	15	12	14	24
layer 3	-	-	-	24
total # sensors	96	96	150	288
sensor size				
layer 1	51.2 × 51.2	70 × 38	60 × 33	48 × 19
layer 2	51.2 × 51.2	70 × 38	60 × 33	58 × 26
layer 3	-	-	-	58 × 32
sensor thickness [μm]	280	300	250 (×2)	280
strip pitch rφ	25	25	25	25
[μm] z	50	50	50	
Manufacturer	CSEM Neuchâtel	CSEM Neuchâtel	MICRON SEMI- CONDUCTOR, UK	S.I. Oslo
Coupling to readout electronics	DC, external AC coupling chip	DC, external coupling chip	AC	AC
Bias method p-side n-side	p ⁺ reach through n ⁺ accum. layer	p ⁺ reach through n ⁺ accum. layer	FOXFET	Polysilicon
Ohmic separation on n-side	p ⁺ blocking strips	p ⁺ blocking strips	z strips pn junction	-
z readout	electronics mounted in sensitive area	L print 50 μm thick kapton foil	Z print on 200 μm thick glass	-

Table 2

Results on spatial resolution for different detectors

Experiment	Manufacturer	Rad. Length	Strip Pitch [μm]		Readout Pitch [μm]		Approx. Detector Dimensions [mm ²]	Detector Thickness [μm]	Module Size in Experiment [mm ²]	Resolution at 0° [μm]	
			rφ	z	rφ	z				rφ	z
ALEPH	CSEM	0.6%	25	25	100	100	50 × 50	280	100 × 50	12	12
DELPHI	SI Oslo	0.32%	25	-	50	-	60 × 32	280	120 × 32	8	-
DELPHI Upgrade	SI Oslo	0.30%	25	50	50	50	6.4 × 6.4	280		4	9
	SI Oslo ⁽¹⁾	0.30%	25	35	50	35/70	50 × 20	280		3	7
	VTT ⁽¹⁾	0.30%	25	50	50	50/100	19.2 × 19.2	280		4	7
	VTT ⁽¹⁾	0.30%	25	50/100	50	50/100	77 × 19.2	280		5	10/23
	Si Oslo ⁽²⁾	0.33%	25	43/85	50	43/85	120 × 32	280		5.5	7
L3	CSEM	0.35%	25	50	50	150/200	70 × 40	300	140 × 40	7	15
OPAL	MICRON ⁽³⁾	0.65%	25	25	50	100	60 × 32	2 × 250	180 × 33	6	6
OPAL Development	MICRON	0.30%	25	50	50	100	60 × 32	300		5	11

(1) Double-Sided Double-Metal

(2) Half module with 2 daisy-chained sensors

(3) Both rφ and z are measured on separate single-sided pn-junction sensors

Figure Captions

- Fig. 1 : Measurement of τ lepton lifetime from 3-prong decays of 1991 data sample (DELPHI).
- Fig. 2 : Event display for a $Z^0 \rightarrow b\bar{b}$ candidate, DELPHI experiment.
- Fig. 3 : Relation between the error on the projected impact parameter (y_{imp}) and the errors on the transverse co-ordinates (y_1, y_2) at x_1 and x_2 .
- Fig. 4 : Schematic layout of the DELPHI Microvertex Detector :
a) Perspective view;
b) Projection on the plane transverse to the beam.
- Fig. 5 : The error on the impact parameter as a function of p_t , in real data for the DELPHI Microvertex Detector. The dashed data gives the contribution from the error on the vertex, which has been subtracted quadratically from the error per track. The full line is a fit to $\sqrt{69^2 / p_t^2 + 24^2}$ μm (p_t in GeV/c). The expected error transverse to tracks at the beamspot is represented with a dotted line.
- Fig. 6 : Charge distribution measured with a Si strip sensor with readout pitch of 25 μm and S/N of 70 [7]. x is the distance from the impact $x = 0$ of the track.
- Fig. 7 : Charge division between neighbouring strips due to charge cloud diffusion. The spread of the part of the charge that is created closest to the n-side surface is illustrated. The hatched part of the charge is collected by the left strip (Q_L) and the rest is collected by the right strip (Q_R). The dashed lines represent the direction of the electric field lines in the detector.
- Fig. 8 : Sensors with integrated "reach through" biasing structures on the junction side. With gate for FOXFET operation [5]. (a) Top view showing drain consisting of p^+ implant with metal contact (hatched) and p^+ strips acting as source. A metal gate is overlapping drain and source. (b) A cut along the strip.
- Fig. 9 : The reach through phenomena in a p^+np^+ structure [22]. (a), (b) and (c) show the potential distribution between the source and drain for different voltage differences.

- Fig. 10 : The strip potential as a function of device bias for reach through structure for different gap and strip width.
- Fig. 11 : Dependence of strip voltage on gate voltage in a fully-depleted FOXFET bias device.
Parameters : gap dimension, strip width, manufacturer (S.I., Oslo, Norway; MICRON SEMICONDUCTOR, UK; CSEM Neuchâtel,, Switzerland).
- Fig. 12 : Current voltage characteristics for a strip with FOXFET biasing structure with gate at 0 V and 5 V. Bias voltage : 90 V.
- Fig. 13 : Leakage current dependence of dynamic resistance R_{dyn} of a FOXFET structure. The variation of leakage current was obtained by heating the device.
- Fig. 14 : Dynamic resistance for two FOXFET structures from 2 different manufacturers as a function of gate voltage. The two devices differ mainly in leakage current.
- Fig. 15 : Techniques for n-strip separation. a) The connection of strips through the electron accumulation layer. b) Field plate separation with a separate field plate. c) Field plate separation with extended AC-coupled electrodes. d) Separation with intermediate p-type strips.
- Fig. 16 : Interstrip resistance as function of field plate voltage for sensors using field depletion technology.
Parameter : Width of metal strips.
- Fig. 17 : Schematics of cross-section of a sensor with readout on both sides and double metal layers on n-side.
- Fig. 18 : Schematic layout of contact regions for field plate design. The connection between polysilicon resistor and diffusion strip necessitates a second metal layer to guarantee a complete interruption of accumulation layer.
- Fig. 19 : a) Layout of a sensor with FOXFET type structures on both p-side and n-side;
b) I-V characteristics of "field plate" biasing device for n-strips from Fig. 19a.

- Fig. 20 : Principle of double metal readout scheme.
- Fig. 21 : The glass z-print used in the OPAL experiment for routing z strips.
- Fig. 22 : Pulse height distributions measured on $r\phi$ and z side of sensors for L3 experiment.
- Fig. 23 : Residuals measured in test beam for L3 sensors on $r\phi$ and z side.
- Fig. 24 : Signal (PH), noise and signal over noise measured with 10 double-sided double metal Si strip sensors produced by VTT Helsinki. Squares are for p-side and circles for n-side.
- Fig. 25 : Spatial resolution as a function of angle obtained with a VTT prototype detector. Dots are p-side and triangles are n-side.
- Fig. 26 : Signal over noise measurements on p-side and n-side for sensors as described in Fig. 19; a) p-side, b) n-side.

Fig. 1

Delphi Vertex Detector
Run 21582 event 6995

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

p⁺ isolation strip bias

n⁺ readout strip bias

a)

b)

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23

Fig. 24

Fig. 25

Fig. 26