Recent Developments in Silicon Sensors

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ABSTRACT
An overview of current and upcoming new Silicon detector technologies is presented here. Long ladders, and wedge-shaped detectors are looked into more detail.

1 Introduction
Physics interests for future high energy particle accelerators require large, fast, and high precision detectors in both the barrel and forward regions. We present here the recent developments of such sensors. In particular, long ladders and wedge-shaped detectors are looked into more detail, as our group is deeply involved in R&D in these.

2 Basic Principles of Silicon Sensors
Silicon sensors are achieved by reverse biasing an n-p junction. This creates a depletion region, which increases with increasing voltage. A particle passing through this will form electron-hole (e-h) pairs. These then drift to opposite sides of the detector.

In practice the sensor is 300 μm thick, with the bulk of the material being n-type. The p-type is heavily doped, and is arranged as strips. Aluminum strips on top of these are used to collect the charge by the readout chips. These strips are ohmically separated using SiO2. If there is a double sided readout, then the back (ohmic) side has heavily doped n-type strips. The depletion region extends throughout the whole bulk for bias voltages above ~ 50V. The strips are normally readout every 50 μm. There often are intermediary strips, which by charge-sharing increases the resolution of the sensor.

Advantages
- Silicon sensors are characterized by a very high efficiency. This can be virtually 100% for working channels (these are 95% to 99% of the total channels).
- They are extremely fast, with risetimes of around 40 μsec achieved.
- Accuracies of up to 1 μm are reported[1] (with a 25 μm readout pitch). In accelerator enviroments

![Figure 1: Silicon sensor](image)

the resolutions are usually between 5 and 15 μm, depending on size of the sensor, readout pitch, external noise, and alignment.

- Very high signal to noise (S/N) ratio can be achieved. A S/N ratio of 140 has been achieved using the Viking chip[2]. In practice a S/N ratio of around 10 is sufficient to have reliable position predictions.

Noise sources
Some of the main factors that make the silicon detectors non-ideal are:

- readout electronics: the readout chips themselves are a noise source, which depends on the capacitance of the detector. An example of a very low noise readout chip is the Viking, having a noise of 125e- + 14 × Ctotal e- . Ctotal is the total detector capacitance seen by the input of the amplifier.

- interstrip capacitance: this is usually around a few pF/cm of strip length. This is the main source of the above mentioned detector capacitance. Thus the longer the sensor, the larger the noise. This puts limits on how long the sensors can be made.
• leakage currents: can prohibitively increase under high radiation exposure.

• δ electrons: electrons knocked out by the incoming particle. Smears the signal and probably limits the resolution to $\sim 1 \mu m$ (for 300 $\mu m$ sensor thickness).

A further problem which will have to be considered at high radiation environments like the LHC($\sim 10$ Mrad and $\sim 10^{14}$ neutrons/cm$^2$ over 10 years) is radiation damage.

The capacitances (and hence noise) increases with exposure. Furthermore, the voltage necessary for depletion can get so high that it can reach breakdown. The detector is then not fully depleted and the signal is reduced. Also, annealing of the material with time causes inversion of the bulk material from n-type to p-type, rendering the sensor useless.

It has been found that cooling the sensor below $10^6$C can slow down the annealing[3]. A further option is to use Gallium Arsenide detectors. These have a much higher radiation tolerance. The signal to noise ratio though is not as high as for Silicon sensors.

3 Wedge Sensors
The logical geometry for forward tracking detectors is a circular one. This can be achieved by wedge-shaped sensors(Figure 2). And a radial layout of the strips(i.e. variable pitch) makes them particularly suitable for the ease in constructing fast $P_T$ triggers [4]. This makes wedge-shaped detectors a natural choice for fast forward-backward tracking, complimenting the barrel region.

Figure 2: Wedge-shaped sensor

An investigation was done by our group into the dependence of resolution of pitch. The results are plotted in figure 3. The behavior is clearly linear (Resolution = $(0.21 \pm 0.01)$Pitch), and thus no unexpected problems arise at both high and low strip separation. Also plotted is the geometrical resolution due to single strips ($Pitch/\sqrt{2}$).

A further property investigated was the variation of cluster size with pitch. This is shown in Figure 4a. The distribution is essentially uniform. We also studied the resolution and cluster size if the sensors were read out in digital mode by considering only strips with signals above $4\sigma_N$ and replace the charge weighted mean by the unweighted mean. We found the cluster size again is independent from the pitch(Figure 4b). Therefore if the strips are readout digitally as in a sparse data mode, no significant loss of resolution is expected.

4 Long Ladders
One can design very large detectors by wirebonding together several smaller ones(usually ~ 8 cm long) into so called silicon ladders (Figure 5). This enables the readout of an increased area with both the number of channels read out and total dead area due to electronics staying the same as for the single sensor.

One problem with long ladders is that the noise can get prohibitively large with longer strips(larger interstrip capacitance). A full testbeam study was done using sensors with length up to 64 cm[6].

Table 1 shows the preliminary results for a single sided 60 cm design by VTT, Finland. The readout was done using the Viking chips. The results show that even at the longest lengths we have a satisfactory S/N ratio(10 at 60cm). The efficiencies are also good. The active area reduction is mostly due to scratches and mishandling, and it is believed that this can be easily avoided in the future.

Large number of tracks in LHC-like environments pose a problem when using very long ladders. One is faced with about 30 events per crossing, 40 tracks per
event. Then the occupancy per strip can be high, and one ends up with multiple particles appearing as just one. A 2-D readout would help this. But here so called ghost particles can appear. These are caused when different combinatorics of 2-D positions are equally valid.

5 Pixel Detectors

The above mentioned problems may turn out to be insurmountable for the closest layer to the interaction point. A likely solution is to use pixel detectors. Here instead of strips, square pads about 100 μm across are read out individually by bump bonding readout chips on top of the sensor[6]. This avoids the ambiguities. Further, since the elements are smaller, one has lower capacitances and thus lower noise. Hence thinner sensors can be made, reducing multiple scattering (important for particles with momenta less than a few GeV/c).

And since the leakage current induced by radiation is proportional to the surface of the detector element, pixel detectors are more radiation resistant than strip detectors. Also, pixels withstand more noise increase and defects in charge collection.

The problem is of course that a huge number of channels has to be read out. Pile up problems arise (at LHC there will be 25 ns between beams, and 2 μs between level 1 triggers). Recent research indicates that these problems can be handled, although large areas may not be able to be covered successfully.

6 Conclusion

Silicon sensors with their high S/N, efficiency and accuracy are ideal for vertex detectors, and will be the main component of most future central trackers. Very long ladders and wedge detectors perform well under testbeam conditions and should not present any major obstacles to be incorporated in future central trackers. Pixel detectors are very feasible and are probably necessary for closest layers in high flux environments.

Acknowledgments

Many thanks go to the Aachen Germany, INFN Florence, INFN Perugia, SEFT Finland, and NCU Taiwan groups, without which our joint testbeams would not have been possible.
References
[5] Adriani et al., Beam test results on Si and GaAs microstrip detectors with length up to 64 cm, to be published in NIM(1995)