Presented at the Semiconductor
Detector Workshop Fermilab
15-16 October 1981

CERN/EF 81-16
15 December 1981

SILICON MICROSTRIP DETECTORS, A NEW TOOL FOR HIGH ENERGY PHYSICS

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1. PARTICLE DETECTION IN SILICON

The characteristic property of a monocrystalline semiconducting material is the small separation between the electronic conduction band and the valence band. A small amount of energy, $E_g = 1.12$ eV in the case of silicon, is therefore sufficient to excite an electron into the conduction band. The hole left in the valence band behaves like an independently moving positive charge carrier and has a mobility which is comparable to that of the free electron ($1500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for e^- and $600 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ for the hole [1]). At a given temperature there is equilibrium between the generation and recombination of free electrons and holes. Impurities and crystal defects act as generation or recombination centers and reduce therefore the mean free carrier lifetime. The introduction of electrically active donor or acceptor impurity atoms ("doping") results in a n-type or p-type conductivity semiconductor with an excess of electrons respectively holes. The product of the concentrations of electrons n and holes p remains however constant

$$n \cdot p \propto e^{-\frac{E_g}{kT}}$$

Free charge can be generated in excess of this thermal equilibrium value by electromagnetic or particle irradiation. It has been found that on the average 3.62 eV is deposited in the silicon for every generated electron-hole (e-h) pair. This value is apparently independent of the type of particle. The difference with the bandgap energy ($3.62 - 1.12$ eV) is spent on other types of excitations in the Si lattice. If the mean free carrier lifetime is sufficiently long, the radiation-produced charge can be

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integrally collected by applying an electrical field to the semiconductor. In the case of Si at room temperature however, a rectifying diode structure with non-injecting contacts must be used, to avoid a large steady current, which would mask the small radiation induced signals.

Minimum ionizing particles deposit energy in thin silicon detectors, and the energy spectrum is similar to the one described by Landau for energy loss. The most probable energy deposit is about 27 keV per 100 μm of Si and this energy deposit is nearly independent of momentum, as shown in fig. 1 (see also ref. [2]). The specific energy deposit is however a non-linear function of the detector thickness, and for a 1 mm thick detector the value is about 32 keV per 100 μm of Si. To collect all the charge generated in the detector thickness, the electrical field, and therefore the diode space charge region must extend from the rectifying side to the back contact on the silicon wafer, and this imposes the use of very high resistivity, very pure silicon, containing less than 10^{13} cm^{-3} doping atoms. The thickness X_D of the diode space charge region, or "depletion layer", can be found by solving the Poisson equation, and depends on the applied reverse bias voltage V_B and the doping density N_D , which appears macroscopically as the material resistivity ρ (in $\text{k } \Omega \text{ cm}$)

$$X_D = \sqrt{\frac{2 \epsilon \epsilon_0}{q N_D} (V_0 + V_B)} = .5 \sqrt{\rho (V_0 + V_B)}$$

q is the unit electrical charge, V_0 is the built-in diode voltage (about .8V), ϵ and ϵ_0 are the relative and absolute dielectric constants.

The signal formation in semiconductor detectors is basically different from the process in gaseous MWPC or drift chambers. There is no multiplication in the semiconductor, and the signal is induced on the contacts as soon as the electrons and holes start separating from the initially neutral cloud of excited carriers. The drift velocity is proportional to mobility and field, up to a saturation velocity of 10^7 cm s^{-1} at room temperature, which can be attained at a field of $\sim 10^4 \text{ V cm}^{-1}$. The total collection time in a 400 μm thick detector at 200 V is then about 8 ns for electrons and 20 ns for holes, but the rise

Fig. 1: Total energy loss for muons in silicon, including ionization loss, pair production, Bremsstrahlung and nuclear loss (calculated by Claude-Serre [3]) compared with measured energy deposition in thin silicon detectors. The lower points are the most probable deposit (peak of the Landau distribution), the higher points represent the mean values. Data were obtained with pions, protons and muons by Esbensen et al. [2] and Heijne, Jarron and Viertel (unpublished).

time of the current signal is only about 6 ns. The integrated charge from a single minimum ionizing particle in such a 400 μm thick detector is about 5 fC or 30 000 e-h pairs. Such a signal is shown in fig. 2 at the output of the fast preamplifier (described in sect. 3).

Fig. 2: Typical signal at the output of the preamplifier (10 ns/div.) for a particle which deposits about 120 keV or 5 fC of charge.

2. MICROSTRIP STRUCTURES

Silicon detectors of 1 mm^2 to 10 cm^2 area and a few μm to a few mm of thickness are available commercially since a long time; initially mostly diffused diode structures, more generally now with a Schottky surface barrier as the blocking contact. Also lithium drift (for thick diodes) and ion-implantation (for resistive surface layers) have been used. Recently, J. Kemmer [4,5] proposed an improved ion-implantation process, which involves planar oxidation and photo lithography techniques, now commonly used in the electronic industry. This process leads to very low diode reverse leakage current and low noise detectors.

Occasionally, silicon strip detectors and silicon "checker board" detectors were used for position sensitive particle detection, as early as 1963, but for nuclear physics the position sensitive resistive readout was brought to perfection [6]. The spatial resolution $\Delta x/L$ is limited by the position noise N_x , which is > 50 keV for 100 pF detector capacity and a

2 μ s signal shaping time. For signals of several MeV this leads to a resolution of better than 1%, but the particle rate and the time resolution are limited.

$$\frac{\Delta x}{L} = \frac{Nx}{E}$$

Because of the very small signals of minimum ionizing particles, around 100 keV in a 400 μ m thick silicon detector, silicon microstrip detectors are proposed for detection in high energy physics experiments, where good spatial resolution is required [7,8]. It is expected that the application of micro electronics silicon technology could result in detecting elements of 5 to 20 μ m diameter.

The first prototypes for use in high energy test beams were made with surface barrier technology and had 1 mm [7] respectively .4 mm [8] elements. Results of the tests will be discussed in sect. 4. More recently [9] a detector was built with 100 elements of 50 μ m pitch, covering a 30 x 5 mm area. The masks and the mounting used during the evaporation are illustrated in fig. 3. In fig. 4 enlarged pictures of this mask and the resulting aluminium pattern on the silicon are shown. These detectors were manufactured in close collaboration with Enertec-Schlumberger in Strasbourg (France).

Fig. 3: Masks and mounting used for the vacuum evaporation of a 50 μ m strip pattern on silicon surface barrier detectors. The right-hand mask is used for the reinforcement of the contacts on the epoxy edge.

Fig. 4 (a) Photo micrograph of the mask shown in fig. 3. Contacts are made alternatively to the left and the right, so that there is one contact every 100 μm .
(b) Aluminium strips on the silicon surface, evaporated through this mask.

An alternative approach for building microstrip detectors makes use of the already mentioned improved ion-implantation planar ("IP") process. This eventually leads to a better pattern definition, much lower leakage currents and a lower electrical noise. In fig. 5 a cross section is shown of two such ion-implanted strip detectors, which were also manufactured in collaboration with Enertec. In a suitable mounting, such IP detectors can be annealed to 200°C, or possibly higher temperatures, which could be useful in a ultra-high vacuum environment or for the curing of radiation damage.

Fig. 5: Structure of planar versions of a 200 μm pitch and a 50 μm pitch parallel microstrip detector.

If one compares the strip structure for particle localization with the resistive read-out detector, the former has a number of advantages for the use in high energy physics experiments:

- (a) Fast signals can be obtained with a relatively thin detector ($.05 \text{ g cm}^{-2}$, corresponding to 30 cm of Ar), which enables high particle rates and good timing ($\sim 1 \text{ ns}$).
- (b) High multiplicity events can be accepted, although a true 2 dimensional discrete structure would be much better than combined strip detectors, because of the ambiguities in strip combinations.
- (c) If a parallel electronic treatment is used, the information can be used to establish fast triggers.
- (d) The position resolution does not depend directly on detector noise, which may increase with time, due to radiation damage.
- (e) Room temperature operation is possible.

Clearly, the main disadvantage is the multitude of electronic channels. The number of channels for $10 \text{ }\mu\text{m}$ resolution detectors for any realistic system rapidly attains a few times 10^4 for a fixed target experiment or a few times 10^6 for a collider experiment.

3. ELECTRONICS FOR SILICON MICROSTRIP DETECTORS

Successful application of silicon microstrip detectors in high energy physics experiments will be critically dependent on the possibilities which can be found to handle the large number of low noise electronic channels. Moreover, detector and electronics have to be very close to minimise noise. An integrated design of detectors, electronics and the mechanical structure is necessary in view of the required high density. Several iterations in miniaturization of the electronics have already been made or are being studied. One makes use of the improved characteristics of bipolar microwave transistors, to build small, relatively cheap, low noise preamplifiers with low power dissipation [9]. When dealing with the

Fig. 7: Preamplifier and line-driver circuits shown along with a surface barrier microstrip detector with 100 strips of 50 μm pitch.

special case of small capacitance microstrip detector elements (< 10 pF), an extremely simple current sensitive preamplifier can be used [8]. In fig. 6 a schematic diagram is shown, and in fig. 7 such a preamplifier is shown, besides a microstrip detector with a 5×30 mm central sensitive region (100 strips of $50 \mu\text{m}$).

MICROSTRIP DETECTOR PREAMPLIFIER

Fig. 6: Electronic scheme of a current sensitive low noise preamplifier to be used with a low input capacitance microstrip detector.

Fig. 8: Schematic drawing of a complete read-out chain for a microstrip, which provides a fast analog output signal and a discriminated logic signal.

Depending on the experimental situation, the signal output of the preamplifier can be immediately discriminated or has to be transmitted to an electronics barrack. In fig. 8 is shown in a complete electronic chain which provides both logic and fast analog signals, transmitted over nearly 100 m. The implementation of this system is illustrated in fig. 9 and signals are shown in fig. 10. The r.m.s. electronic noise is about 1400 electrons, which corresponds to a 15 keV FWHM in Si.

Fig. 9: Mounting of the 48-channel preamplifier driver modules next to the detector, which is shown without its precision support. The two NIM modules below are the 12-channel receiver driver modules, which can be located 40 m away from the detector.

Fig. 10: Output signal of receiver module with pole-zero cancellation.
The input charge of the pulser was 5 fC.

The electronic noise in general depends on the detector and the preamplifier. The diode reverse current and the cross talk resistance determine the detector noise. In the course of time, the detector noise may become worse due to increased reverse current by radiation damage and incomplete charge collection. The preamplifier noise is mainly determined by the detector capacitance and the noise performance of the input transistor [9,10]. With the presently designed electronics, a sufficient signal/noise ratio is obtained with a detector thickness of 250-400 μm silicon.

A completely parallel linear signal processing, as described here, certainly cannot be used for future large detectors. On the one hand, a reduction in the number of channels can be obtained by a charge interpolation method on the detector level. On the other hand, parallel to serial conversion using digital techniques, or possibly analog devices like charge transfer devices (CCD), may diminish the number of outputs to an acceptable quantity. Also the off-line data analysis has to remain manageable, therefore some on-line data reduction seems needed, possibly in connection with a high level trigger logic.

Fig. 11: Typical spectrum for a strip. The pedestal width is a measure of the electronic noise. The Landau spectrum of 10 GeV π^- is shown enlarged in the insert.

4. RESULTS OF BEAM TESTS

A typical spectrum obtained for a single strip in a test beam of 10 GeV π^- is shown in fig. 11. The detector thickness was 280 μm . The channel numbers obtained in the pulse height analysis can be converted to keV, using a ^{57}Co calibration, and the zero-energy corresponding to the position of the pedestal peak. The small tail on the low energy side of this Landau type distribution is included because of the "hit" definition. It is clear that the particle signals are well separated from

the noise peak. In our definition, a strip is hit, if its signal exceeds the average pedestal value by more than three standard deviations of the pedestal noise distribution (PND).

Sometimes one finds several adjacent strips hit. This is called a cluster. A double hit is then by definition a cluster of only two adjacent hits. This double hit phenomenon was studied by rotating the detector 45° in the beam. It was verified that the sum of signals in three adjacent strips (fig. 12) was $\sqrt{2}$ times the signal at perpendicular incidence. Therefore, no signal loss occurs between the strips.

Obviously, also an efficiency measurement can be used to ascertain that there are no dead regions between the strips. The set up of fig. 13 was used to this aim. In table 1 an analysis is given for 49181 events which were triggered by all three scintillators.

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Fig. 12: By comparing signals at 45° incidence with those in the normal case it could be verified that within our measurement accuracy (5-10%) no signal loss occurs for particles crossing the inter-strip boundaries.

Fig. 13: Situation of the microstrip detector M between wire chambers with centre of gravity read-out. S1, S2, S3 are scintillators used to trigger the read-out.

TABLE 1

Analysis of hits on 200 μm IP detector (run 4026 beam)

All events	49181		100%	
No hits in Si	295		.6%	
Only 1 cluster	44042		89.6%	
		1 hit	41965	85.3%
		2 hits	1952	4.0%
		3 hits	84	.2%
		>	41	.08%
2 Clusters	4440	2 x 1 hit	4099	8.3%
3 Clusters	355			
	49132		99.9%	97.9%

The inefficiency is only .6%. For this planar detector only 4% of double hits are observed. In the case of a surface barrier detector the number of double hits is 15-25%. This is mainly related to the lower interstrip resistance, which can be $\sim 100 \text{ k}\Omega$ for surface barrier detectors and is in excess of $1 \text{ G}\Omega$ for the IP detectors.

To study further the phenomenon of double hits a comparison was made of double hits in the case of a ^{57}Co gamma irradiation and the beam test. In the gamma irradiation the events were recorded, using only one strip for the trigger. Of 100 000 events somewhat more than one third were rejected because more than 10 strips had a signal or because the triggering signal was below the off-line threshold of three standard deviations of the PND.

The remaining sample had 9% double hits, which is twice the amount in the beam test. The energy spectra for single hits and double hits in both cases are compared in fig. 14. Double hits in the case of ^{57}Co yield

Fig. 14: Comparison of single and double hit energy spectra for ^{57}Co (left) and 10 GeV π^- (right).

exactly the same total energy as single hits, but double hits in the beam shown an excess of events with high energy content. Therefore it is concluded that double hits do not all originate from simple charge division, but that a significant fraction of them are special events with an extended delta electron or gamma shower. Further study of the double hits seems however needed.

In the set-up of fig. 13 the particle position can be predicted with the wire chambers. The residu between prediction and actual measurement on the silicon strip detector is shown in fig. 15 for 16 GeV π^- . The FWHM is 140 μm , which corresponds to a resolution of $\sim 60 \mu\text{m}$, nearly the limit of these wire chambers.

Fig. 15: Residu of predicted and observed position of a 50 μm pitch surface barrier microstrip detector. The width of one detector element is indicated.

5. RADIATION DAMAGE

Radiation damage in silicon is caused by the creation of charged defects in the crystalline lattice which disturb the electronic band structure. Single vacancies can be created by the excitation of a silicon atom from its lattice position, to which it is bound by an energy of $\sim 25 \text{ eV}$. These single vacancies are mobile above 55° K and recombine with other vacancies or with impurity atoms, to form stable "point-defects", like vacancy-vacancy, vacancy-oxygen or vacancy-phosphorus. The

predominant defects will depend on the type of silicon, the impurities present, the irradiation temperature, etc., and it is difficult to give general quantitative rules, valid for all cases of irradiation.

The study of radiation damage can be conducted at the microscopic level with a number of methods. Some information on the effect of GeV muon irradiation was obtained using the Thermally Stimulated Current (TSC) arising from certain deep electronic levels [11,12].

Macroscopically, the reverse diode ("leakage") current is for detectors the most accessible parameter which is influenced by the irradiation. The point-defects act as generation-recombination centers for e-h pairs and therefore increase the current and the noise in the diode. But also the space charge distribution, and therefore the capacitance can be modified by irradiation.

From experience in using silicon detectors in a high energy muon flux, the following conclusions can be drawn [12]:

- (a) The damage caused by minimum ionizing particles themselves may be relatively unimportant compared to that which is caused by a "hidden" component like low energy neutrons or electromagnetic cascades.
- (b) Degradation with time is not only related to irradiation, there may be other effects.
- (c) Electronics often breaks down before the detector, when it contains the more sensitive MOS devices.
- (d) If one introduces a damage tolerant design both for detector and electronics, the lifetime can be extended by several orders of magnitude.

From the foregoing discussion it must be clear that it is not justified to quote numbers with general validity. But signs of radiation damage will appear beyond 10^{10} – 10^{12} cm⁻² and detectors can be functioning up to 10^{11} – 10^{14} cm⁻². In a test of 4×10^{16} γ cm⁻² of ⁶⁰Co, which corresponds to about 2×10^7 rad, some detectors degraded considerably, others were still quite unaffected.

It is possible to remove some of the radiation damage by annealing the detector at 150-350°C. If one intends to do this, the detector and its environment have to be designed very carefully, because several metals like Na and Au have a high diffusion speed even at 150°C, and they create deep levels in the silicon, which are worse than the radiation damage levels. In this context one should remember that the initial electrical characteristics of the detector grade silicon are determined by $\sim 10^{12} \text{ cm}^{-3}$ doping impurities for $5 \times 10^{22} \text{ atoms cm}^{-3}$. Therefore even very slight contamination has considerable influence.

6. FUTURE DEVELOPMENTS

Silicon particle detectors may prove to be useful for the detection of short lifetime particles, events with high multiplicity or as detectors inside a vacuum chamber. At present, the spatial resolution is already better, or at least equal to that obtained in the gaseous or liquid detectors. High particle rates can be accepted because of the small element size, and the short collection time of both positive and negative charges. Therefore they may be suitable to study low cross section phenomena in intense beams.

Whereas the application in fixed target experiments appears rather straightforward, and the more so the higher the energy, applications in colliding beam experiments pose a number of problems. The most severe is the solid angle to be covered, and therefore the most immediate use of silicon detectors in colliding beam experiments may be limited to the forward detection region. There also one may find enough place for the electronics, which has to be close to the detector elements. For the central detection region, silicon could only enter into consideration if more sophisticated methods for connections, read-out and data processing have been developed [13,14].

Experimental groups at CERN, Pisa, Saclay, Munich, Milano, Brookhaven and Berkeley are at present working on various aspects of microstrip detectors. The commercial firm Enertec/Schlumberger near Strasbourg (France) is taking an active part in the production of these devices. Other firms like Ortec/EG & G, EMI (Ltd) and Centronic are intending also an effort in this direction.

In the near future a number of silicon microstrip detectors will be installed in running experiments at CERN, and this will enable a better evaluation of possibilities and problems. It is hoped that progressively solutions can be found for the electronics problems, for new contacting technologies and for true two-dimensional, or even three-dimensional detection.

It may be concluded that detector development reached the demonstration level, but that most of the work is still ahead if reliable devices are to be produced in significant quantity. The electronics development will be ultimately determining the usefulness of the multielement microdetectors. However, to the extent that both detector and electronics development consist in applying existing technologies to a new field of application, a rapid progress can be expected, at least initially.

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