CAPACITATIVE CHARGE DIVISION READ-OUT
WITH A SILICON STRIP DETECTOR

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ABSTRACT

We describe a silicon strip detector, measuring position with capacitive charge division read-out. It has a resolution determined by a strip pitch of 40 μm . The application and ultimate resolution of the method for minimum ionizing particles and α 's are discussed.

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and thus provides stable characteristics in addition to good junction characteristics. A uniform aluminium electrode is evaporated on the lower side of the detector.

The detector is mounted on a machinable glass support. A printed-circuit fan-out is glued to the glass, coplanar with the top surface of the detector. The silicon, printed board, and glue form a smooth surface on which a number of different strip patterns have been evaporated. One pattern, A, was that shown in Fig. 1, except that owing to a masking alignment error, strips d and 3, d and 4, etc., made electrical contact, thus giving three instead of four floating strips. (Three successive evaporations of layers, each $\sim 2000 \text{ \AA}$ thick, were used for this pattern.) Another pattern, B, was that of Fig. 1, but with the floating strips a, b, c, d omitted.

The counter has been tested using a 7 mm diameter, 13 μCi , ^{241}Am α -particle source ($E_{\alpha} = 5.5 \text{ MeV}$), collimated with a slit $\sim 20 \text{ }\mu\text{m}$ wide, 4 mm deep, and 15 mm long. The source and slit were mounted on a goniometer table and on a trolley system, giving x, y, z displacements reproducible to $\sim 2 \text{ }\mu\text{m}$. The slit was aligned parallel to the strips and about 1 mm above them. The α -particles were used so as to give a conveniently large charge, localized to a few tens of microns.

The signals from the read-out strips were amplified by conventional charge-sensitive amplifiers, followed by integration and differentiation time constants of 180 ns, and an output signal channel with fast rise-time.

The signal amplitudes were encoded with voltage-sensitive ADCs, and recorded and processed via a CAVIAR microcomputer³).

3. MEASUREMENTS AND DISCUSSION

The device described above acts as a diode counter with either polarity of applied voltage. With a negative voltage applied to the strips, the resistance between them was a few megohms. It was used with this polarity, was fully depleted at 25 V, and was operated at 40 V. With reversed polarity the interstrip resistance was so low that signals spread over a number of strips.

1. INTRODUCTION

We describe a silicon strip counter capable of measuring tracks with a precision of $\sigma \approx 12 \mu\text{m}$ and of giving a fast timing signal. It uses a novel method of charge division by capacitive coupling. This device was initially designed to measure the vertices of short-lived "charmed" particles produced in high-energy interactions.

Silicon surface barrier strip counters have been used for many years¹⁾, but have not until now achieved micron resolution. Counters with read-out strips with $\leq 30 \mu\text{m}$ pitch are costly, and connections to amplifiers are inconvenient for many channels at this density.

Charge division read-out can greatly reduce these difficulties. Resistive charge division involves a number of problems, including a compromise between introducing "parallel" noise and increasing the signal rise-time. To avoid these, we have investigated the method of charge division by capacitive coupling. The geometry of Fig. 1 illustrates the principle. The "floating" strips (a, b, c, d) charge up by surface leakage current to the applied bias voltage V_B . If a particle traverses strip 2a perpendicular to the counter, the charge liberated is collected on this strip in $\sim 20 \text{ ns}$ and decays away slowly. Thus image charges of $\sim 4/5q$ and $\sim 1/5q$ are induced on read-out strips 2 and 3, respectively, by capacitive coupling. The charge division is given purely by the geometry, provided that the bias voltage depletes the full thickness of the detector. We demonstrate that the resolution is determined by the strip pitch. This is $40 \mu\text{m}$, leading to a standard deviation of $40/\sqrt{12} \mu\text{m}$.

2. COUNTER AND MEASURING APPARATUS

The counter is a $350 \mu\text{m}$ thick silicon surface barrier detector, $20 \times 30 \text{ mm}^2$ in area. Surface barrier-type junctions were prepared on both sides of the silicon crystal by evaporating a $30 \mu\text{g}/\text{cm}^2$ layer of germanium onto the silicon, using the technique described by England and Hammer²⁾. This England-Hammer contact effectively seals the device from the influence of the ambient atmosphere

Using the unshaped fast output channel, we measured the signal rise-time to be 40 ns with the floating-strip pattern. The rise-time was mainly determined by the resistance of strips 2 and 3, which was around 5000 Ω . With strips with 1 μm thickness of evaporated Al, the rise-time should drop to ~ 20 ns, the collection time of the charges.

Figure 2 shows spectra of the quantity $S_3/(S_2+S_3)$ for successive x coordinate positions of the α -source over pattern A; S_2, S_3 are the amplitudes of the signals from strips 2 and 3, respectively. One sees clearly the quantization of this ratio as the source irradiates successive strips. These plots include only events with, at most, small signals from strips 1 and 4 to select α -particles on or between strips 2 and 3. A small fraction of counts with values of S_2+S_3 much less than the α -line peak, presumably due to scattered α 's, were also rejected.

Figure 3 shows the peak value of S_2+S_3 , the sum of the charges collected, as a function of the source position between two read-out strips.

The same measurements have been repeated for pattern B, without floating strips, and are shown in Figs. 4 and 5.

We explain the lower total charge collected from α -particles midway between the pick-up strips (Fig. 5 compared with Fig. 3) of pattern B (no floating strips) as follows. The floating strips were measured to reach the full applied bias voltage, from which we conclude that the unmetallized surface also reached this potential. However, the α -particles penetrate ~ 20 μm and release 1.5×10^6 electron hole pairs, whereas the surface charge density is only 7×10^5 charges per 100×100 μm^2 . Thus the α -particle neutralizes the charge producing the biasing field over a surface with linear dimensions that are large compared with our resolution, and approaching the detector thickness. This greatly increases the charge collection time, allowing the charge to expand under space-charge repulsion -- causing poor localization -- and also allowing a considerable fraction of the charge to be trapped. When the charge of the α -particles is collected under the floating strips, their capacity is large enough to maintain the biasing field. For minimum ionization particles this effect will be negligible, and the floating strips may not be necessary.

The ratio R of the capacity of a strip to ground and its capacity to its neighbours is given approximately by

$$R = \ln(p/w) / \ln(4t^2/wp) ,$$

where p and w are the pitch and width of the strips ($w < p$), and t is their separation from ground. This gives a rough indication of the fraction of the total charge not induced on the read-out strips. The variation of total charge measured, shown in Fig. 3, is consistent with this effect.

The minimum fraction of the read-out pitch which can be measured is determined by the signal-to-noise ratio. For minimum ionizing particles, $1 \times 10^5 t$ charges are liberated (t , the detector thickness in millimetres). A typical noise at room temperature for a charge-sensitive amplifier connected to our strips, with a capacity of ~ 10 pF, is $< 10^3$ electrons r.m.s. Thus, in principle, interpolations can be made to $< 1/(100t)$ of the read-out pitch.

While charge division will find the exact centre of a uniformly ionizing inclined track, energy loss fluctuations introduce a measurement error due to uneven deposition of ionization. For relativistic particles incident at 45° , this error is calculated to be roughly $t/30$.

This method, which uses the large ratio of interstrip capacity to strip-to-ground capacity, loses its value for a strip pitch that is large compared with the device thickness. Nevertheless it appears possible, for $t = 1$ mm, to obtain a resolution of ~ 10 μm for α -particles with read-out every few millimetres.

We mention a further observation which is relevant to the use of this device for measuring heavily ionizing particles. As shown in Fig. 2, the charge of α -particles incident on the "strip" side of the detector is collected preferentially by one or another strip and, as explained above, little charge is collected locally on the unmetallized surface between two strips. Figure 6 displays the sum of the spectra of Fig. 2, and two additional measurements at $x = 0$ and 190 μm . Since all these spectra contain equal numbers of events, Fig. 6 is essentially identical to the spectrum we observed by irradiating with a broad uncollimated

source. These "quantized" charge division ratios make even more evident the collection of the charge at discrete positions. We observed, however, that irradiating with an α -source on the lower (unstructured) side of the detector, the "quantized" structure disappeared. This arises from the expansion of the α -particle charge distribution under its own electrostatic field once the holes and electrons have separated. One may readily calculate that in a medium where a unit charge has a constant mobility, $\mu[(\text{cm/sec})/(\text{V/cm})]$, an expanding charge distribution approaches a spherically symmetric, uniformly charged expanding sphere of radius r , with a time dependence

$$r = \left[4.5 \times 10^{-7} \frac{\mu N}{\epsilon} \tau \right]^{1/3} \text{ cm ,}$$

where N is the number of charges, ϵ the dielectric constant, τ the time in seconds. For $E_{\alpha} = 5.5 \text{ MeV}$, $N = 1.5 \times 10^6$, and a time $\tau = 20 \times 10^{-9} \text{ s}$ corresponding to the transit time of the holes across the detector, $r \approx 100 \text{ } \mu\text{m}$. This explains the lack of "quantization" of the ratio R for this geometry.

For heavily ionizing particles, this expansion of the charge over a few strips gives rise to interpolation of the charge division ratio between the quantized values observed for an ionization deposit which is well localized. This allows a resolution much below the strip pitch. For minimum ionization particles, the expansion amounts to less than $1 \text{ } \mu\text{m}$.

4. CONCLUSION

We have demonstrated a spatial resolution with a standard deviation of $11.5 \text{ } \mu\text{m}$ for $5.5 \text{ MeV } \alpha$ -particles.

For minimum ionization tracks, capacitive charge division appears capable of localizing the trajectory to a fraction $< 1/(100t)$ of the read-out electrode pitch (t , the detector thickness in millimetres). Long-range knock-on electrons impose a limiting uncertainty of a few microns between the charge centroid and the trajectory.

For heavily ionizing particles, the position of the charge centroid should be measurable to a few microns with pick-up electrodes over 1 mm apart, and with a strip pattern that is coarse compared with the resolution.

For fast and slow particles, a pulse with a rise-time of $\sim 20 \times 10^{-9}$ s can be obtained.

For minimum ionizing particles, it may be possible to use a pattern without floating strips and still obtain the above performance. We will investigate this in the future, with three detectors in a high-energy beam.

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Figure captions

- Fig. 1 : Plan view and side section of counter, showing part of the repetitive pattern.
- Fig. 2 : Distributions of $R = S_3/(S_2+S_3)$ for different source positions. Channels 0 and 100 correspond to $R = 0$ and 1, respectively.
Strip pattern A.
- Fig. 3 : Variation of mean value of S_2+S_3 with x coordinate.
Strip pattern A.
- Fig. 4 : Distribution of $R = S_3/(S_2+S_3)$ as in Fig. 2.
Strip pattern B.
- Fig. 5 : Variation of mean value of S_2+S_3 with x coordinate.
Strip pattern B.
- Fig. 6 : Distribution of $R = S_3/(S_2+S_3)$ for pattern A, as arises from an uncollimated source.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6