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Simulation of charge collection and sharing in microstrip detectors

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Abstract

The various mechanisms which can cause broadening of the signal distribution in a microstrip detector are discussed, in turn, via a simple simulation. Some analytic results for calculating the effect of dead areas are also presented. A comparison is made of GaAs test beam data with the results of the simulation.

0. Introduction

In order to study the relative effect of various different factors affecting charge collection and therefore spatial resolution, we have set up the simplest possible simulation which would give an understanding of the basic phenomena. A distinction is drawn between signal cluster broadening due to real charge spread caused by track inclination or diffusion and that due to incomplete collection.

Each effect is examined in turn, the other effects being turned off.

1. The simulation

The program GARFIELD [1] was used to calculate the electric fields. A two-dimensional layout of backplane at +200 V with strips at 0 V, 300 µm away, was set up. The strip pitch was 50 µm. The electrodes were modelled as sets of 1 µm diameter wires with separation between centres 1.01 × the wire diameter [2]. Strip widths of 5, 25 and 45 µm were used at different times.

The induced charges were calculated using the weighting fields generated by the same program. The weighting field for strip i is obtained by setting the potential of strip i to +1 V and the potentials of all other strips and the backplane to ground potential. The weighting fields have the dimensions of inverse length and are purely geometrical functions of the electrode layout, effectively describing how the field lines from an isolated charge end at the electrodes. Via Ramo's theorem [3] the charge induced on the ith electrode by a charge q moving through a small displacement $\mathbf{ds}$ is

$$\mathrm{d}q_i = -q\mathbf{ds} \cdot \boldsymbol{E}_i, \tag{1}$$

where $\boldsymbol{E}_i$ is the weighting field for the ith electrode.

It is a consequence of Eq. (1) that if a single {e, h} pair is liberated anywhere within the detector and the electron arrives by any path at electrode i_1, and also the hole arrives by any path at electrode i_2, then the induced charges are −1 on electrode i_1, +1 on electrode i_2, and 0 elsewhere.

A real spread of charge within the detector due to track inclination or diffusion does produce charge sharing between the strips (see Section 4). Beyond this, incomplete collection is the sole cause of charge sharing.

The charges induced on the four neighbouring strips on each side of the central strip 0, have been calculated in addition to the signal on strip 0 itself. Strips ±5, ±6 were set up as 'guard' strips to minimise edge effects. The fields were calculated on a grid with pitch 6.6 µm in x and 2.0 µm in y, and the field value at any point was obtained by interpolation.

Silicon electron and hole mobilities were used with saturation at 8×10^6 cm/s, however, the main results are insensitive to the precise details of the carrier drift. Every 10 ps the carrier velocity, displacement and induced charge on all the electrodes were recalculated.

Consider a hole drifting along the line $y = 0$ from the backplane towards the centre of strip 0. It can be seen from Fig. 1, which shows the direction of the weighting field for strip −1, that at first the signal induced on strip −1 is of the same sign as the signal induced on strip 0. However, as the hole approaches strip 0, at $\sim x = 270$ µm, the signal induced on strip −1 flips sign, whereas that on strip 0 maintains the same sign.

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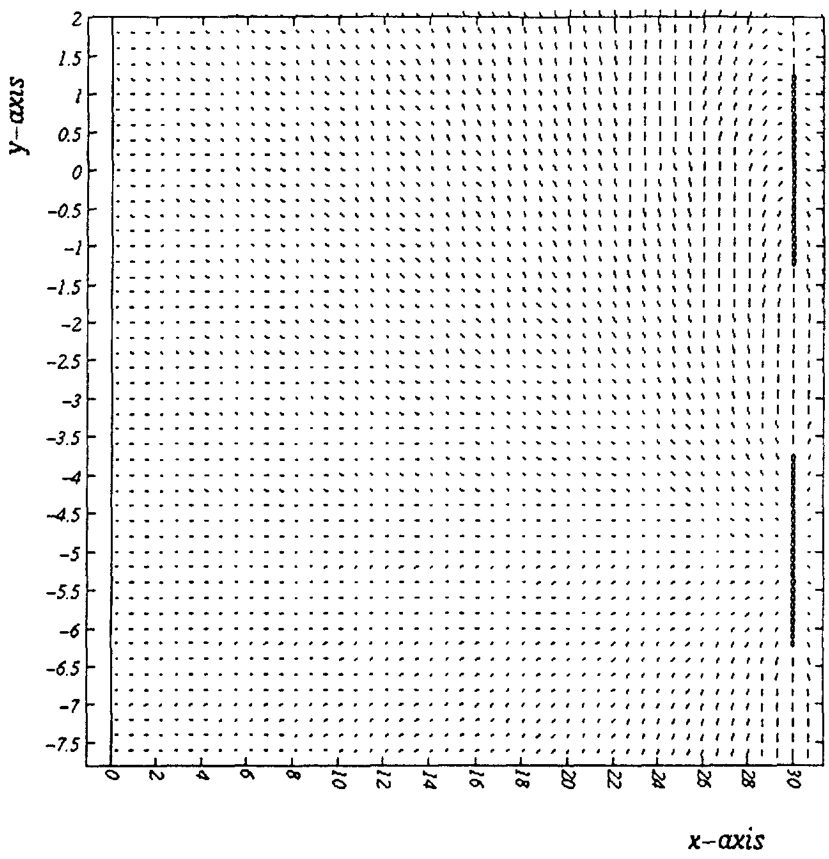

Fig. 1. The direction of the weighting field for strip −1. The units are 10 μm.

2. The effect of trapping in the bulk

A traversing minimum ionising particle (mip) was made to deposit one unit of charge evenly along its pathlength in 100 equal 'buckets'. Electrons and holes were given lifetimes τ_e, τ_h which diminished the contribution from a particular 'bucket' like $\exp(-t/\tau)$. The lifetimes were allowed to take one of only two values – either very short to trap immediately that kind of carrier, or very long to represent no trapping for that kind of carrier. By this means the effects of electrons and holes could be separately studied.

Fig. 2 shows the cluster profile for a mip traversal at $y = 0$, that is directly centred on strip 0. Fig. 2 (a), for both electrons and holes, shows the effect mentioned previously, i.e. that in the end all the holes finish on strip 0 and so the signal on all other strips is equal to zero within the accuracy of the calculation ($\leq$ 1%). Fig. 2 (c), for holes only, shows the effect of the sign flip in $\mathbf{d}s \cdot \boldsymbol{E}_i$ discussed above. Every hole generated along the 300 μm traversal is collected finally at strip 0 and most of them suffer the sign flip in their contribution to all induced strip signals except strip 0.

For electrons (Fig. 2 (b)) the story is very different. A minor fraction of the electrons produced evenly along the traversal feel the sign flip as they are drifting away from the strips. The cumulative signals induced on all strips by the electrons have therefore the same sign and the produced cluster is very broad.

The wings of the broad electron-induced cluster exactly compensate for the negative wings of the hole-induced cluster so that the cluster for electrons and holes together shows the spike at strip 0.

The integral is 0.5 for both Figs. 2 (b) and 2 (c), but the contribution to the signal on strip 0 is 0.84 for the carriers drifting to the strips and 0.16 for those moving to the backplane.

3. The effect of dead regions

For GaAs the undepleted (or low field) part of the bulk behaves like an insulator for fast signals and carrier movement in the bulk induces charge on the outer electrodes of

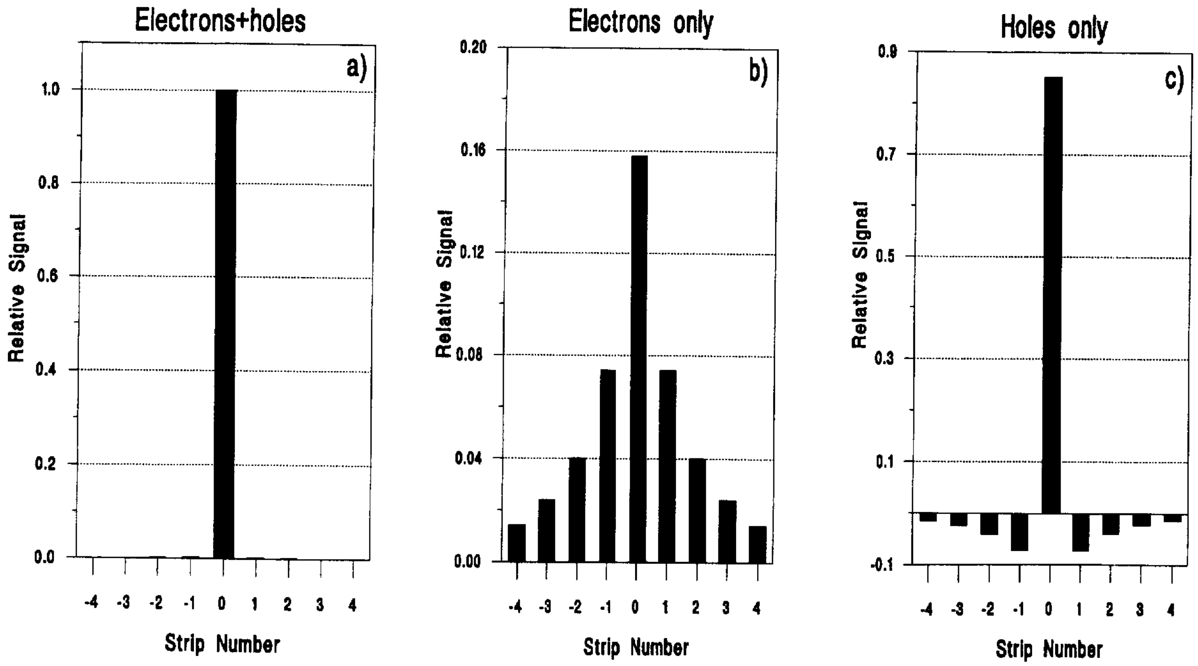

Fig. 2. Simulated cluster profiles for a traversal at $y = 0$.

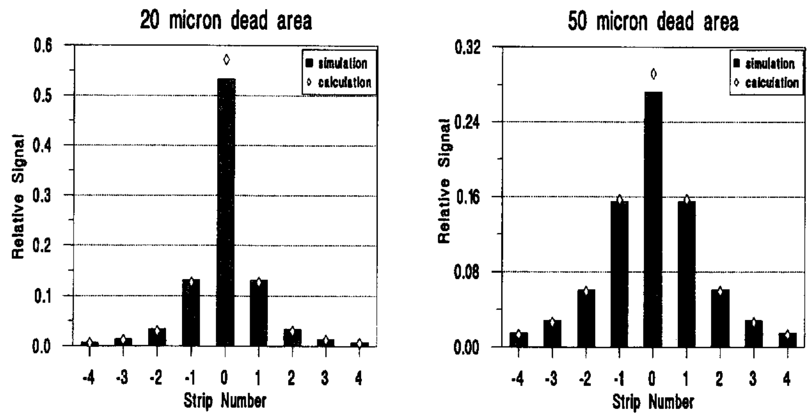

Fig. 3. Signal distributions for two thicknesses of dead region close to the strips.

the detector. In the next simulation the drift of all carriers was stopped in a layer successively 20, 50 μm thick next to the strip plane and the broadening observed – Fig. 3.

Also shown in Fig. 3 are the results of analytic calculations performed as follows. Using the method of images, the charge on plane 1 of two infinite planes, a distance w apart induced by a charge $+q$ at a distance d from plane 1, was integrated over a centred strip of width s. The solution for the relative charge collected at the strip q_s/q is an infinite series which is illustrated in Fig. 4 as a function of the normalised distance $x = d/w$ for different values of the strip width s.

Consider a charge released within the detector very close to the backplane $[(1-x) \ll 1]$ and drifting directly towards the centre of the strip. Via Ramo's theorem the curves tell us the charge induced on the strip as x diminishes from $1 \rightarrow 0$. At $x = 0$ we have full collection when $q_s/q \rightarrow 1$. For $s = \infty$ we have $q_s/q = 1 - x$, the simple linear dependence expected from the weighting field $1/w$ for a parallel-plate capacitor.

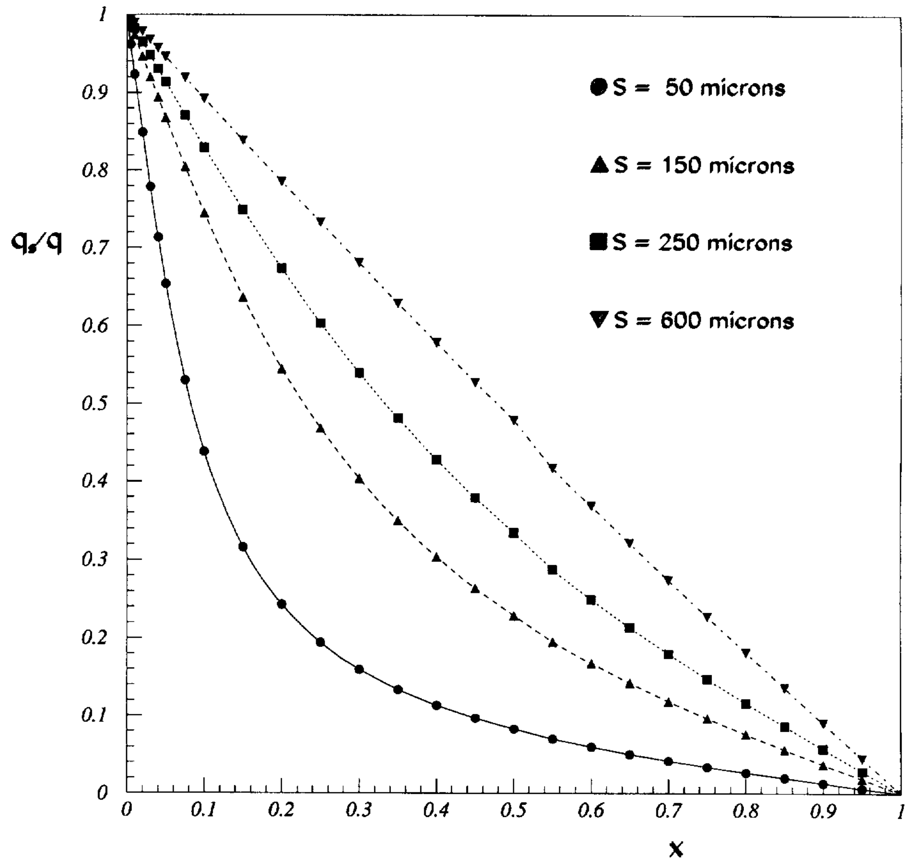

Fig. 4. The induced charge from the analytic calculation based on the first 100 terms of the infinite series.

For small x the series can be reduced to

$$\frac{q_s}{q} = 1 - \frac{4d}{\pi s}.$$

The conditions for this approximation to be good are $d \ll s$ and $d \ll w$.

The agreement between the analytic calculation for $s = p = 50\,\mu\text{m}$ and the simulation for $s = 25\,\mu\text{m}$ and $p = 50\,\mu\text{m}$, as shown in Fig. 3, is very good.

4. Track inclination and diffusion

Sharing effects were studied using the widely used parameter $\eta = A_+/(A_+ + A_-)$, where A_+ *and* A_- are the signal amplitudes on adjacent strips.

Inclined tracks with 10, 40 µm projection produce the sharing shown in Fig. 5. There are no surprises here, but it is noteworthy that this particular broadening mechanism uniquely produces sharing that is linear in η.

The simulation of diffusion presented in Fig. 6 was cross-checked by (a) interchanging D, μ for electrons and holes and observing very little difference, and (b) reducing the mobility μ by a factor 4, which is equivalent to reducing the bias voltage by the same factor, and observing the broadening to increase by a factor 2.

A triangular space charge field was added to or subtracted from the nearly constant electric field due to the electrodes in order to produce two extreme electric field profiles. A '+ve' space charge field increased the drift field close to the strips while leaving the drift field just > 0 close to the backplane. A '−ve' space charge field reduced the drift field near the strips and increased the field near the backplane.

The diffusion broadening was found to change very little between these two extremes, as shown in Fig. 6.

5. Surface trapping

In the gaps between the strips the GARFIELD drift field lines exit the nominal detector volume and curl around to approach the strips from outside that volume. This is of course unphysical but effectively the carriers stop at the surface if their drift along the surface is slow compared to the integra-

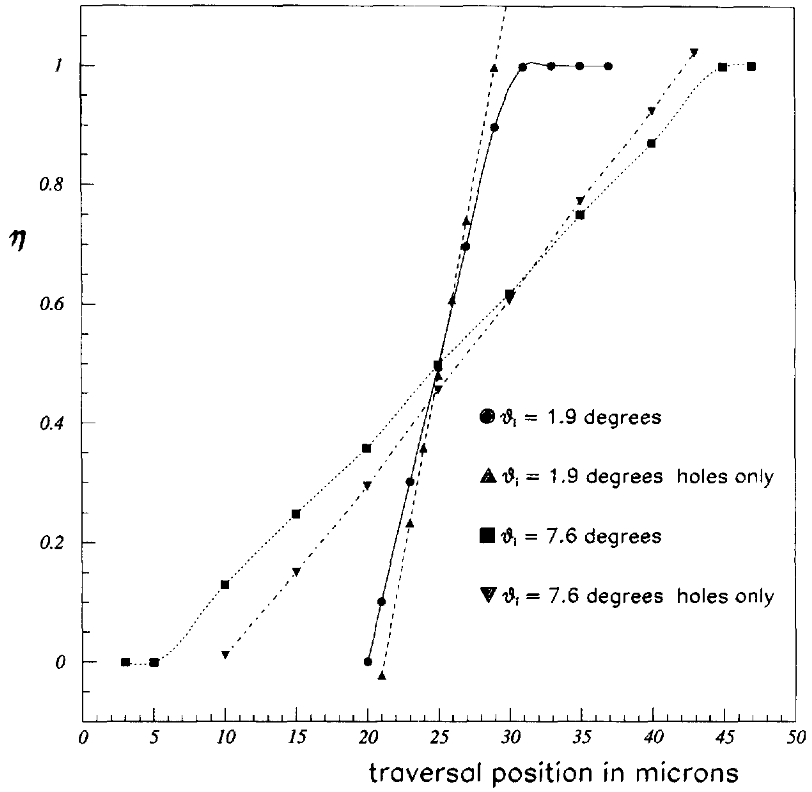

Fig. 5. Charge sharing due to track inclination. Trapping of all the electrons makes little difference.

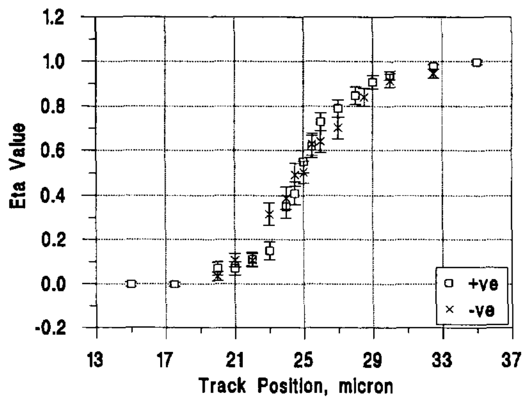

Fig. 6. Charge sharing due to carrier diffusion for the two extreme electric field profiles (see text).

tion time (~25 ns). A '+ve' space charge field increases the sharing and a '−ve' space charge field focuses the carriers onto the strips and practically eliminates the sharing. This sharing due to 'surface trapping' is stronger, the smaller the aspect ratio (s/p), as shown in Fig. 7 without any space charge.

6. Discussion and comparison with test beam data

Of all the cluster broadening effects separately investigated above, only hole trapping in the bulk or a ~50 μm dead layer near the strips give the same order of magnitude of very broad cluster as observed in the GaAs test beam [4].

Trapping is preferred as an explanation because (a) there is no known reason for the existence of any dead layer, and (b) there is independent evidence from experiments with an α source suggesting that in this particular detector the carriers are mainly electrons.

Fig. 8 shows the mean test beam cluster compared with the properly averaged simulation cluster with all holes trapped. Fig. 9 shows via the η sharing both that the effect is unambiguously linked to the real track position and that the agreement with the simulation is very good in the central region of the η plot which is almost insensitive to noise.

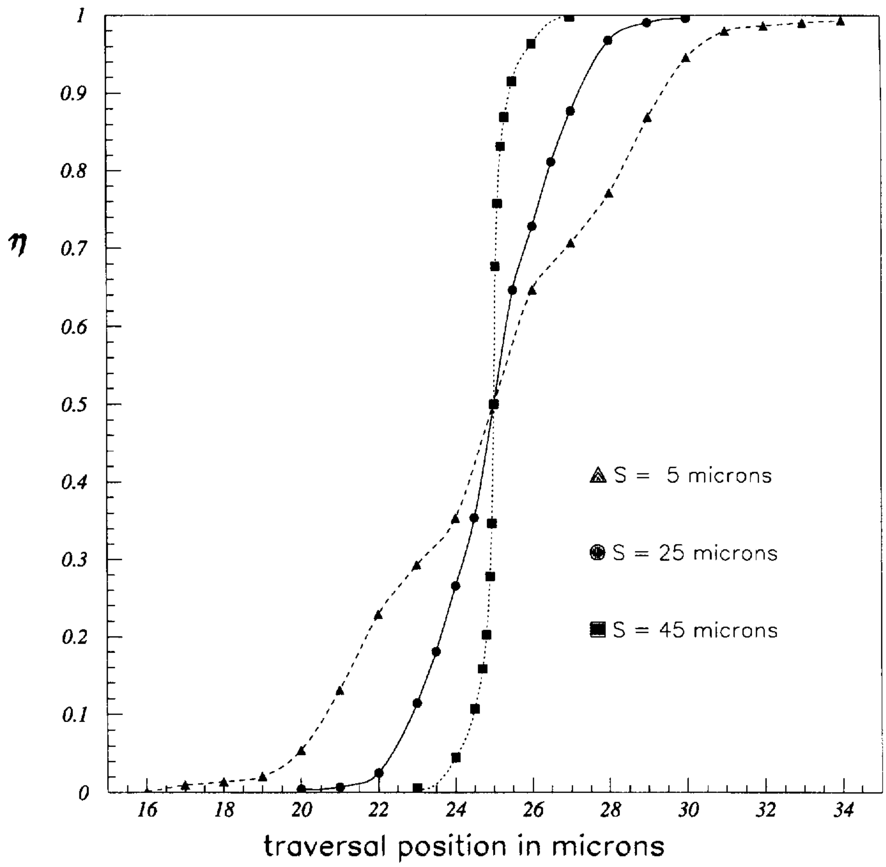

Fig. 7. Sharing due to "surface trapping" as a function of strip width (no space charge).

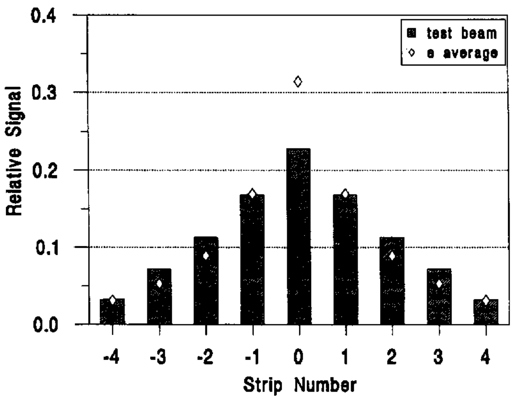

Fig. 8. Test beam signal cluster compared with the simulation.

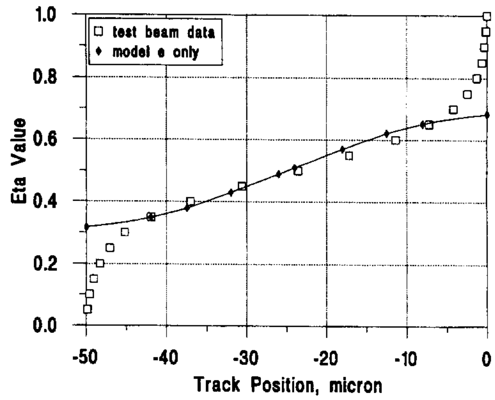

Fig. 9. Test beam sharing compared with the simulation.

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[4] T.J. Brodbeck, A. Chilingarov, RD8 Note 13/2/96.