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Backscattering in Hybrid Photodetector Devices

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Introduction

A hybrid photodetector (HPD) consists of a photocathode and a PIN diode [1]. Photoelectrons are liberated at essentially zero kinetic energy from the photocathode, and are accelerated to impact on the PIN diode. The electrons typically fall through a voltage of 10 kV in traveling a distance of 3 mm. The diode is backside illuminated with a contact layer thickness of about 2 kV or about 120 nm. The electrons range out in the silicon, and are stopped within about the first 2.5 μm of the 300 μm depletion layer. It takes about 3.6 eV to make an electron hole pair, which means the gain of the device is roughly 8000/3.6 = 2222.

The electrons are sunk into the contact layer and contribute little to the current. The signal arises from the motion of the holes across the depletion layer, making the device somewhat slower than is desired. Running the PIN diode at high bias voltages, thus driving a large drift field into the full depletion layer moderates this effect. At elevated bias voltages the charge collection time is adequately short.

In some applications, the use of finely segmented pixels is planned [2]. The use of wavelength shifter (WLS) fiber to read out scintillators in CMS uses pixel sizes of a few mm to accommodate the WLS fibers. An HPD with many pixels offers a low cost, magnetic field insensitive, high gain photon transducer.

Electron Optics – Initial Impact

The general case of electron motion in an electric field directed along the z axis, and a magnetic field in the (y,z) plane inclined at an angle θ with respect to the electric field was discussed elsewhere [3] under the assumption that the initial velocity was essentially zero. We consider here the special case when the angle is small. In that case the magnetic force along the z axis is small, and the motion along the z axis is that in the presence of an electric field, V/d, alone, with acceleration a. The applied voltage is V, while the electrode spacing is d.

$$a = e(V/d)/m \qquad (1)$$
$$z = (at^2/2)$$

The motion transverse to the electric field follows from the general case in the limit where the angle is small. The cyclotron frequency is ω.

$$x = -(a/\omega^2)\theta[\varphi - \sin(\varphi)] \qquad (2)$$
$$y = (a/\omega^2)\theta[\varphi^2/2 + \cos(\varphi) - 1]$$
$$\omega = eB/m$$
$$\varphi = \omega t$$

Note that the transverse position is proportional to θ. For typical values appropriate to CMS, V = 10 kV, d = 3mm, B = 4T, one finds that $a = 5.86 \times 10^{20}$ mm/sec^2, so that z = d when t = 0.1 nsec. The impact velocity along the z axis is 0.2 x c. In the transverse view the frequency is, $\omega = 6.8 \times 10^{11}$ /sec, and the characteristic phase rotation, φ is 68 radians, or ~ 11 full helical rotations in the transverse plane. The characteristic radial dimension is a/ω^2, which is 0.0013 mm with the parameters given here.

Note that the expressions given in Eq.2 show that for long times, $\varphi >> 1$, the transverse motion has a piece which centers on $x = 0$ and $y = \theta z$, with deviations which are small, characterized by a/ω^2. Therefore, the magnetic field captures the electrons and they move in very tight helices along the B direction, being accelerated by the electric field along the z axis. For short times the transverse radius, r, increases roughly linearly with B and t, $r \sim z/3[\theta(\omega t)]$, while for long times $r \sim \theta z$. The radius is proportional to θ at fixed distance, $z = d$.

In terms of energy deposit in the Si, there is an increase in path length of the dead layer by a factor $1/\cos(\theta i)$. The result of differentiating in Eq.1 and Eq.2 for the components of the impact velocity gives;

$$\cos(\theta i) = \phi/\sqrt{\{\sin^2(\theta)[(1-\cos(\phi))^2+(\phi-\sin(\phi))^2]+\phi^2\}} \qquad (3)$$

For small angles the initial impact angle, θi, is essentially zero, so that the increased loss effect is rather small.

Backscattering

The electrons incident on the PIN diode do not simply range out. There is a substantial probability to backscatter.[4] These effects have been inferred in studies of the resolution of the photoelectron peaks in HPD devices [5,6]. There is an implication for devices with many small pixels. The general case of a backscattered electron requires the solution of the equations of motion with initial velocity. This can be done in closed form, but the results are not particularly transparent. Therefore, we quote only results for small angles between the electric and magnetic fields. As we have shown above, this condition is necessary in any case if the image shift in a multi-pixel device is to be limited [2].

We consider the backscattering of an electron with (x,y,z) initial velocity components (α,β,γ) at position (0,0,0). The time, t, for the electron to make a secondary impact on the Si is:

$$\begin{aligned} t &= 2\gamma/a \qquad (4) \\ z &= \gamma t - at^2/2 \end{aligned}$$

This time is just the time required for the acceleration, a, to change the velocity component along the z axis from $+\gamma$ at $t = o$ to $-\gamma$ at t. The motion along z is again, for small angles between the E and B fields, simply that due to acceleration in the electric field. The motion transverse to the z axis is again dictated by the magnetic field.

$$\begin{aligned} x &= [\alpha\sin(\varphi) - \beta(\cos(\varphi)-1)]/\omega \qquad (5) \\ y &= [\alpha(\cos(\varphi)-1) + \beta\sin(\varphi)]/\omega \end{aligned}$$

As before, the characteristic phase angle is, $\varphi = \omega t$. The second impact angle of the velocity vector is just the initial angle of the velocity vector. The z component is flipped at the time of re-impact, and the magnitude of the transverse velocity is constant, as can be verified by differentiating Eq.5 with respect to t, squaring the x and y velocity components, and adding them.

There are illuminating limits to these expressions. For small phase, $x \rightarrow \alpha t$ and $y \rightarrow \beta t$. Since $t = 2\gamma/a$, the characteristic transverse distance is, $r \sim T/(ma)$, where T is the backscattered kinetic energy of the electron. Clearly, from Eq.1 and Eq.2, in the absence of a magnetic field the transverse size is ~ d(T/eV). Since the backscattered electrons have a rather flat kinetic energy spectrum from the initial value of eV to zero, the image spread due to backscattering extends from zero size to the size of the electrode gap, d if the magnetic field is effectively absent.

In the case of a strong magnetic field, the backscattered electrons are captured in tight helices, which limits the image size. The characteristic size in this case is the initial velocity, v, divided by ω, as is easily seen from Eq.5. The velocity ,v, follows from energy conservation, $T < eV$, $mv^2/2 = T$. As mentioned above, for our numerical example, $v = 0.3c$ or 6×10^9 cm/sec. Therefore, we expect a focusing effect due to the magnetic field, $r < v/\omega$. For the parameters used above, this implies transverse sizes of 0.0088 cm. Compared to the no B field case of $r < d = 3$mm, the focusing effect is dramatic in the case of backscatters.

Monte Carlo Model

In order to quantify the above considerations, a Monte Carlo model was made of the initial impact and the backscattering processes. The full field tracking to next order in the angle of the magnetic field, B, with respect to the electric field, E, was used. The equations are not quoted here, as they are rather cumbersome and not very illuminating. In fact, little new in the way of physical effects appear to be generated by working at higher order in θ.

For backscattering, the electron energy was taken to be uniformly distributed from zero to the full impact energy, eV. The angular distribution was assumed to be fairly soft. The cosine of the scattering angle was distributed as a cosine [4]. All angular effects of going through the dead contact layer were taken into account.

The results for fixed B/E angle of zero at 0T and 4T magnetic field are shown in Fig.1. All events are backscattered, while we expect [4] that the probability to backscatter is 18%. Those electrons which strike the dead layer and range out deposit 8 kV of energy in the active Si. The backscattered electrons deposit an amount depending on their energy and their angle with respect to the dead layer. It is found that the energy deposit is insensitive to the magnetic field or to the angle of the b field (up to 10 degrees) and is, on average 2.25 kV for backscattered events. Therefore, the energy deposit is 0.82*8 + 0.18 * 2.25 = 6.96 kV on average instead of the expected 8 kV. In addition, there are fluctuations on the backscattered fraction which limit the device resolution.

The focusing effect is illustrated in Fig.1, where radial distributions of backscattered electrons with respect to the impact point are plotted for B = 0T and B = 4T. The mean radial distance is 2.37 mm for B = 0T and 0.05 mm for B = 4T. There seems to be little change for angles of B and E up to 10 degrees. Note that there is a mean image shift of the initial impact point of dθ as discussed above. For an angle of 10 degrees, the shift is 0.52 mm which is large on the scale of the backscattered radii in the case where B = 4T.

Conclusions

The electron optics in combined electric and magnetic fields has been explored for both the initial photoelectrons emitted by the photocathode and for the electrons backscattered off the dead contact layer or the Si active layer. There is a marked focusing effect of the magnetic field , which reduces the effective crosstalk in devices with many small pixels. However, there appears to be little effect on the "gain" of the device either with the magnitude or the direction of the magnetic field.

References:

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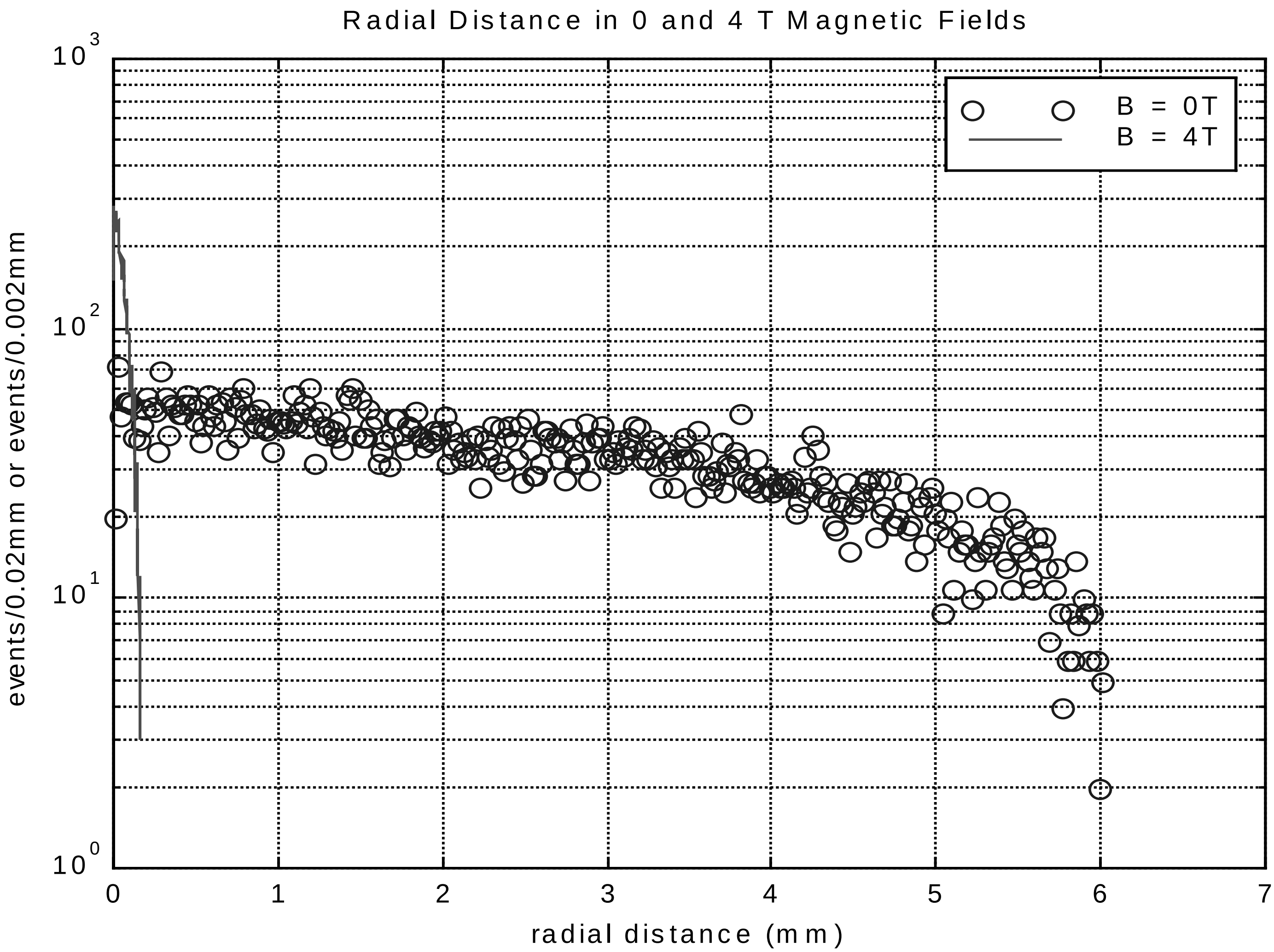
Figure Captions:

Fig.1 Radial distance with respect to the impact point for V = 10 kV, d = 3 mm and θ = 0 degrees for B = 0 and 4T.



Radial Distance in 0 and 4 T Magnetic Fields
B = 0T
B = 4T
events/0.02mm or events/0.002mm
radial distance (mm)
10^3
10^2
10^1
10^0
0
1
2
3
4
5
6
7

Figure 1