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OPTIMISATION OF SILICON AND DIAMOND MICROSTRIP DETECTORS FOR HIGH FLUX DENSITY EXPERIMENTS

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Abstract

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Paper presented at the 4th Advanced Training Course MIXDES'97, Poznan, June 1997

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Abstract

New arguments for optimising the design of a silicon microstrip detector proposed for a high flux experiment [1] and an alternative of a diamond detector are presented. The signal/noise ratio and the operation rate are the principal elements discussed, considering the high exposure of the detector. The noise and signal analysis confirms the advantage of using a silicon microstrip detector with 50 μm pitch, 200 μm readout pitch, 300 μm thickness, which could work at room temperature. No improvements are expected by the increase of the thickness and the diamond alternative has a worse detection efficiency.

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1. NOISE ANALYSIS

The electronics and the detector itself contribute to the signal to noise ratio in different ways. Without considering the associated detector bias resistor and the leakage current, the noise is dominated by the component of the input transistor. The noise is caused by three different mechanisms: the flicker noise (1/f noise behaviour), channel noise and bulk resistance noise (white noise behaviour).

In terms of standard deviation in the charge measurement, independent of frequency f, the above components are given by [2]:

$$ENC_{1/f} = \frac{C_t e}{q}\sqrt{\frac{F_m}{2wl_{eff}}} \tag{1}$$

$$ENC_{ct} = \frac{C_t e}{q}\sqrt{\frac{\Gamma(\eta+1)kT}{3g_m T_p}} \tag{2}$$

$$ENC_{br} = \frac{C_t e}{q}\sqrt{\frac{R_b \eta^2 kT}{2T_p}} \tag{3}$$

where C_t is the total input capacitance of the preamplifier in addition to the detector capacitance and all stray capacitances, e is the base of natural logarithms, q the electron charge, w/l_{eff} are the input transistor dimensions, Γ is the excess noise factor, η the slope factor, g_m the transconductance, T_p the peaking time (the integration time of the shaper), R_b the bulk resistance of the transistor, T the temperature, k the Boltzmann constant.

To minimize the noise we should choose the highest possible g_m, the lowest possible η and Γ, we should optimise the dimensions with respect to the input capacitance. If C_d is the detector capacitance and C_f the feedback capacitance of the preamplifier, the optimal input capacitance varies between $C_d + C_f$ (only 1/f noise) and $(C_d + C_f)/3$ (only white noise). The correct choice will be a value between these two, depending upon the ratio between the different kinds of noise. For a peaking time of about 1 μs or smaller, the channel thermal noise dominates over the flicker noise.

It has been shown [3] that two other noise sources exist due to the detector leakage current I_{lk} and the bias resistance R_p. Taking into account also the noise due to the detector, an optimum peaking time will result:

$$T_p^{opt} = \{\frac{2kTR_pC_t^2[2\Gamma(\eta+1) + 3g_m R_b \eta^2]}{3g_m(I_{lk}qR_p + 2kT)}\}^{1/2} \tag{4}$$

For a correct evaluation of the total noise charge, in addition to equations (1-3) we have to add the contribution due to detector bulk leakage current and bias resistor which are given by [4]:

$$ENC_{det} = \frac{e}{q}\sqrt{\frac{qI_{lk}T_p}{4}} \tag{5}$$

$$ENC_{R_p} = \frac{e}{q}\sqrt{\frac{kTT_p}{2R_p}} \qquad (6)$$

then the total noise charge will be:

$$ENC = (ENC^2_{1/f} + ENC^2_{C_t} + ENC^2_{br} + ENC^2_{det} + ENC^2_{R_p})^{1/2} \qquad (7)$$

The evaluation of the leakage current as a function on the radiation damage has been described in [1].

We assumed a readout pitch of 200 μm and a strip length of 4 cm and computed the leakage current for different detector thicknesses between 300 μm and 1000 μm.

The 300 MeV/c electrons deposit in the detector a dose of 10-30 kGy for 600 h of beamtime. The surface leakage current induced is 144 nA/readout pitch for a detector biased at 80 V [5]. The bulk damage is a function of the silicon thickness and varies between 75 nA/readout pitch at 300 μm and 249 nA/readout pitch at 1000 μm.

Using the above considerations and the following values for electronics [2]: Γ=2, η=0.15, C_f=0.6 pF, C_d=10 pF, R_b=2 kΩ, g_m=3 mA/V, R_p=2 MΩ, we obtained the optimum peaking time (T_p^{opt}) as a function of the silicon thickness (fig. 1.) for

$$C_t = C_d + \frac{C_d + C_f}{3}$$

Fig. 2 gives the total noise charge (ENC) for two values of the temperature and two values of the bias resistance.

As it can be seen, the largest total equivalent noise charge is obtained for the highest temperature and the smallest value of the bias resistance. However the differences are not significant for the detector performances.

Moreover the noise can be reduced by cooling the detector, increasing the bias resistance value, and by decreasing the detector capacitance and consequently the input capacitance. Diamond could be a solution for lower noise, as its dielectric constant is about two times smaller than that of silicon.

2. SIGNAL ANALYSIS

Minimum ionising particles deposit in silicon on average 390 eV/μm and create 108 e-h/μm. The charge created depends on detector thickness and varies between 32500 e-h pairs for 300 μm and 108300 pairs for 1000 μm thickness.

The charge is collected by the readout strips by capacitive charge division. In [1] we computed the charge collected for a particle passing between two strips at zero incidence, and concluded that the fraction of charge obtained is higher if the readout capacitance (C_R) is high, and the interstrip capacitance (C_s) has an intermediate value so that $C_g << C_s << C_R$. For particle tracks inclined at 45° (see fig. 3) we obtained the results presented in table 1.

			300 μm				
incidence	Q_1/Q_0	Q_2/Q_0	Q_3/Q_0	Q_4/Q_0	Q_5/Q_0	Q_6/Q_0	Q_7/Q_0
1	0.3563	0.6281	0.0844	0.0018			
2	0.1921	0.6676	0.1921				
3	0.0844	0.6281	0.3563	0.0018			
4	0.0243	0.5204	0.5204	0.0243			
			1000 μm				
1	0.1503	0.2368	0.2368	0.2368	0.2368	0.0865	0
2	0.0853	0.2356	0.2368	0.2368	0.2368	0.1516	0.0012
3	0.0412	0.2219	0.2368	0.2368	0.2368	0.1956	0.0149
4	0.0137	0.1944	0.2368	0.2368	0.2368	0.2231	0.0424

Table 1: Simulation results of the collected charge for inclined tracks at 45°

The 300 μm thick detector collects on a readout strip at least 52% of the total deposited charge, i.e. the average value of the signal is 16900 electrons, while the 1000 μm thick detector collects at least 24% of the charge, the signal being of 26000 electrons.

There is another effect which should be taken into account, i.e. the charge collection efficiency due to the limited carrier lifetime of the charges. The distance traversed by the free charges before recombination is: $d = \mu E \tau$, where μ is the mobility (μ_e=1350 cm^2/Vs, μ_h= 480 cm^2/Vs in silicon), E the electric field and τ the carrier lifetime (τ_e=20 ns, τ_h=60 ns). The charge collection efficiency is [6]:

$$CE = \frac{Q_{coll}}{Q_{ion}} = \frac{d}{W}(1 - \exp(-W/d)) \qquad (8)$$

where W is the detector thickness. The collection efficiency increases with the depletion voltage and it is about 83% for holes in a 300 μm thick detector. For a 1000 μm thick one, the full depletion voltage increases up to 500 V. The collection efficiency is in this case 73%.

In conclusion, the increase of the detector thickness is not an advantage, because even if the number of pairs created is higher, the collection efficiency is smaller and the bias voltage for detector operation is much higher.

3. LANDAU FLUCTUATIONS

Our previous considerations have been based on the average energy loss by ionisation in silicon. In fact the energy lost by the electrons is distributed over a large range.

Fig. 4 gives the Landau distributions of the energy loss in silicon detectors (300 and 1000 μm). We used the model of J.F. Bak et al [7] which has the advantage of being tested experimentally for silicon. The Landau distribution has been folded with a

Gaussian resolution function related to the total noise – this results in a broadening of the distribution more important for the thin detector than for the thick one.

We should stress that the noise has been evaluated at the end of the exposure (after 600 h of beamtime). Due to the Landau straggling, the S/N ratio could decrease from 20 to 10, and the detection efficiency is close to 100%.

4. OPERATION RATE

The detector for electrons is operated at $10^7 e/cm^2 s$ on average. At this rate, one readout pitch is hit by electrons at an average time interval of 2 μs. This interval is much larger than the charge collection time which is about 23 ns for a 300 μm silicon detector and 42 ns for a 1000 μm one. Using a Poisson distribution of the time intervals between particles hitting the detectors, we found 0.115% for the dead time correction for 300 μm, and 0.21% for 1000 μm. For T_p=0.2 μs, the dead-time correction due to the electronics is ~16%.

6. STRENGTHS AND WEAKNESSES OF A DIAMOND DETECTOR

A group from NCCU [8] made a proposal for a diamond microstrip sensor for high flux density electron detection as an alternative to the silicon microstrip detector.

The first advantage of such a detector would be the long lifetime granted by its high purity and therefore very high radiation tolerance. No increase in the leakage current was observed for exposures up to 10^{16} p/cm^2. The dielectric constant is twice that of the silicon, thus its capacitance is half of that of the silicon.

The wide band gap ensures a reduced thermal noise (5.5 eV compared to 1.1–1.4 eV in Si).

At the same time the average energy for the e-h pair creation of 13 eV (3.6 eV in silicon) leads to a lower signal of about 7000 e-h pairs on average for a 250 μm thick detector. The carrier lifetime in diamond is only 1 ns, and though the charge mobility is 2.5 times higher, we have to apply 300–400 V bias voltage to obtain a charge collection of 60%. Hence the advantage of a lower noise is overruled by the disadvantage of a small signal. This results in a lower detection efficiency. The higher carrier mobility is not of much use in our experiment, where the operation rate is not very high.

6. CONCLUSIONS

The noise and signal analysis confirmed the advantage of using a silicon microstrip detector with 50 μm pitch, 200 μm readout pitch, 300 μm thickness, which could work at room temperature, with 10<S/N<20 and a detection efficiency of about 100%.

The increase of the thickness is not an advantage and the diamond alternative has a worse detection efficiency.

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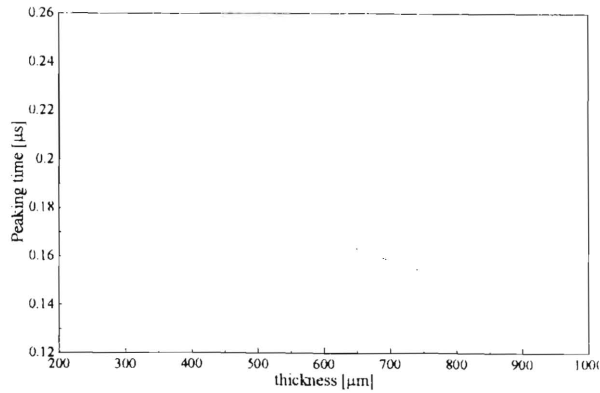


Fig. 1 Optimum peaking time versus detector thickness

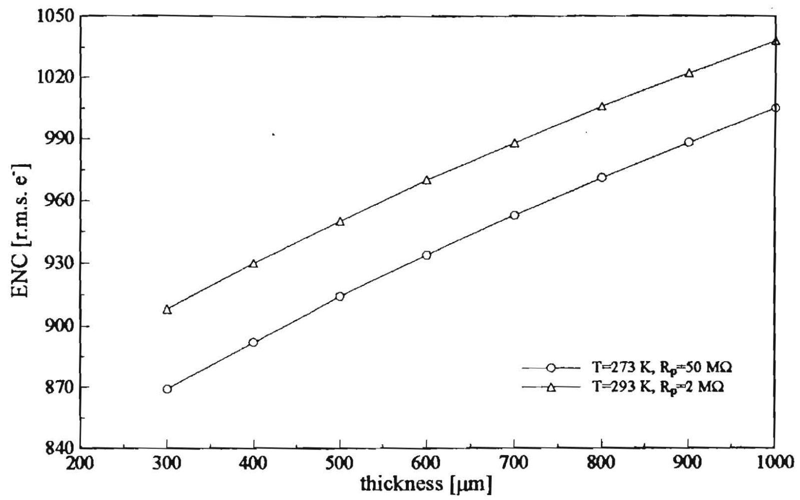


Fig. 2 Equivalent noise charge r.m.s. versus detector thickness

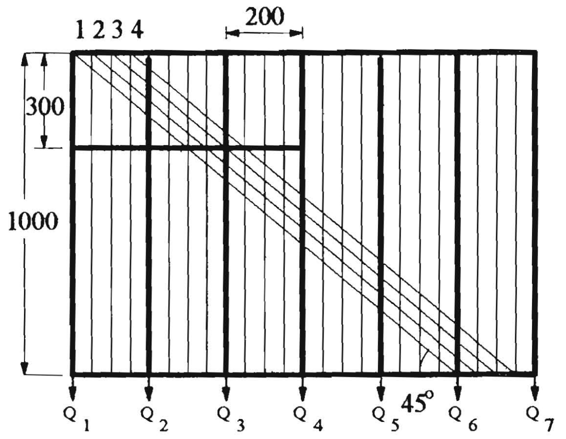


Fig. 3 Silicon sensors crossed by inclined tracks at 45°

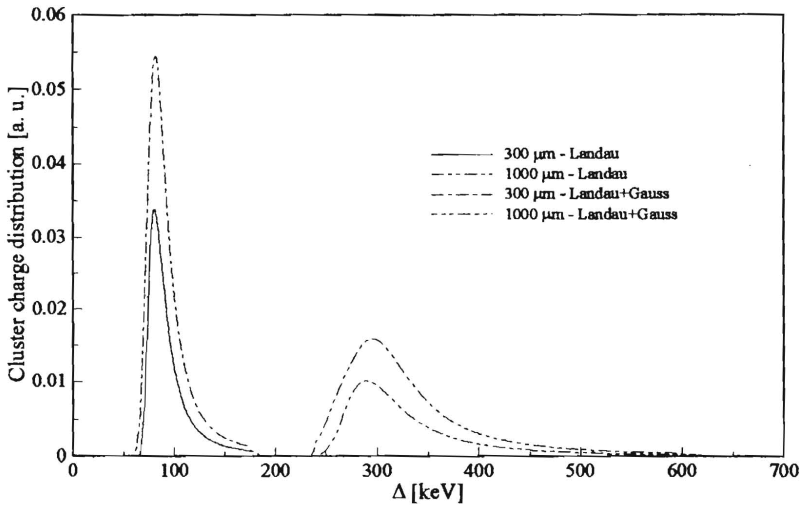
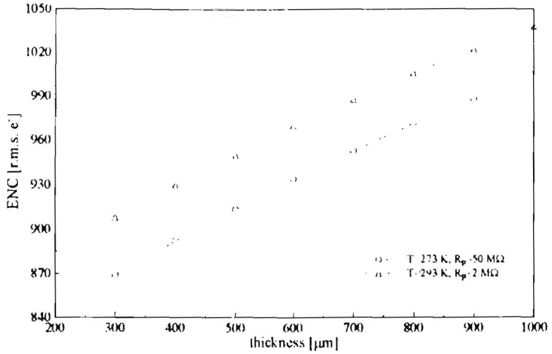


Fig. 4 Distribution of cluster charge for thin and thick detector



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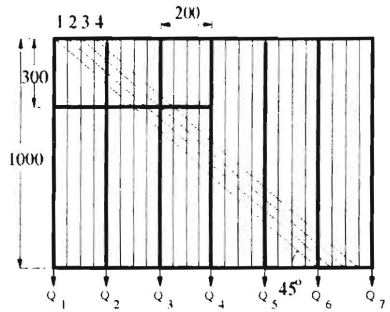

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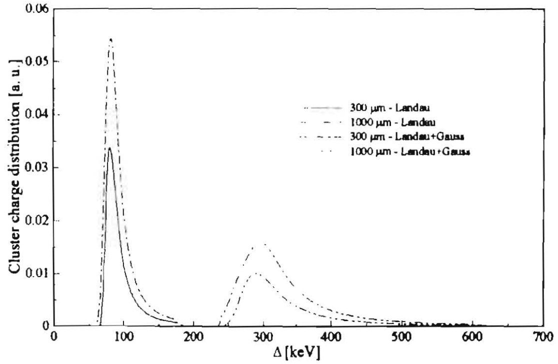

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