сообщения
объединенного
института
ядерных
исследований
дубна

E1-93-115

K.Yu.Akimov*, V.V.Ivanov

ENERGY LOSSES OF FAST CHARGED PARTICLES IN THIN SILICON DETECTORS

* Moscow Engineering Physics Institute

1993

1 Introduction

Thin silicon detectors are widely used in experimental particle physics, particularly in experiments on high energy accelerators. A reduction of a counter thickness allows one to increase its internal fastness and radiation resistance. Silicon PIN diodes have a thickness of $x \leq 100$ μm and can be used in arrays for charged particle detection [1]. The detector of another type - CCD has a typical thickness of $x \leq 20$ μm [2]. The silicon detector with an avalanche amplification described in ref.[3] has as thin a thickness of the space charge region as 2 μm. A variety of analytical approximations for the energy loss calculation in layers have been used to calculate straggling functions [4]. However, the interactions of charged particles in an absorber are simulated most closely by the Monte Carlo method. This has prompted us to perform the calculations of energy losses in a wide range of thicknesses from 1 μm to 100 μm using this method.

2 Monte Carlo calculations

In the Monte Carlo calculations particles are assumed to make collisions at random intervals. In a single collision any amount of energy can be lost from *0* to ε, which for relativistic particles is given by:

$$\varepsilon = \frac{2m_e^2\beta^2\gamma^2}{1+2\gamma\frac{m_e}{m_x}+(\frac{m_e}{m_x})^2},$$

where m_e is the mass of the electron, m_x the mass of a particle, β is the velocity of a particle expressed in light speed units, $\gamma = (1-\beta^2)^{-\frac{1}{2}}$.

The probability of an energy loss E in a single collision is given by the differential collision cross section spectrum *f(E)* [4], obtained for 45 Gev/c pions in solid silicon. For this momentum the corresponding value of $\beta\gamma$ is 228.8. As it is mentioned in ref.[4], the differences in the most probable energy loss Δ_p and the full width at half maximum *FWHM* for different spectra are not more than 1% for $\beta\gamma$ >100. Therefore, the results obtained here can be generalized for other particles and energies provided that $\beta\gamma$ >100. For $\beta \to 1$ the total collision cross section σ_t=3.84 collisions/μm [5].

The probability *P(n)* of *n* interactions for the mean number of collisions per particle $m = x\sigma_t$ is given by a Poisson distribution:

$$P(n) = \frac{m^n}{n!} e^{-m}.$$

In ref.[5] the function *f(E)* was integrated to obtain the function *Q(E)* varying from *0* to *1*. *Q(E)* was given by a random number generator and a definite value of *E* corresponded to each *Q(E)*. In the present work the random number generator giving random numbers according to the *f(E)* distribution was designed. Each number gave directly the energy *E* lost in a single collision.

3 Results and discussion

Electrons in the silicon atom form three shells: *K,L,M*. The number of electrons on each shell equals accordingly: *2, 8, 4*. For *K*-shell electrons the binding energy is I_k=1839 eV and they do not contribute to energy losses below I_k, neither do *L*-shell electrons below I_l=99 eV. 90% of the time the K-shell ionization is attended with an emission of Auger electron carrying the energy of ionization with a range about 0.2 μm. The rest of the time this energy is taken in the form of *X*-rays. For *M*-shell electrons the collisions produce mainly collective excitations.

The kinematic limit E_{max}=20 keV has been set in all calculations because of the technical difficulties arising from the use of the 32 bit computer. The effective range of 20 keV electrons in a silicon absorber is 3 μm. The electrons with a range comparable with the thickness of a detector are able to go beyond its limits, leaving inside only a part of their energy. There is a difference between the energy deposition in a detector and the energy loss of a particle due to the escape of such δ-rays. Let us see how the choice of E_{max} can affect the whole pattern, for example on the thickness of 10 μm, which is not much more than the range of 20 keV electrons. Fig.1 presents three spectra for the thickness of x=10 μm for different values of the maximum energy loss

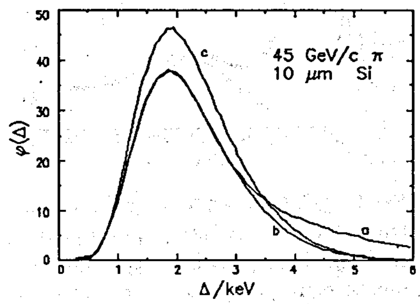

Fig.1. Calculated energy-loss spectra $\varphi(\Delta)$ for 45 GeV/c pions passing through the 10 μm Si detector. The ordinate is an arbitrary scale. For details, see the text

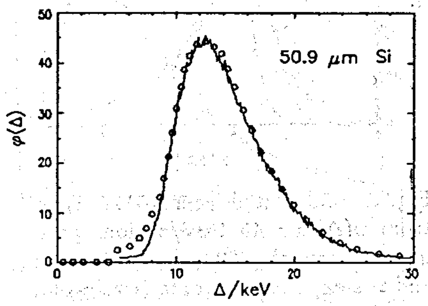

Fig.2. Calculated energy-loss spectrum $\varphi(\Delta)$ for 45 GeV/c pions passing through the 50.9 μm Si detector and the experimental data (circles) for $\beta\gamma$=3914 electrons. The ordinate is an arbitrary scale

in a single collision E_{max}. Let us say in case *a:* E_{max}=20 keV, in cases *b* and *c:* $E_{max} = I_k$. In case *b* all events with $E > I_k$ are exempted, but in case *c* only single collisions with $E > I_k$ are disregarded, however, the whole events remain. In other words, the areas under the curves *a* and *c* are the same, therefore the maximum of the curve *c* appears to be higher than that of *a*. However, the location of the maxima and *FWHM* in all three cases is the same. It means that *K*-shell electrons do not influence the most probable energy losses and the full widths at half maximum. The same is true for the electrons from other shells if $E > I_k$. These electrons affect only the tail of a distribution. The probability of the energy loss being more than 20 keV is less than 1%, therefore the setting of the kinematic limit must not change greatly the spectra even for larger thicknesses.

For the differential collision cross section *f(E)* [4] the range of possible errors is given. Within that range we have used the data for *f(E)* and obtained straggling functions for different thicknesses which agreed rather well with the experimental data [6].

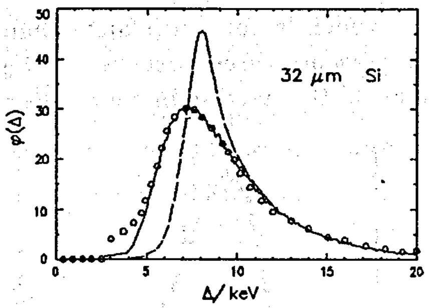

Fig.3. Calculated energy–loss spectrum $\varphi(\Delta)$ for 45 GeV/c pions passing through the 32 μm Si detector and the experimental data (circles) for $\beta\gamma$=3914 electrons. The ordinate is an arbitrary scale.The Landau function is shown as a dashed line

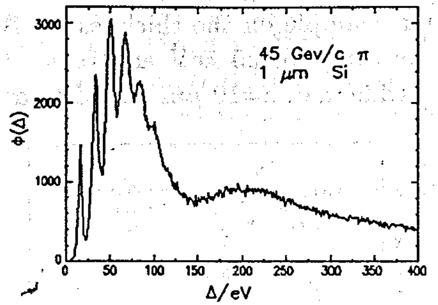

Fig.4. Calculated energy–loss spectrum $\Phi(\Delta)$ for 45 GeV/c pions passing through the 1 μm Si detector. The ordinate corresponds to 10^6 π, and $\Phi(\Delta)$ represents the number of π found in 1 eV bins

Fig.2 and Fig.3 present the Monte Carlo calculation for x=50.9 μm and x=32 μm respectively compared to the experimental data. The differences for small energy losses between the experiment and the model are ascribed by the authors of ref.[6] to "edge effects". The Landau function on fig.3 is shown to see the importance of electronic binding effects. The theory of Landau assumes that the typical energy loss in an absorber is large compared to the binding energy of the most tightly bound electron, the condition which is not satisfied here.

The spectrum for the minimum thickness of x=1 μm is given on fig.4 which is similar in principle to the one obtained in ref.[5]. The mean number of collisions here is 3.84. The separate peaks at *17,34,51...*eV correspond to *1,2,3...*plasmon excitations and the rise at ~150 eV is due to *L*-shell excitations. We see that the spectrum does not have anything in common with the Landau distribution.

Fig.5 and Fig.6 refer to the thicknesses of x=2 μm and x=3 μm respectively. It is clearly seen that the microstructure is being smoothed fairly quickly with the increasing of the thickness. The spectrum for x=2 μm makes it possible to evaluate the efficiency of a diode with an avalanche amplification discussed in ref.[3]. To get a 99% efficiency the

registration threshold should be set equal to about 70 eV.

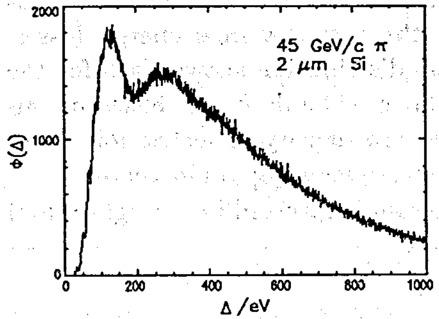

Fig.5. Calculated energy–loss spectrum $\Phi(\Delta)$ for 45 GeV/c pions passing through the 2 μm Si detector. The ordinate corresponds to 10^6 π, and $\Phi(\Delta)$ represents the number of π found in 1 eV bins

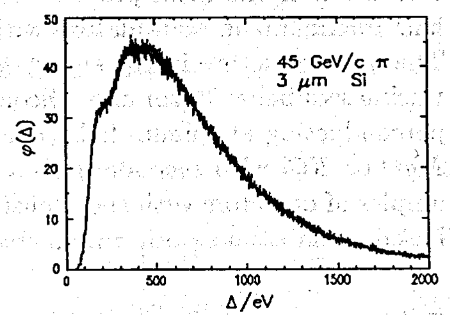

Fig.6. Calculated energy–loss spectrum $\varphi(\Delta)$ for 45 GeV/c pions passing through the 3 μm Si detector. The ordinate is an arbitrary scale

The table provides the values of the most probable energy losses and the full widths at half maximum obtained *a)* in the present work, *b)* experimentally [6], and *c)* by means of the convolution method [4] for highly relativistic particles. The general observation is that the results obtained through the Monte Carlo calculation follow closely the experimental data and the data from the convolution method. It is also seen that the ratio of the most probable energy loss over the thickness of a detector is lessening with the decrease of the detector thickness.

4 Conclusive remarks

The existing experimental data and the data from the convolution method have been used to compare with the calculation from the Monte Carlo method. A substantial agreement has been reached from these three proven methods.

It is known that the character of particle interactions with atomic electrons for different solids is qualitatively similar to each other. Therefore, the results obtained in this work for silicon can be applied for the evaluation of the most probable energy losses and the full widths at half maximum in scintillators with the same average energy losses. The microstructure in the energy-loss distribution shows itself for the thicknesses below 3 μm of a silicon layer. The detectors based on superconducting aluminum foils [7] and low-density dielectric foils from MgO or KCl with secondary electron emission [8] could serve as examples of detectors with such thicknesses (expressed in a weight scale) based on substances other than silicon.

Table. The most probable energy losses Δ_p and the full widths at half maximum $FWHM$ for different silicon layers

x, μm	2	3	5	10	20	32	51	100
Δ_p, keV, this work	0.125	0.42	0.82	1.87	4.2	7.2	12.3	26.7
Δ_p, keV, [6]						7.137	12.24	26.86
Δ_p, keV, [4]				1.857	4.12	7.36	12.397	26.544
$\frac{\Delta_p}{x}$, $\frac{keV}{mm}$, this work	62.5	140	164	187	210	225	242	266
$FWHM$, keV, this work	0.455	0.75	1.1	1.8	3.4	5.6	7.8	13.9
$FWHM$, keV, [6]						5.49	7.74	13.97
$FWHM$, keV, [4]				1.758	3.338	5.611	7.861	13.836

References

[1] Shapiro S.I. *et al.* - Nucl. Instr. and Meth., 1989, A275, p.580.

[2] Baily R. *et al.* - Nucl. Instr. and Meth., 1983, 213, p.201.

[3] Burbaev T.M. *et al.* - Preprint PIAS, No.5, Moscow, 1992.

[4] Bichsel H. - Rev. Mod. Phys.,1988, Vol.60, No.3, p.663.

[5] Bichsel H. - Nucl. Instr. and Meth., 1990, B52, p.136.

[6] Bak J.F. *et al.* - Nucl. Phys., 1987, B288, p.681.

[7] Gabutti A. *et al.* - Nucl. Instr. and Meth., 1990, A289, p.274.

[8] Kavalov R.L. *et al.* - Nucl. Instr. and Meth., 1985, A237, p.543.

Received by Publishing Department
on April 6, 1993.