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# Response of Si detectors to electrons, deuterons and alpha particles

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The response of silicon detectors to conversion electrons in the decay of $^{109}$Cd, $^{233}$Pa and $^{137}$Cs, to deuterons in the energy range 35–440 keV from a Van de Graaff accelerator and to alpha particles from a mixed $^{239}$Pu, $^{241}$Am, $^{244}$Cm source has been measured. The results were found to be in agreement with the model proposed by Lennard et al. (1986) which describes the nonlinear detector response in particular for the case of light ions. For electrons, the nonlinearity was found to be negligible within experimental uncertainties. For deuterons the nonlinearity observed in Rutherford-backscattering measurements at low energies was used to accurately measure the window thickness of the detectors. For alpha particles in Si it has been confirmed that the energy required to create an electron–hole pair depends on the stopping power. Our value for the nonlinearity parameter $k = 2.8 \pm 0.3$ nm/electron–hole pair is larger than the one which was originally proposed.

## 1. Introduction

In silicon semiconductor detectors, when exposed to light ions, part of the particle kinetic energy does not contribute to the pulse height, hence, to the creation of electron–hole pairs in the depleted layer of the detector. For the resulting nonlinear energy response of the detector essentially two different energy-loss mechanisms were generally accepted: inelastic interactions with atomic electrons in the detector's entrance window, and elastic interactions within the Si lattice. For electrons and light ions ($^1$H, $^2$H, $^4$He) trapping and recombination of charge carriers in the depleted region of the detector are negligible if the detector is operated under bias conditions for saturation [1]. For heavy ions, incomplete charge collection becomes significant.

It has been shown by several authors, however, that these mechanisms cannot explain the nonlinear response of surface-barrier detectors to light ions [1–5]. Recently, a semi-empirical model for another mechanism has been suggested which traces the residual nonlinearity to a dependence of the average energy $\epsilon$ required to create an electron–hole pair in Si on the energy-loss rate of the ionizing particle [6–8].

The aim of the present work was to test this model for high-resolution PIPS (passivated implanted planar silicon) detectors and alpha particles from a thin mixed-radionuclide source by two different methods. The nonlinear response of the detector to low-energy deuterons was measured in RBS experiments using a Van de Graaff accelerator. From this, an accurate determination of the entrance-window thickness of the detector was made. The linear response of the detector to conversion electrons from sources of $^{109}$Cd, $^{237}$Np + $^{233}$Pa and $^{137}$Cs was measured and used in one of the methods for investigating the model.

## 2. Pulse-height model

The pn junction of the PIPS diode is produced by low-energy implantation of B into the Si crystal [9,10]. This yields a thin dead layer of which the thickness $d_w$ may vary with the applied bias voltage. In traversing this dead layer, the incident particles will lose an amount of energy

$$E_w = S(E) d_w, \tag{1}$$

where $S(E)$ ($>0$) is the stopping power of the medium for the particular projectile. In the Si crystal the projectiles will transfer energy in collisions with Si nuclei, especially at low kinetic energy where the scattering cross section is large. Part of this energy will in turn contribute to the creation of electron–hole pairs; the remainder $E_n$ ends up in nonelectronic excitations, e.g. phonons which will not contribute to the pulse height. For light ions the charge-carrier density in the plasma is relatively low and if the electric field strength in the depleted layer is sufficiently high (about $7 \times 10^5$ V/m in the present work), recombination and trapping of charge carriers are negligible.

Alpha particles of accurately known energy $E_0$ from a very thin actinide source (effective thickness $d_s$) provide an efficient tool to investigate the energy response of a PIPS detector system. The energy loss $E_s$ in the source obeys an expression similar to eq. (1). The particle energy $E_h$ which is effectively converted to pulse height is $E_h = E_0 - E_s - E_w - E_n = E_0 - E_L$.

For light ions in Si, Lennard et al. introduced a model for the pulse height $H$ according to

$$H = \epsilon_0 \int_0^{E_0 - E_L} \frac{\mathrm{d}E}{\epsilon_0 - kS(E)}, \tag{2}$$

where $\epsilon_0 = 3.67$ eV per electron–hole pair is the value for photons in Si, independent of the quantum energy, and $k$ is a constant. The basic idea is the assumption that $\epsilon = \epsilon_0 - kS(E)$ depends on the density of the charge carriers in the plasma or, in other words, on the projectile stopping power. By comparing the pulse height for $^1$H, $^4$H and $^7$Li ions (including α-particles from a mixed-nuclide source) in surface-barrier detectors, a value $k = 2 \times 10^{-4}$ to about $3 \times 10^{-4}$ nm/electron–hole pair was obtained [6–8], hence $kS(E)/\epsilon_0 \approx 1 \times 10^{-2}$. From eq. (2) one obtains

$$\frac{\mathrm{d}H}{\mathrm{d}E} = \frac{1}{1 - kS(E)/\epsilon_0} \left(1 - \frac{\mathrm{d}E_L}{\mathrm{d}E}\right). \tag{3}$$

Since $E_n$ and $E_w$ show opposite energy dependences, $\mathrm{d}E_L/\mathrm{d}E \approx -10^{-4}$ is small. Assuming a strictly linear electronic system, the channel number $C$ is related to the pulse height $H$ via

$$C = C_0 + \eta H, \tag{4}$$

with $C_0$ the electronic offset and $\eta$ the amplification; hence eq. (3) becomes

$$\frac{\mathrm{d}E}{\mathrm{d}C} = \frac{1}{\eta}\frac{\mathrm{d}E}{\mathrm{d}H} = \frac{\left[1 - \dfrac{kS(E)}{\epsilon_0}\right]/\eta}{1 - \dfrac{\mathrm{d}E_L}{\mathrm{d}E}}. \tag{5}$$

### 3. System parameters and response to deuterons

The spectrometric measurements have been done at CBNM. Details of the measurement equipment can be found elsewhere [11]. A mixed-radionuclide source containing approximately equal activities of $^{239}$Pu, $^{241}$Am and $^{244}$Cm and produced by sublimation in vacuum was kindly provided by the Harwell Laboratory, UK. The energy loss of the α-particles in the source layer, $E_s$, was obtained from the energy shift of the major peaks using two configurations: the source parallel to the detector, and the surface normal of the source rotated 60°. The peaks were fitted using an existing code [12]. A value $E_s = 1.6 \pm 0.1$ keV was obtained. From stopping-power data of $PuO_2$, this corresponds to an areal-mass density of the source material of about 11 μg/cm$^2$.

The nuclear losses $E_n$ were calculated by the Monte Carlo code TRIM T2D [13], which is widely used to obtain detailed information on ion–solid interactions. As a result, the energy loss $E_n$ for deuterons of energy $E_d$ in the range 40–500 keV by elastic collisions in Si is well described by a power law:

$$E_n = 0.658 E_d^{0.195} \text{ [keV]}. \tag{6}$$

Similarly, for α-particles in Si in the energy range $E_\alpha$ from 4 to 7 MeV, $E_n$ is well approximated by the linear relationship

$$E_n = 9.62 + 6.12 \times 10^{-4} E_\alpha \text{[keV]}. \tag{7}$$

Although for α-particles the $E_n$-values obtained in different calculations may differ by about 1 keV [13,14], no substantial difference for the energy dependence of $E_n$ was found. For the two detectors of 50 mm$^2$ area used, the relative change of the α pulse height with the bias was $< 10^{-4}$ V$^{-1}$ (#849) and $< 10^{-5}$ V$^{-1}$ (#845).

RBS measurements were made at the 700 keV Van de Graaff accelerator of Linz University to determine $d_w$ of the detectors. The target was a 5 μg/cm$^2$ thick Pt layer on a Si backing covered with 50 μg/cm$^2$ of boron; the backscattering angle was 90°. Deuterons backscattered from Pt were measured for a number of energies $E = KE_d$ between 35 and 440 keV, where $K$ is the kinematic factor (0.980 in our case) [15]. The relative uncertainties of $E$ are $\pm 3 \times 10^{-3}$ at the lowest energies [16] and substantially less at higher energies. The peaks in the RBS spectrum were fitted using Gaussians and allowing for a background. Differences in the peak positions (d$C$) as a result of differences in the deuteron energies (d$E$) were deduced from these measurements. Choosing either the peak positions or their centroids, the results for d$C$ were found to agree within ±0.09 channels, i.e. ±1% of the peak FWHM.

In fig. 1 the differential-energy width per channel

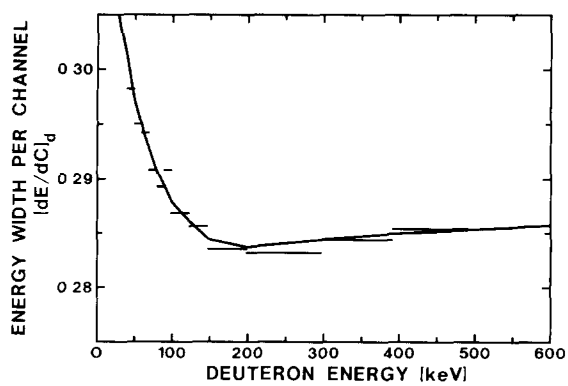


Fig. 1. Energy width per channel $(\mathrm{d}E/\mathrm{d}C)_d$ versus deuteron energy. The horizontal bars refer to the measured data. Their length corresponds to the deuteron-energy step width. The solid line is calculated using eq. (9) (see text).

$(\mathrm{d}E/\mathrm{d}C)_d$ is plotted versus the energy $E$ of the backscattered deuterons. The index d relates to the use of deuterons. The length of the horizontal bars marks the energy-step width in the measurements from which $\mathrm{d}E$ is obtained. This figure clearly shows a nonlinearity which is most pronounced below energies of ~150 keV. This nonlinearity results from $S(E)$ in eq. (5), where $E_s$ can be taken to be zero.

Introducing eq. (1), one may rewrite eq. (5) into the quasi-linearized form

$$\frac{1-kS/\epsilon_0}{1-\mathrm{d}E_n/\mathrm{d}E}\frac{\mathrm{d}C}{\mathrm{d}E} \approx \eta - \eta d_w \frac{\mathrm{d}S}{\mathrm{d}E}, \tag{8}$$

from which $\eta$ and $\eta d_w$ are obtained by a linear regression as the intercept and the slope, respectively. Using $S(E)$ from refs. [17,18], $E_n$ according to eq. (6) and a tentative value for $k = 2 \times 10^{-4}$ nm/electron–hole pair [6], values $d_w = 54 \pm 5$ and $50 \pm 3$ nm were obtained for the detectors #849 and #845, respectively. These results are quite insensitive to the chosen value of $k$. For 5.5 MeV α-particles the $d_w$-values correspond to energy losses $E_w = 7.3 \pm 0.7$ and $6.8 \pm 0.4$ keV, respectively.

The full line in fig. 1 is calculated from eq. (9) which is an approximation to eq. (5) for both $|(\mathrm{d}E_L/\mathrm{d}E)| \ll 1$ and $kS(E)/\epsilon_0 \ll 1$:

$$\frac{\mathrm{d}E}{\mathrm{d}C} \approx \frac{1}{\eta}\left[1 - \frac{kS(E)}{\epsilon_0} + \frac{\mathrm{d}E_L}{\mathrm{d}E}\right]. \tag{9}$$

In fig. 1, the good agreement between the calculated and measured nonlinear response to deuterons gives confidence to the reliability of the stopping-power data and the adopted model. In table 1, the magnitude of the different contributions to the nonlinearity is listed. From these data it can be seen that at low deuteron energies the contribution from the detector window is by far the largest effect. Above 500 keV, the nonlinearity is very small and stems mainly from the assumed stopping-power dependence of $\epsilon$.

Table 1
Calculated contributions to the nonlinearity of a Si detector to deuterons in the energy range 20–1000 keV, from eqs. (1) and (9) for $d_w = 50$ nm, $k = 2.8 \times 10^{-4}$ nm/electron–hole pair and $\eta = 1$ keV/channel

| $E$ [keV] | $kS(E)/\epsilon_0$ | $d_w\,\mathrm{d}S(E)/\mathrm{d}E$ | $\mathrm{d}E_n/\mathrm{d}E$ | $\mathrm{d}E/\mathrm{d}C$ [keV/channel] |
|---|---|---|---|---|
| 20 | 0.0057 | 0.0670 | 0.0115 | 1.0728 |
| 30 | 0.0069 | 0.0536 | 0.0083 | 1.0550 |
| 40 | 0.0076 | 0.0450 | 0.0066 | 1.0440 |
| 50 | 0.0083 | 0.0338 | 0.0055 | 1.0310 |
| 60 | 0.0088 | 0.0263 | 0.0048 | 1.0223 |
| 80 | 0.0095 | 0.0148 | 0.0038 | 1.0091 |
| 100 | 0.0097 | 0.0050 | 0.0032 | 0.9985 |
| 125 | 0.0098 | −0.0013 | 0.0026 | 0.9915 |
| 150 | 0.0095 | −0.0063 | 0.0023 | 0.9865 |
| 200 | 0.0090 | −0.0085 | 0.0018 | 0.9843 |
| 300 | 0.0076 | −0.0066 | 0.0013 | 0.9871 |
| 400 | 0.0067 | −0.0046 | 0.0010 | 0.9897 |
| 600 | 0.0057 | −0.0026 | 0.0007 | 0.9924 |
| 1000 | 0.0050 | −0.0014 | 0.0005 | 0.9941 |

## 4. Response to electrons and α-particles

Conversion-electron spectra of $^{109}$Cd ($E_K = 62.520$ keV and $\bar{E}_{LMN} = 85.03$ keV), $^{137}$Cs ($E_K = 624.213$ keV, $\bar{E}_L = 656.05$ keV and $\bar{E}_{MN} = 661.01$ keV) and $^{233}$Pa ($E_{K300.1} = 184.51$ keV, $E_{K312} = 196.37$ keV and $E_{K340.5} = 224.93$ keV) have been measured with one of the detectors (#845) under identical experimental conditions as for the α-spectra. Electron-peak positions were fitted using Gaussians and allowing for a background distribution. Since the total stopping power of electrons in this energy range is very small [19], eq. (9) reduces to $(\mathrm{d}E/\mathrm{d}C)_e \approx 1/\eta$. The index e stands for electrons. A linear fit was made to the electron-peak positions; the reduced chi-square obtained (0.76) supports the expected linear response.

Because of a very slight integral nonlinearity of the electronic system, the peak positions in the spectra were converted into pulser-dial readings $P$ [V] by performing pulser-peak measurements in connection with the spectrum measurements. This provides the expression for the response of the detector system to electrons under identical experimental conditions as for α-particles:

$$\left(\frac{\mathrm{d}E}{\mathrm{d}C}\right)_e \frac{\mathrm{d}C}{\mathrm{d}P} = \left(\frac{\mathrm{d}E}{\mathrm{d}P}\right)_e,$$

for which the value $(\mathrm{d}E/\mathrm{d}P)_e = 896.4 \pm 0.4$ keV/V was obtained (#845). Neglecting the smallest term in eq. (9) for the case of α-particles, one obtains

$$k \approx \frac{\epsilon_0}{S(E)}\left[1 - \frac{(\mathrm{d}E/\mathrm{d}P)_\alpha}{(\mathrm{d}E/\mathrm{d}P)_e}\right]. \tag{10}$$

Considering that the slope of the response curve, $(\mathrm{d}E/\mathrm{d}P)_\alpha$, for α energies between those of $^{239}$Pu and $^{244}$Cm is very nearly constant, the value at the corrected α energy of $^{241}$Am was, to a good approximation, obtained from a linear fit in that region. Peak positions were taken at the peak centroids. The α energies [20] have been corrected for an energy loss $E_L$ as described above. A fitted slope value $(\mathrm{d}E/\mathrm{d}P)_\alpha = 887.0 \pm 0.8$ keV/V was obtained for detector #845. In eq. (10), the ratio $(\mathrm{d}E/\mathrm{d}P)_\alpha/(\mathrm{d}E/\mathrm{d}P)_e = 0.9895 \pm 0.0010$ is close to unity, however the slopes could be measured quite accurately.

Using a value $S = 135.6$ eV/nm for the mean α-particle stopping power [21] in the energy range considered, we obtain for detector #845 the value $k = (2.84 \pm 0.30) \times 10^{-4}$ nm/electron–hole pair. The quoted uncertainty

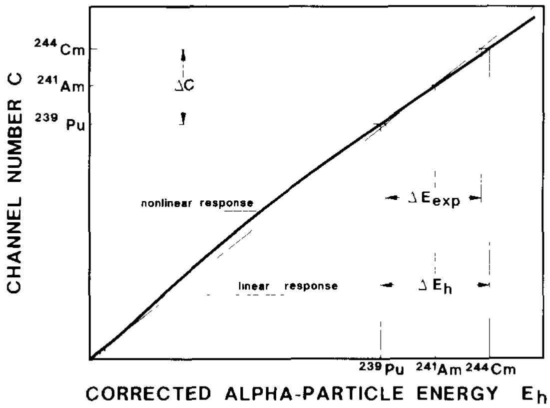


Fig. 2. Schematic representation of the pulse-height model [eq. (2)] for the response of Si detectors to α-particles. The value chosen for $k$ in this figure has been increased arbitrarily to show the nonlinear effect. Elements required to calculate $k$ (see text) are also included in this figure.

is an estimate of the overall standard deviation for uncorrelated uncertainty components.

The linear response to electrons is shown in fig. 2 as a dotted straight line. In order to demonstrate the response to α-particles, the nonlinearity shown in fig. 2 (heavy line) was magnified by arbitrarily choosing a value $k = 40 \times 10^{-4}$ nm/electron–hole pair in connection with eq. (2).

The model parameter $k$ was also obtained by the method described in ref. [6]. According to fig. 2 the measured apparent energy difference $\Delta E_{\text{exp}}$ for a given channel distance $\Delta C$ between alpha peaks in the spectrum is

$$\Delta E_{\text{exp}} = \Delta C\left(\frac{E_{\text{h}}}{C}\right)_{\text{Am}} = \Delta P\left(\frac{E_{\text{h}}}{P}\right)_{\text{Am}}. \tag{11}$$

The precision of the pulser measurements being better than 0.01%, with data from table 2 the right-hand side of eq. (11) yielded an apparent energy difference between the $^{239}$Pu and $^{244}$Cm main peaks of $\Delta E_{\text{exp}} = 644.4 \pm 0.8$ keV for #849, and $\Delta E_{\text{exp}} = 644.2 \pm 0.8$ keV for #845. These figures have to be compared with the difference between the corrected energies, $\Delta E_{\text{h}} =$

Table 2
Alpha-particle energies $E_0$, corrected α-energies $E_{\text{h}}$ and corresponding pulser readings $P$ for the two detectors used

| Detector | | $E_0$ [keV] | $E_{\text{h}}$ [keV] | $P$ [V] |
|---|---|---|---|---|
| #849 | $^{239}$Pu | 5156.59 | 5134.47 | 5.7800 |
| | $^{241}$Am | 5485.56 | 5463.51 | 6.1487 |
| | $^{244}$Cm | 5804.77 | 5782.74 | 6.5052 |
| #845 | $^{239}$Pu | 5156.59 | 5134.70 | 5.8267 |
| | $^{241}$Am | 5485.56 | 5463.74 | 6.1983 |
| | $^{244}$Cm | 5804.77 | 5782.95 | 6.5575 |

$648.26 \pm 0.17$ keV. Eq. (2) was iteratively solved for $k$ in order to match the energy difference $\Delta E_{\text{h}} - \Delta E_{\text{exp}} = 3.96 \pm 0.80$ keV. This was done by numerical integration using an analytical approximation for $S(E)$ in the entire energy interval [21]. A value $k = (2.65 \pm 0.60) \times 10^{-4}$ nm/electron–hole pair was obtained in this manner. The uncertainty associated with this result is relatively large as a result of the difference $\Delta E_{\text{h}} - \Delta E_{\text{exp}}$.

The two results for $k$ in this work are mutually consistent and have been obtained following rather different methods. Our mean value $k = (2.8 \pm 0.3) \times 10^{-4}$ nm/electron–hole pair is higher than the one originally proposed by Lennard et al. [6]. The quoted uncertainty is an estimate of the overall standard deviation.

The ratio of the slopes $(\mathrm{d}E/\mathrm{d}P)_\alpha/(\mathrm{d}E/\mathrm{d}P)_\mathrm{e}$ obtained as an intermediate result in the first method [eq. (10)] is in fact the ratio of the mean energies expended per ion pair formed, $\overline{W}_\alpha/\overline{W}_\mathrm{e}$, in Si. Our result is in agreement with evaluated data from the literature, $\overline{W}_\alpha/\overline{W}_\mathrm{e} = 0.985$ $(\pm 0.008)$ [22]. It is concluded that the pulse-height model of eq. (2), proposed by Lennard et al., provides an adequate description of the Si-detector response to α-articles from a radionuclide source. This offers a reliable way of measuring the energy corresponding to peaks in α-particle spectra from a calibrated semiconductor system.

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