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ABSTRACT

Detailed laboratory measurements have been made of the electron response of solid state detectors as a function of incident electron energy, detector depletion depth, and energy-loss discriminator threshold. These response functions were determined by exposing totally-depleted silicon surface barrier detectors with depletion depths between 50 μm and 1000 μm to the beam from a magnetic β-ray spectrometer. The data were extended to 5000 μm depletion depth using the results of previously published Monte Carlo electron calculations. When the electron counting efficiency of a given detector is plotted as a function of energy-loss threshold for various incident energies, the efficiency curves are bounded by a smooth envelope which represents the upper limit to the detection efficiency. These upper limit curves, which scale in a simple way, make it possible to easily estimate the electron sensitivity of solid state detector systems.

1. INTRODUCTION

The response of solid-state detectors to normally incident mono-energetic electrons has been the subject of many investigations, both experimental and theoretical[1,2,3,4]. As a result, the response function is well-known for many values of detector depletion depth d and electron incident kinetic energy E. We define the response function as:

$F(d,E,E')$ = probability of energy loss E' per unit energy-loss interval

In many instances, however, it would be more useful to know the detector counting efficiency $\varepsilon(d,E,\Delta E)$ above a given energy-loss threshold ΔE, which is given by

$$\varepsilon(d,E,\Delta E) = \int_{\Delta E}^{\infty} F(d,E,E')\,dE' \qquad (1)$$

It is this function $\varepsilon(d,E,\Delta E)$ rather than $F(d,E,E')$ which is directly related to the electron sensitivity of a detector system. The determination and interpretation of these efficiency functions are described in the following sections.

A magnetic β-ray spectrometer was used to irradiate silicon surface barrier detectors with depletion depths of 50, 100 and 1000 μm with electrons between 0.2 and 2.0 MeV. The results of this experimental work for d = 1000 μm are shown in Figure 1. The efficiency curves for a given detector thickness form a smooth envelope $\varepsilon_{max}(d,\Delta E)$, which is a very useful and compact expression of the electron response. The envelope function ε_{max} allows one to easily assign an upper limit to the electron counting efficiency for a detection system dessribed by a detector thickness d and an energy-loss threshold ΔE. It is also evident that electrons with incident energy $E \simeq \Delta E$ yield the highest detection efficiency.

2. EFFICIENCY ENVELOPES FOR DETECTORS OF VARYING THICKNESSES

Response functions of the form $F_{mc}(d,E,E')$ have been previously published using a Monte Carlo technique for detector thicknesses between 0.05 and 10.0 mm and for incident energies between 0.15 and 5.0 MeV[4]). We have modified these functions, which do not include the effects of noise fluctuations, by folding them with a gaussian noise distribution in a straightforward way:

$$F_{mc}(d,E,E',\sigma) = \int_0^\infty \frac{1}{\sigma\sqrt{2\pi}} \exp\left\{-\frac{(E''-E')^2}{2\sigma^2}\right\} F_{mc}(d,E,E'')dE'' \qquad (2)$$

By using the 15 keV value for σ which closely approximates our experimental conditions, we were able to achieve good agreement with our laboratory results and to thereby extend our efficiency envelopes $\varepsilon_{max}(d,\Delta E)$ up to d = 5.0 mm. These Monte Carlo results are plotted along with our actual experimental values in Figure 2.

3. SCALING

When the efficiency envelopes ε_{max} are plotted vs. log ΔE as in Figure 2, the similarity of the shapes of the curves suggests that a generalized efficiency function exists which will describe the electron response for any detector thickness. As a first attempt at scaling the curves, the energy-loss values ΔE for a given detector thickness d were normalized by dividing by the energy $E_R(d)$ corresponding to the energy of an electron with an extrapolated range[5]) equal to the detector thickness. This technique worked well for higher energies, but produced discrepancies at lower energies due to the broadening effect of the noise fluctuations. It was found, however, that this noise effect could be taken into account by replacing the normalizing energy $E_R(d)$ by $E_0(d,\sigma)$, where

$$E_0(d,\sigma) = E_R(d) - 1.3\sigma \tag{3}$$

The normalized energy-loss values ΔE_n for a detector of thickness d and a noise resolution σ are given by

$$\Delta E_n = \Delta E/E_0(d,\sigma) \tag{4}$$

The envelope curves are plotted vs. ΔE_n in Figure 3 for both experimental and Monte Carlo results. Note that the point $\Delta E_n = 1.0$, which should correspond to detection of all incident electrons, yields $\varepsilon_{max} = 80\%$. The missing 20% are most likely electrons which have backscattered and "escaped" without depositing all of this incident energy, and which thus make no contribution to the detection efficiency at $\Delta E = E_{inc}{}^{1/2}$). The values of the scaling energy $E_0(d,\sigma)$ are compared in Figure 4 with the Evans extrapolated range-energy curve and with the 80% efficiency points from Figure 2.

4. SUMMARY

The intent of this paper has been to organize information on detector electron responses into a more useful form. We have generated the following very simple recipe for making estimates of the maximum electron detection efficiencies:

1. Define the detector thickness d, gaussian noise σ, and energy-loss threshold ΔE which characterize the detection system.
2. Determine the scaling energy $E_0(d,\sigma) = E_R(d) - 1.3\sigma$ using the Evans extrapolated range curve $E_R(d)$.
3. Calculate the normalized energy $\Delta E_n = \Delta E/E_0(d,\sigma)$.
4. Find ε_{max}, the upper limit to the electron detection efficiency from Figure 3.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1. Experimentally determined electron detection efficiency $\varepsilon(d,E,\Delta E)$ vs. energy-loss threshold ΔE for a 1.00 mm depletion depth detector. The individual curves for various incident electron energies E are bounded by the curve $\varepsilon_{max}(d,\Delta E)$.

Fig. 2. Maximum electron efficiency envelopes $\varepsilon_{max}(d,\Delta E)$ vs. energy-loss threshold ΔE for detector depletion depths from 0.05 to 5.0 mm. Both experimental and Monte Carlo[4]) data are included.

Fig. 3. Maximum electron efficiency $\varepsilon_{max}(d,\Delta E)$ vs. normalized energy loss $\Delta E_n = \Delta E/E_0(d,\sigma)$. All experimental and Monte Carlo data points have been plotted.

Fig. 4. Scaling energy $E_0(d,\sigma)$ vs. detector thickness d, as given by Eq. 3. Also included for comparison are the Evans[5]) extrapolated range-energy curve $E_R(d)$ and the 80% efficiency points from Fig. 2.

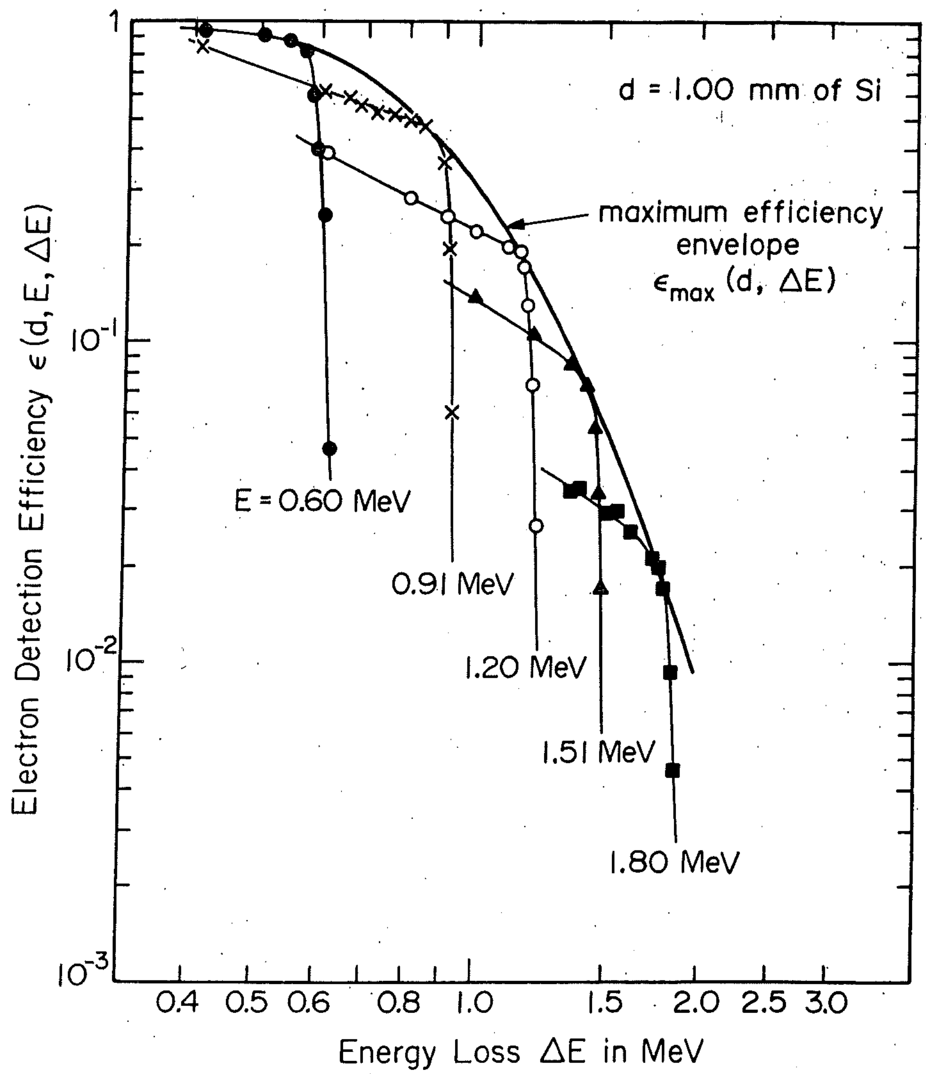
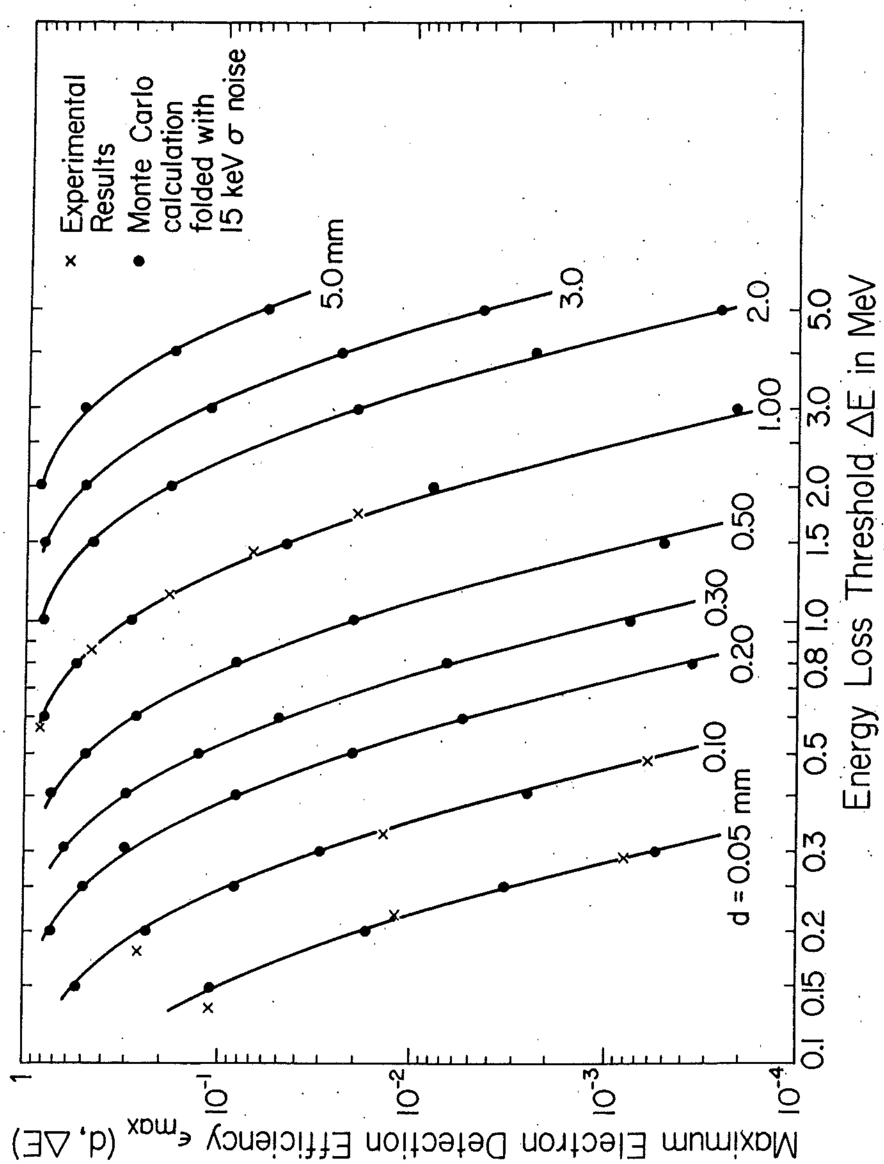
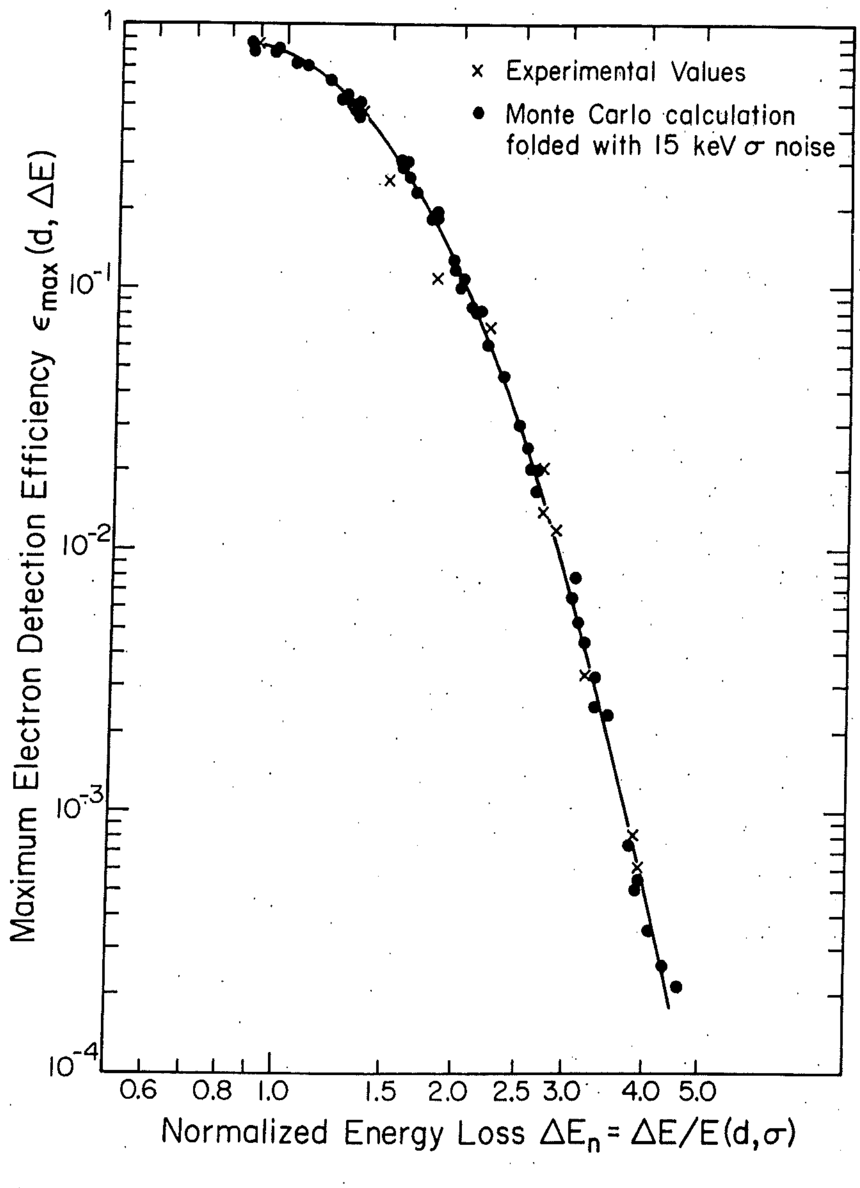

d = 1.00 mm of Si
maximum efficiency envelope $\epsilon_{max}(d, \Delta E)$
E = 0.60 MeV
0.91 MeV
1.20 MeV
1.51 MeV
1.80 MeV
Electron Detection Efficiency $\epsilon(d, E, \Delta E)$
Energy Loss ΔE in MeV
1
10^{-1}
10^{-2}
10^{-3}
0.4
0.5
0.6
0.8
1.0
1.5
2.0
2.5
3.0

Fig. 1



Maximum Electron Detection Efficiency ϵ_{max} (d, ΔE)
Energy Loss Threshold ΔE in MeV
× Experimental Results
● Monte Carlo calculation folded with 15 keV σ noise
5.0 mm
3.0
2.0
1.00
0.50
0.30
0.20
0.10
d = 0.05 mm

Fig. 2



Maximum Electron Detection Efficiency $\epsilon_{max}(d, \Delta E)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
× Experimental Values
● Monte Carlo calculation folded with 15 keV σ noise
0.6
0.8
1.0
1.5
2.0
2.5
3.0
4.0
5.0
Normalized Energy Loss $\Delta E_n = \Delta E / E(d,\sigma)$

Fig. 3

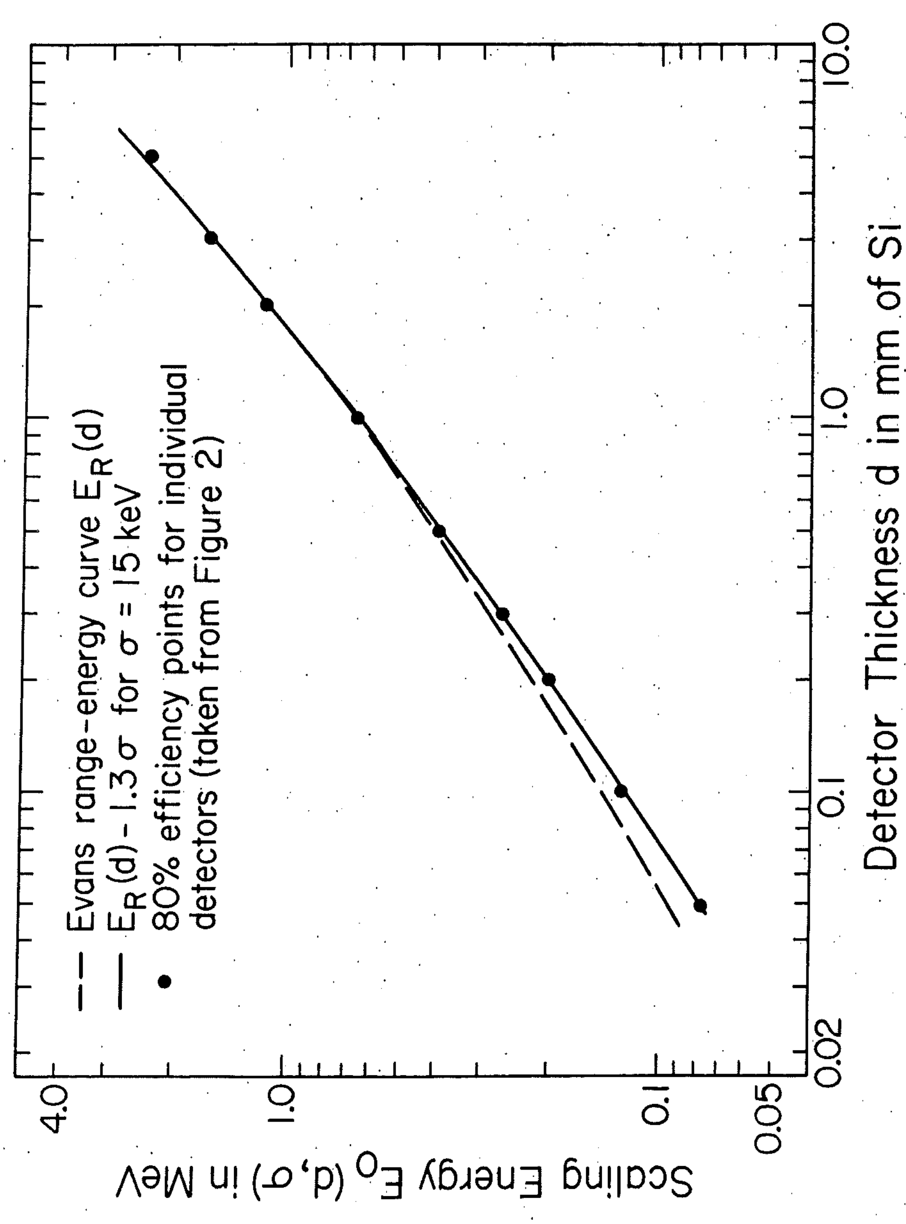

Evans range-energy curve $E_R(d)$
$E_R(d) - 1.3\sigma$ for σ = 15 keV
80% efficiency points for individual detectors (taken from Figure 2)
Scaling Energy $E_0(d,\sigma)$ in MeV
4.0
1.0
0.1
0.05
0.02
0.1
1.0
10.0
Detector Thickness d in mm of Si

Fig. 4