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# ENTRANCE WINDOWS IN GERMANIUM LOW-ENERGY X-RAY DETECTORS

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# ENTRANCE WINDOWS IN GERMANIUM LOW-ENERGY X-RAY DETECTORS*

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ABSTRACT

We have found experimentally that high-purity Ge low-energy X-ray detectors have a relatively thick entrance window which renders them practically useless below ~ 2.3 KeV. A simple X-ray fluorescence experiment establishes clearly that the window is physically in the Ge material itself. Experiments with detectors made from different Ge crystals, and with Schottky barrier contacts of different metals indicate that the effect is due to a basic property of the transport of electrons near a surface. Theoretical considerations and a Monte Carlo calculation show that the window is caused by the escape of warm electrons which are the end product of a photo event. The mean free path of the electrons becomes longer as they lose energy by optical phonon collisions and they can be trapped at the surface before they are picked up by the electric field.

## INTRODUCTION

It is clear that Ge detectors could have a significant role in the detection of X-rays with energies below the $K_\alpha$ edge of Ge (9.88 KeV). The lower value of $\overline{\varepsilon}$ (i.e. the energy needed to create an e-h pair) of Ge may result in a 28% reduction in energy equivalent electronic Noise Line Width (NLW) with respect to Si. Additional benefits may be obtained from the low Fano factor of high-purity Ge. The techniques needed to fabricate very low-leakage Ge detectors (< 4 x $10^{-14}$A) have been discussed in Ref. 1.

Although the performance of test detectors with Mn X-rays (5.89 KeV) results in peak-to-background ratios which compare well with good Si detectors, considerable degradation of spectral line shapes has been observed by us with X-rays at energies below ~ 2.3 KeV (i.e. S $K_\alpha$)

Figure 1 (bottom) shows spectra obtained by X-ray fluorescence of S, P, Si, Al and Mg targets using a spectrometer having a n-type Ge detector made from a

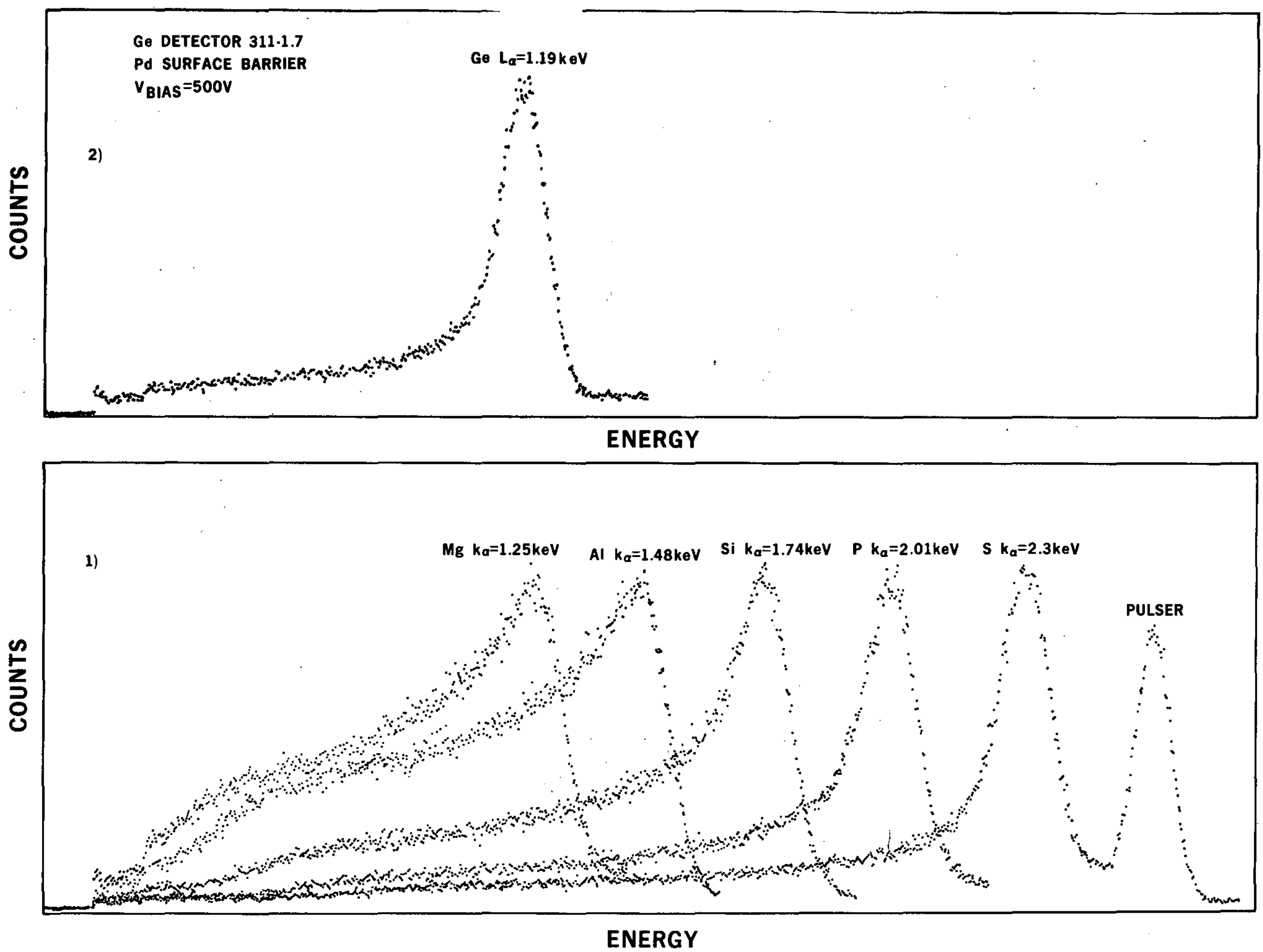


Fig. 1. Experimentally observed spectra of low-energy photons obtained by X-ray fluorescence using an n-type high-purity Ge Detector. Notice improvement of spectral shape when the incident photons have energy just below the Ge $L_{II}$ and $L_{III}$ absorption edges.

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crystal exhibiting an impurity concentration of $\sim 5 \times 10^9\ cm^{-3}$ and fabricated with a Pd surface barrier of about 500 Å thickness. All spectra were obtained by irradiating through the Pd contact, in which case only electrons create the electrical signal. The degradation of the spectral shape particularly in regard to the presence of a low energy tail is evident and this indicates that as the penetration depth of the X-rays decreases, a larger fraction of the charge carriers generated by the photons fails to be properly collected. Also in Fig. 1 (top) we present the $L_\alpha$ spectrum of a Ge target obtained using exactly the same method and configuration as the previous spectra. Considerably improved spectral shape therefore occurs when the photon energy changes from slightly above to slightly below the Ge $L_{II}$ and $L_{III}$ absorption edges (1.249 and 1.217 KeV, respectively). This effect indicates that the spectrum degradation is due primarily to a Ge window and not to any geometric or other experimental factors. Moreover, the possible contribution of the surface barrier metal is limited to the minor effect it may have on the charge collecting properties of the Ge beneath. The observed spectral shapes are only slightly dependent on the detector bias for values between 300 and 1000 V on a 4 mm thick detector (fully depleted at $\sim$ 20 V).

Evaluation Of Window Thickness

A very simple model has been used to determine window thickness. There exists a thickness $d_1$ such that if a photoelectric interaction occurs at $x < d_1$, the result will be a count in the tail of the spectrum. If the interaction occurs at $x > d_1$, the count will fall in the photopeak. Then, the probability $P_t$ of a count in the tail is given by

$$P_t = \mu \int_0^{d_1} \exp(-\mu x)\, dx = 1 - \exp(-\mu d_1) \qquad (1)$$

and the probability of a count in the photopeak will be $P_p = 1 - P_t$. $\mu$ is the absorption coefficient of germanium at the incident energy.

The ratio $P_t/P_p$ can then be solved for $d_1$. The probabilities $P_p$ and $P_t$ are proportional to the areas $A_p$ and $A_t$ shown in Fig. 2. From the spectrum for P in Fig. 2 (bottom), we obtain $P_t/P_p = 0.81$ and, if $\mu = 1.61\ (\mu m)^{-1}$, a window thickness $d_1 = 0.37\ \mu m$ results. For the Al spectrum in Fig. 2 (top), $P_t/P_p = 3.23$, $\mu = 3.46\ (\mu m)^{-1}$ and $d_1 = 0.41\ \mu m$. The agreement between the two sets of data is therefore quite good.

Similar but thinner windows are obtained for silicon detectors irradiated by X-rays in the energy region of the Si K-edge. While these results are not presented here, it is reasonable to suppose that the same mechanisms are at work.

On The Nature Of The Ge Window

Windows whose characteristic are almost identical to the one reported above have been observed in other Ge detectors fabricated from n-type material with impurity concentrations ranging between $5 \times 10^9$ and $5 \times 10^{10}\ cm^{-3}$ and with Pd surface barriers. Again only a slight dependence on detector bias was observed. A device with a Cr surface barrier, a metal having a lower work function than Pd, showed slightly bigger window effects than those obtained with Pd barriers.

A detector fabricated with p-type material and Pd barrier also showed the window effects as soon as fully depleted and they improved only slightly with over-voltage--the overall results appearing very similar but slightly worse than those of the n-type devices.

It is therefore apparent that the window effect observed in these cases must be caused by a fundamental transport limitation of electrons in Ge, which is only slightly affected by the amount of band bending in the vicinity of the Schottky barrier and by applied external field.

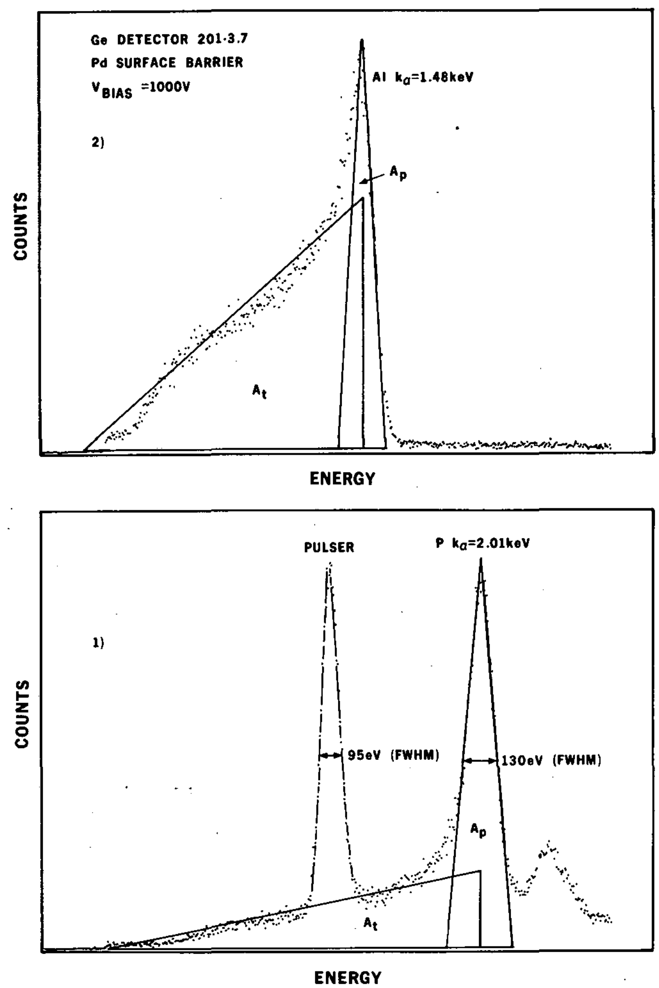


Fig. 2. Approximate geometrical determination of areas under peak ($A_p$) and tail ($A_t$) for the calculation of window thickness.

Baertsch and Richardson[2] observed a loss of efficiency in Ag-GaAs Schottky barrier ultraviolet detectors when the energy of the incoming radiation was such the e-h pairs were generated within 100 or 200 Å of the surface. They attributed this effect to escape through the barrier of a fraction of the photoelectrons generated, since their initial energy could be as high as 2.5 eV.

In 1970, Caywood, Mead and Mayer[3] published a study on the influence of carrier diffusion effects on window thickness of semiconductor detectors. Data obtained by Siffert[4] from measurements with charged particles in Si surface barrier detectors were analyzed in terms of the balance between carrier diffusion and drift in the depletion layers. The agreement between their theory and the experimental results supports the existence of a window in Si of a thickness of up to 1500 Å for high resistivity Si operated at -40°C. Their diffusion model predicts that window thickness is proportional to temperature.

A calculation carried out by Goulding[5] for Ge with the assumption of saturation velocity for electrons in the window region leads to a window width of 0.265 μm, in reasonably good agreement with the experimental results. Goulding's argument is as follows:

The time needed for an electron to travel a distance d(cm) at a saturation velocity of $10^7$ cm/s is $d/10^7$ (sec). The average diffusion distance L in this time is given by $L = (Dd/10^7)^{1/2}$ cm, where D is the diffusion coefficient. Using Einstein's relation at 77 K

$$D = \frac{kT}{q}\,\mu = 6.64 \times 10^{-3} \times 4 \times 10^{4} = 265 \text{ cm}^2/\text{s} \qquad (2)$$

Significant losses of charge will occur at the surface if L > d. Setting L = d we have $d = D/v_{sat} = 265/10^7 = 0.265$ μm, which is closely in the neighborhood of the window thickness observed. Because of the temperature dependence of μ on temperature ($\mu \propto T^{-1.66}$) and the use of Eq. (2), the predicted window thickness should be proportional to $(1/T)^{0.66}$ in sharp disagreement with the predictions of Caywood, et al.[3]

Upon careful examination of the problem, it becomes evident that although the use of a simple diffusion model for the understanding of window behavior may meet with some limited success, it neglects some rather important facts. When a low-energy photoelectric event occurs, a cascade of electrons and holes is generated within a region which is thin compared to typical window dimensions (since the range of a 1.4 KeV electron in Ge is 0.04 μm, this distance represents the worse case of any direct cascade layer thickness). The cascade ends with a number of e-h pairs whose average number is well known. The energy distribution of the final electrons in the cascade is not known in detail, but it may range from near zero energy to the minimum energy needed to ionize an e-h pair, somewhat above Eg. These electrons may be occupying the customary <111> valleys, or the higher energy <100> or <000> valleys.

As will be shown below, it is primarily the escape of 'warm' electrons (300 to 400K average) that results in the window effects observed. These electrons have mean free paths of ~ 0.3 μm before lattice collisions, a distance comparable to the size of the observed window. Evidently, the motion of these electrons cannot be described well by the concept of diffusion since they may escape without a single collision if their energy after the shower is right. Also, in the use of Eq. (2) to define the diffusion coefficient, the use of lattice temperature for T and low-field mobility for μ does not, in principle, describe properly the behavior of epithermal electrons.

In this paper a more appropriate picture of the nature of the window will be given in terms of the transport properties of hot electrons, a Monte Carlo calculation of collection probabilities and spectral shapes will be described and a tentative prediction of the electron energy distribution after the primary shower will be given.

## Qualitative Window Model

In trying to study the behavior of single electrons which are heated by an electric field and which are interacting with a lattice at temperature T it is useful to think of the electron as the 'average' electron in a distribution of electrons at a temperature $T_e$, which may deviate from Maxwellian. The average energy of electrons travelling in high electric fields has been calculated for T = 27K by Fawcett and Paige.[6] For lower fields, when inter-valley scattering is not important, calculated data on μ vs $T_e$ at T = 78K have been given by Conwell.[7] Since, for very hot electrons, the effect of using the data for low-lattice temperature (T = 27K) for calculations at 77K should not lead to any error of substance, it is possible to calculate, using a combination of results from Refs. 6 and 7, the mean free path between collisions with the lattice for electrons in high fields. In the regions of overlap the agreement is very good. Table 1 shows the mean free path $\ell_1$ for electrons at a temperature $T_e$, with average energy <ε> travelling in a field E. The value of mobility referred to here is defined as $v_{drift}/E$. The relationship between $\mu(T,T_e)$ and $\ell_1$ is the one given by Moll[8]

$$\ell_1 = \mu(T,T_e)\left(\frac{9}{8}\,\pi m^* k\,T_e\right)^{1/2}/q \qquad (3)$$

which assumes a Maxwellian distribution. As shown in Ref. 6, this assumption is not exactly correct, but should yield reasonable results. Data for μ are taken from Chang and Ruch,[9] and m* for the <111> valleys has been used in all cases.

TABLE I

| E (KeV/cm) | $v_{drift}$ (cm/KC) | μ [$cm^2/(V\text{-}s)$] | $T_e$ (°K) | <ε> eV | $\ell_1$ (μm) |
|---|---|---|---|---|---|
| .1 | $0.34 \times 10^7$ | $3.4 \times 10^4$ | 77 | $9.9 \times 10^{-3}$ | 0.43 |
| .73 | $0.96 \times 10^7$ | $1.31 \times 10^4$ | 308 | $39.8 \times 10^{-3}$ | 0.33 |
| 1.0 | $1.02 \times 10^7$ | $1.02 \times 10^4$ | 385 | $49.8 \times 10^{-3}$ | 0.29 |
| 2.0 | $1.2 \times 10^7$ | $6 \times 10^3$ | 772 | 0.1 | 0.24 |
| 4.0 | $1.2 \times 10^7$ | $3 \times 10^3$ | 1005 | 0.13 | 0.14 |
| 8.0 | $1.2 \times 10^7$ | $1.5 \times 10^3$ | 1236 | 0.16 | 0.076 |
| 10.0 | $1.2 \times 10^7$ | $1.2 \times 10^3$ | 1390 | 0.18 | 0.064 |

Figure 3 shows a plot of $\ell_1$ vs <ε> from Table 1, along with a simple linear function which describes it reasonably well.

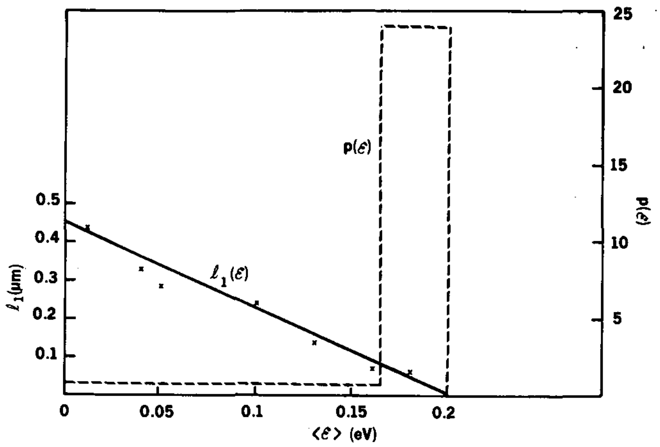


Fig. 3. Mean free path $\ell_1(\epsilon)$ for electrons in Ge at 77K with approximate linear representation. Energy distribution $p(\epsilon)$ of electrons generated as a result of a uniform initial energy distribution up to the ionization energy and short mean free path optical phonon collisions.

The above results allows us to formulate the following qualitative model near a Schottky barrier for electron behavior in high fields:

Electrons from the cascade which have insufficient energy to be able to create new electron-hole pairs will lose energy very rapidly if $\langle\epsilon\rangle$ is above 0.2 eV by emission of phonons with energies of 0.027 or 0.037 eV, depending on whether the collision is inter-valley or intra-valley, respectively. The mean free path for these collisions is so small that the loss of energy to values just below 0.2 eV can be considered to take place in the same tiny region near the point of interaction where ionization occurs. Below that energy the mean free path becomes longer and, since the electrons continue losing energy until they are at equilibrium with a distribution corresponding to the field in which they travel, their mean free path continues to increase. Electrons at the end of the shower that have low energies may escape directly to the surface barrier sink before being captured by the field if their initial direction is outwards. For example, if one assumes that the energy distribution of electrons which have less than the minimum ionization energy after a shower is uniform, one can define an approximate distribution p(E) of electron energies just before 'final' attempts to thermalize by taking all the electrons which would end the shower with $\langle\epsilon\rangle$ above 0.2 eV and placing them between 0.2 eV and (0.2 - 0.037) eV, since 0.037 eV is the optical phonon energy of the most common interaction. This final distribution is also shown in Fig. 3. The value taken for minimum ionization energy is 1.33 eV.[10] The assumption of a uniform distribution of energies after the shower up to 1.33 eV cannot be justified well, as it assumes that the holes created are all near zero energy and that the different 'valleys' are populated in an unlikely manner, but it will be used as a first attempt to solve the problem.

With the above assumption, window effects would be due to the fact that the majority of electrons at the end of the shower are too hot to be collected by the field and as they cool down their mean free path becomes longer and a number of them escape to the surface sink. One can expect the window width to be comparable to the mean free path for 'warm' electrons, as observed in practice.

The window thickness predicted by the present model appears to be practically independent of temperature (considering Eq. (3)), as long as the electrons are in a velocity saturation field. Since $v_{sat}$ is fairly independent of temperature, μ is also independent of temperature. Also, $T_e$ is equally expected not to be very sensitive to lattice temperature for hot electrons. With regard to field dependence of window thickness, it is clear that higher field will result in a higher average energy for most electrons, a shorter mean free path and narrower window. In high-purity Ge detectors even with an inversion layer under the Schottky barrier, fields are too low to modify substantially the window width. The same effect is expected from Li-drifted Si detectors, although surface barrier detectors made on low-resistivity material can have the substantially lowered window thickness reported in Refs. 3 and 4. Measurements to determine window thickness due to warm electron escape as a function of temperature should be carried out with low-energy X-rays, as in the present work, so that plasma effects (occurring with alpha particles, for example) are minimized. Such measurements may unfortunately be very hard to make.

## Monte Carlo Calculation

A meaningful calculation of window effects caused by warm electron escape can only be done by a Monte Carlo method. A complete calculation including all possible kinds of scattering, and taking into consideration the effective masses and scattering rates of different valleys, etc. is beyond the scope of the present work. Instead, a simplified scattering model has been used in which the probability of a lattice collision, $P_c$, in a small time interval Δt, for an electron of energy ε and temperature $T_e$ is given by

$$P_c = \Delta t \, v_{th}(T_e)/\ell_1(\epsilon) \tag{4}$$

where $\epsilon = 3/2\, k\, T_e = 1/2\, m^* v_{th}^2$ .

If $\epsilon < 0.037$ eV (optical phonon energy), a collision (when it occurs), will involve acoustic phonons, in which a phonon of energy[9]

$$\langle\Delta\epsilon\rangle = \frac{4}{3}\frac{c}{v}\epsilon \tag{5}$$

will be emitted or absorbed. The velocity of sound in the crystal, c, is taken to be $3.74 \times 10^5$ cm/s.[11]

The relative probabilities of emission or absorption are calculated by[9]

$$P_e \propto \exp(\langle\Delta\epsilon_a\rangle/kT)/[\exp(\langle\Delta\epsilon_a\rangle/kT) - 1] \tag{6}$$

and

$$P_a \propto 1/[\exp(\langle\Delta\epsilon_a\rangle/kT) - 1] \tag{7}$$

respectively.

On the other hand, if $\varepsilon >$ 0.037 eV, the collision can result in an acoustic interaction, as above, or in the emission of an optical phonon with an energy of 0.037 eV. In order to use the simplest possible collision model, the selection of one or the other type of collision has been made by splitting the collision probability $P_c$ of Eq. (4) into fractions $P_a$ and $P_o = 1 - P_a$ and adjusting $P_a$ for reasonable values of drift velocity at high fields. Figure 4 shows the values of $v_{drift}$ obtained by the Monte Carlo calculation of electron trajectories over a distance of 10 μm for electrons initially at $T_e$ = 77K. A value of $P_a$ = 0.66 was used. In spite of the extreme simplicity of the model, the agreement obtained should be adequate for our purposes. Increasing $\langle\Delta\varepsilon_a\rangle$ of Eq. (5) by a factor of two, would bring the low field velocities in better agreement with experiments.

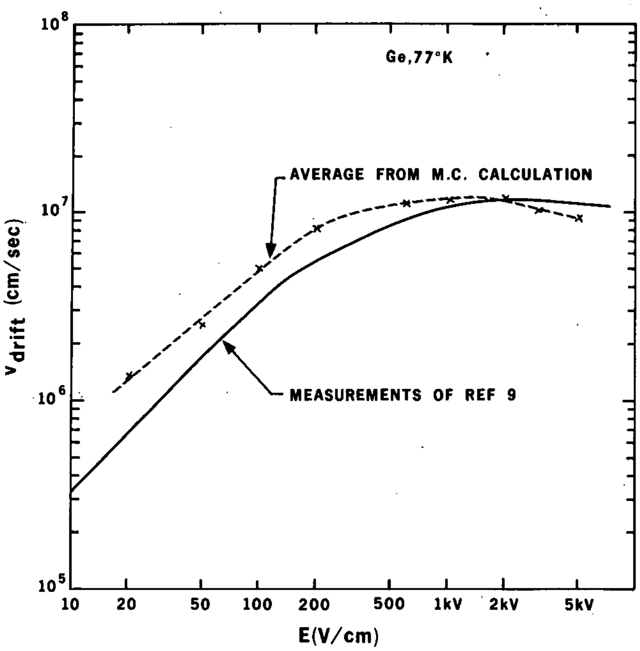


Fig. 4. Drift velocities for electrons in Ge at 77K: comparison between measured results and those calculated by the simplified Monte Carlo model of the present work.

Another relevant point is the electric field in the window region. The results of Malm[12] in measuring the barrier heights in Ge detectors indicate the existence of an inversion layer on n-type high-purity germanium just under the Schottky barrier. In the region where the excess holes of the inversion layer begin to outnumber the fixed ionized donor charge, the solution to Poisson's equation is relatively simple. Starting with

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\varepsilon} n_i \exp[\beta(\emptyset_p - \psi)], \qquad (8)$$

where $\emptyset_p$ is the quasi-Fermi level for holes continuous with the Fermi level in the metal, $\psi$ is the potential (intrinsic center of band gap) and $\beta = q/kT$, one can integrate once and obtain

$$\frac{d\psi}{dx} = \pm\left\{\left[E_1^2 - \frac{2\,q\,C_1\,N_D}{\varepsilon\,\beta}\right] + \frac{2\,q\,n_i}{\varepsilon\,\beta}\exp[\beta(\emptyset_p - \psi)]\right\}^{1/2} \qquad (9)$$

where $E_1$ is the electric field at a point $x_1$ where the free hole concentration is $C_1\,N_D$, with $C_1 = 5$, for example. At $x_1$ the field is essentially the bulk field of the device as calculated by the abrupt approximation. With a further integration of Eq. (9), taking $n_i \exp[\beta(\emptyset_p - \psi)] = p$, we obtain the relationship between x and p as follows:

$$(x-x_s) = \left|\frac{1}{\beta\,E_1}\left\{\ln\frac{[1+a_s]^{1/2}-1}{[1+a_s]^{1/2}+1} - \ln\frac{[1+a_p]^{1/2}-1}{[1+a_p]^{1/2}+1}\right\}\right| \qquad (10)$$

where $(x-x_s)$ is distance from the surface into the material, $a_s = (2\,q\,p_s)/(\varepsilon\,\beta\,E_1)$ and $a_p = (2\,q\,p)/(\varepsilon\,\beta\,E_1)$. The surface concentration $p_s$ can be obtained from the barrier height $\emptyset_B$ by noticing that $(\emptyset_p - \psi_s) = \emptyset_B - 0.366$ (inset of Fig. 5) for Ge at 77K. From the relation of Eq. (10), it is then possible to use Eq. (9) to find E(x). Some calculated values of field are shown in Fig. 5. It is assumed that $\emptyset_B$ = 0.7 eV for a Pd surface barrier is independent of bulk field. It is evident that the field in the window region can be substantially higher than bulk field. The calculated fields have been used in the Monte Carlo calculation for window effects.

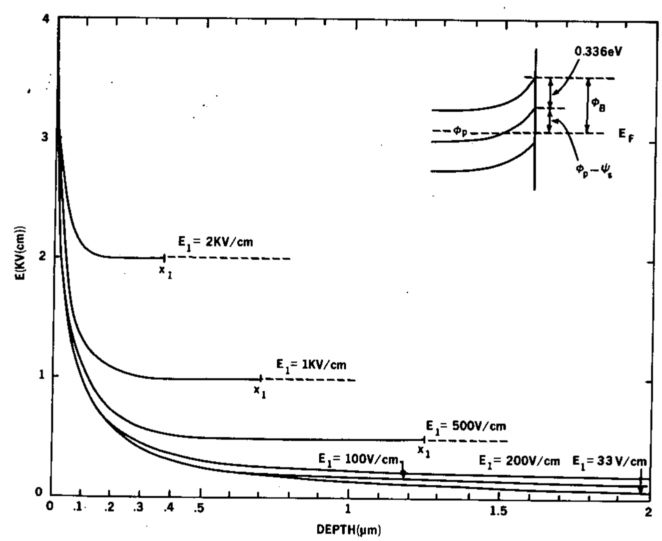


Fig. 5. Field distribution in the vicinity of a Schottky barrier of height $\emptyset_B$ = 0.7 eV as a function of the driving bulk field $E_1$ calculated from abrupt approximation. Point $x_1$ corresponds to a free hole concentration equal to 5 x $10^{10}$ $cm^{-3}$ in n-type Ge of concentration $10^{10}$ $cm^{-3}$.

For the calculation of window effects, it has been assumed that 200 electrons with energy distribution given by p(ε) of Fig. 3 are emitted at a distance x from the surface barrier. They travel initially at the velocity corresponding to their energy in a random direction. The x component of their trajectories is followed through all their collisions. If an electron reaches x = 0, it is considered lost. If it reaches x = 1 μm it is considered effectively collected by the field. The number of electrons collected out of the 200 emitted is tallied in a 200 channel 'analyzer'. The operation is repeated enough number of times to obtain a reasonable distribution. From 50 to 250 repetitions have been used for the results reported here, depending on the value of the initial x.

Figure 6 shows the calculated results in the form of normalized spectra of the number of electrons collected in a device with bulk field $E_1$ = 100 V/mm as a function of position x of the point of emission beneath the surface. The figure shows that for electron showers generated adjacent to the surface (x = 0), approximately 21 out of 200 electrons are collected in the average. For emission at x = 0.5 μm, most of the time 165 electrons are collected, while it is not until x ≃ 0.75 μm that one has nearly full collection. Realizing that the number of collected electrons is proportional to energy in a conventional pulse-height spectrum, the formation of a pulse-height spectrum for a particular source of X-rays is just a matter of evaluating the expression

$$\sum_i p(x = x_i) \exp(- \mu x_i) \Delta x \qquad (11)$$

where $p(x = x_i)$ is the distribution shown in Fig. 6 for electrons emitted at $x = x_i$ and μ is the absorption coefficient for the X-ray. With suitable normalization and after a convolution with a gaussian of 200 eV FWHM to simulate detector and electronic noise, calculated spectra for the same X-ray sources as those of the experimental spectra of Fig. 1 are shown in Fig. 7. It is quite evident that the model used leads to window effects that are too strong. In fact, an examination of the probability of collection vs initial position for the uniform initial energy distribution of shower electron (Fig. 8) shows that for $E_1$ = 1 KV/cm, the window width should be 0.7 to 0.9 μm, in contrast with the experimentally determined width of 0.4 μm. The field dependence of the collection probabilities for bulk fields in the range of those of the detectors tested calculated from the results of the Monte Carlo calculations is also shown in Fig. 8. The dependence is weak, as found experimentally, except at 2 KV/cm where window width begins to change substantially with field.

The initial energy distribution of the shower electrons is the only unadjusted element remaining in the calculations. Assumptions other than a uniform distribution have been tested. Reducing p(ε) of Fig. 3 for ε > 0.163 eV in favor of the distribution below that energy results in collection probabilities which can be made to approach a 0.4 μm window. If one assumes that the energies are uniform out to ε = 0.14 eV, the energy of the <000> valley of Ge, and zero above, one again obtains a collection probability curve with a window of near 0.4 μm, also shown in Fig. 8. For the extreme case of only thermal electrons as end product of the shower, Fig. 8 also shows that the window would be ~ 0.05 μm. The slow thermal electrons are immediately picked up by the high field near the surface and are effectively collected.

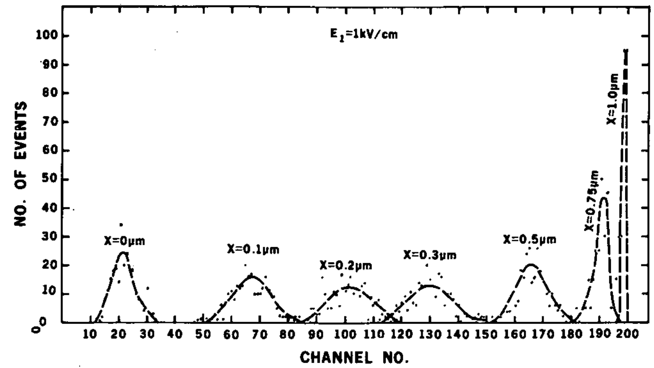


Fig. 6. Collection spectra for electrons resulting from X-ray interactions occurring at depth x. Full collection is at channel 200.

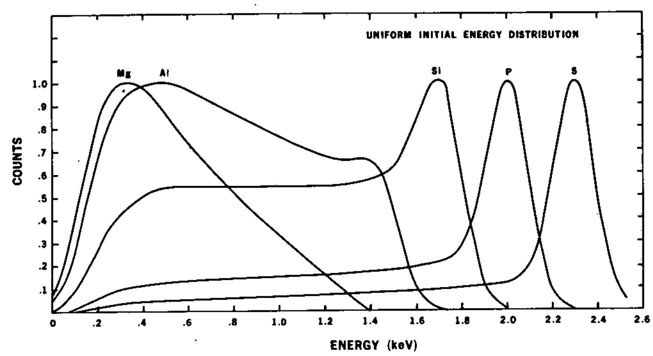


Fig. 7. Calculated energy spectral shapes for Mg, Al, Si, P and S X-rays from the results of the Monte Carlo calculation using a uniform initial energy distribution of shower end-product electrons up to the ionization energy.

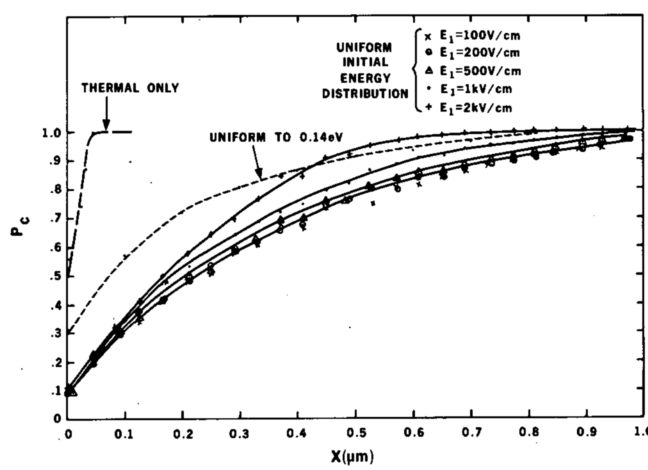


Fig. 8. Effect of field on the collection probability of electrons generated at a depth x for the uniform initial energy distribution, for a distribution which is uniform to 0.14 eV and zero above, and for the assumption of only thermal electrons as the end-product of a shower.

Those electrons cannot be hot enough to be insensitive to the field in contrast to the ones which start too hot and can only be collected by the field after they cool down.

The average energy of the electrons which are trapped at the Schottky barrier (x = 0) for the uniform energy distribution, and uniform to 0.14 eV, as a function of point of generation is shown in Fig. 9. It appears that fairly hot electrons, above $T_e$ = 300K (see Table 1) are involved in the escape process.

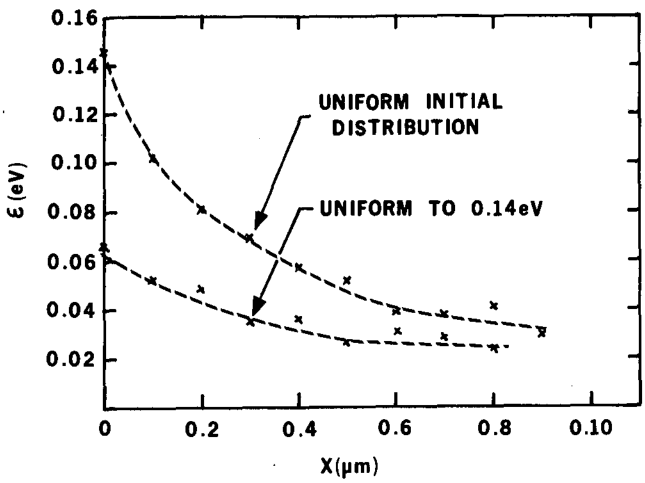


Fig. 9. Average energy of electrons reaching the surface barrier which were generated at a depth x. Thermal electrons for 77K have ε = 0.01 eV.

Finally, it will be shown that a window of approximately 0.4 μm will generate spectra quite similar to the experimental results. If one compresses the x coordinate of the Monte Carlo results of Fig. 6 by a factor of 0.4 (i.e., the 1 μm spectrum corresponds to a new 0.4 μm one) and recalculates the spectra of Fig. 7, one obtains the results of Fig. 10. Except for questions of detail, which cannot be calculated with accuracy, the principal effects observed experimentally are quite apparent in the results.

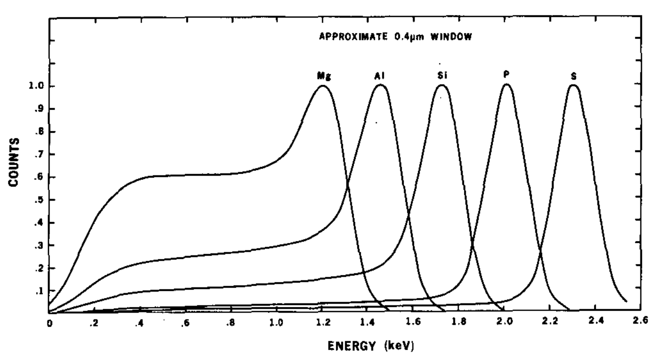


Fig. 10. Calculated energy spectral shapes similar to those of Fig. 7 obtained from a window thickness of approximately 0.4 μm by spatially compressing the spectra of Fig. 6 for electron collection.

## CONCLUSION

The model proposed in this paper for the escape of warm electrons explains most of the characteristics of the observed windows in Ge quite well. The relative insensitivity of window width in high-purity Ge detectors to bias or material type and impurity concentration is due to the insensitivity of hot electrons to the electric field, except after many optical phonon emission collisions. Because of the long mean free path of fairly hot electrons during these 'cool down' collisions, electrons from quite deep into the material, are able to reach the surface. If one assumes that the surface potential depends on surface treatment and slightly on metal work function,[12] the use of CR instead of Pd should result in a lower surface field and somewhat poorer collection of electrons generated near the surface. Poorer spectra were indeed observed with a Cr surface barrier. A calculated window of 0.4 μm can be obtained starting with any of a large set of initial assumptions in which the energy distribution of final shower electrons contains hot electrons in substantial numbers, and it is the escape of warm electrons, above $T_e$ = 300K, which causes the window effect observed. It is felt that the model is sufficiently well established by the above results.

Because of the very high fields that would be needed to significantly reduce or eliminate the excessive window, the use of Ge for a low-energy X-ray detector does not seem possible. It should be pointed out that a similar effect to the one observed in Ge also exists in Si(Li) detectors. A window of ~ 0.15 μm has been measured by the authors by the same procedure described at the beginning of the paper. Again, the window seemed to almost disappear for Si X-rays, indicating the same basic nature of the effect. This window thickness is similar to the one observed by Siffert[4] in high resistivity Si. Fortunately, the absorption coefficient of Si is so much smaller than that of Ge that a window of ~ 0.15 μm is not nearly as damaging in Si as 0.4 μm is to Ge, and Si detectors are very useful as low-energy X-ray detectors.

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