Title
A Direct Comparison of Ge and Si(Li) Detectors in the 2-20 keV Range

Authors
Rossington, C.S.
Giauque, R.D.
Jaklevic, J.M.

Publication Date
1991-10-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

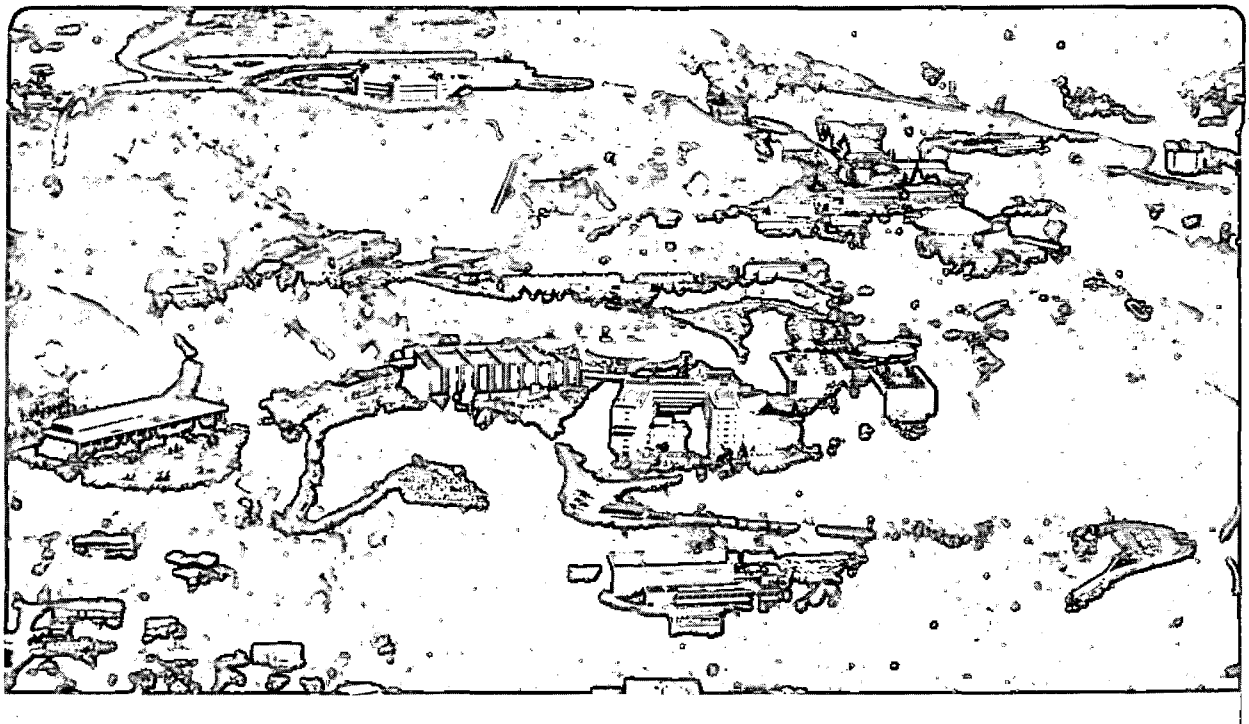
Engineering Division

Presented at the IEEE Nuclear Science Symposium,
Santa Fe, NM, November 5–8, 1991, and to be
published in the Proceedings

A Direct Comparison of Ge and Si(Li) Detectors in the 2 – 20 keV Range

C.S. Rossington, R.D. Giauque, and J.M. Jaklevic

October 1991



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL-30614

A Direct Comparison of Ge and Si(Li) Detectors in the 2 – 20 keV Range

C.S. Rossington, R.D. Giauque and J.M. Jaklevic
Engineering Science Department
Engineering Division
Lawrence Berkeley Laboratory
University of California, Berkeley CA, 94720

October 1991

This work was supported by the Director, Office of Energy Research,
Office of Health and Environmental Research,
U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

A Direct Comparison of Ge and Si(Li) Detectors in the 2 – 20 keV Range

C. S. Rossington, R. D. Giauque and J. M. Jaklevic,
Lawrence Berkeley Laboratory,
University of California, Berkeley, CA 94720 USA

Abstract

The spectral response of high purity Ge (HPGe) and lithium-drifted Si (Si(Li)) surface barrier detectors of similar geometry has been measured over a range of x-ray energies under identical experimental conditions. Detector characteristics such as spectral background, escape peak intensity, entrance window absorption, and energy resolution are presented and compared. Although these characteristics have been discussed in the literature previously, this paper represents an attempt to consolidate the information by making comparisons under equivalent experimental conditions for the two types of detectors. A primary goal of the study is a comparison of the two types of detectors for use in x-ray fluorescence applications.

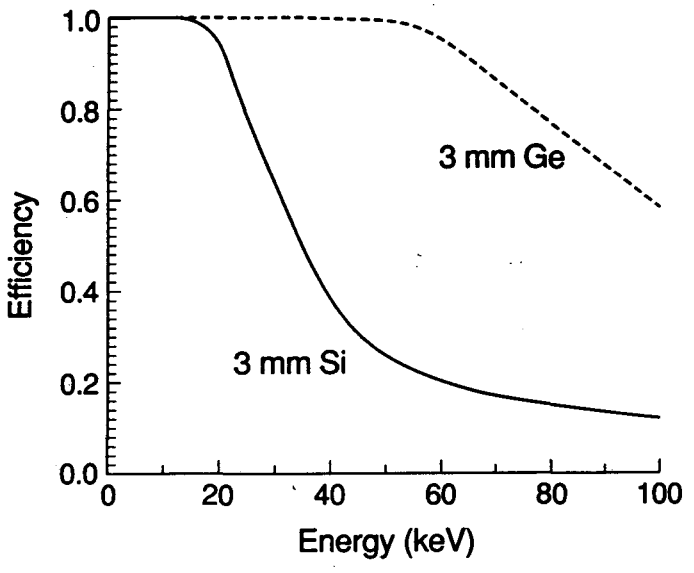


Fig. 1 Calculated material efficiency as a function of energy for 3 mm thick Si and Ge. No account is taken of any reduction in efficiency from absorption by the detector and instrument windows.

I. INTRODUCTION

High purity germanium (HPGe) and lithium-drifted silicon (Si(Li)) are widely used as materials for the manufacture of high resolution, low noise x- and gamma-radiation detectors. For the detection of photons with energies >30 keV, Ge is most often the material of choice, as it absorbs high energy photons more efficiently than Si as shown in Fig. 1. However, for the detection of lower energy photons, or for the measurement of x-rays covering a broad range of energies, the choice between Si(Li) and HPGe is not always clear. It is the intent of this work to provide a reference to facilitate the selection of Si(Li) and HPGe detectors for x-ray spectroscopy applications. The properties of these devices that will be considered and compared include entrance window absorption, escape peaks, spectral backgrounds, detector sensitivity and energy resolution. The two types of devices will be discussed relative to particular x-ray fluorescence applications.

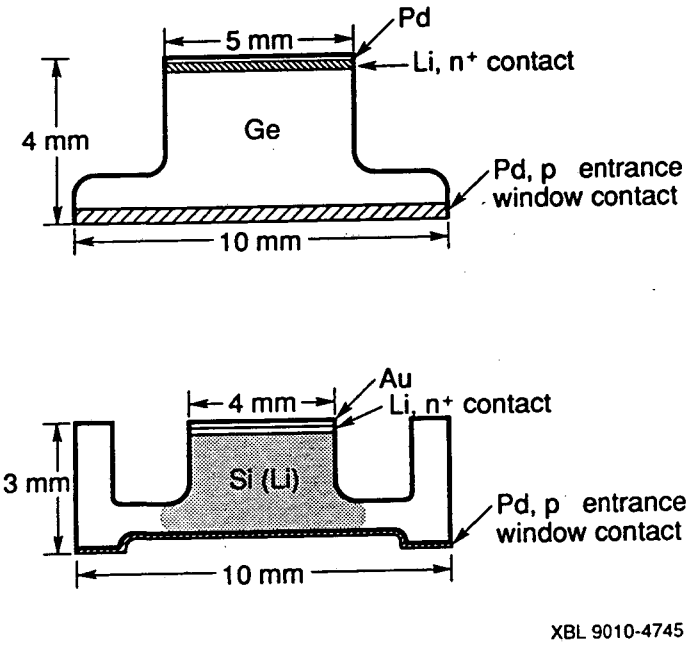


Fig. 2 Cross-sectional schematics of the circular detectors used for this work. The detectors were collimated at the p-type entrance window face with a 1.5 mm diameter Mo collimator.

II. EXPERIMENTAL

The data and spectra presented here were collected using two HPGe and three Si(Li) detectors which were fabricated at Lawrence Berkeley Laboratory. The HPGe detectors were made from two different p-type Ge crystals and the Si(Li) detectors were made from two different p-type Si crystals which were lithium-drifted according to standard procedures. The characteristics of the crystals used are listed in Tables 1 and 2. The detectors were of similar size and geometry, and had similar contact structures, as shown in Fig. 2. The n^+ contacts consisted of diffused Li covered with a thin layer of Pd or Au,

and the p-type surface barrier entrance window contacts consisted of ~200 Å of Pd; no surface passivation coatings were used. These detectors are similar to high quality Si(Li) and HPGe surface barrier detectors available commercially. The detectors were collimated on the entrance window face with a 1.5 mm diameter Mo collimator to eliminate anomalous effects associated with the detector periphery. The detector properties were measured at ~80 K in two essentially identical cryostats with similar electronics. The detectors were biased well above the depletion voltage to ensure adequate charge collection.

Table 1
Si material used to fabricate detectors

Detector #	Orientation	Resistivity (300K) Ω-cm	Lifetime (μsec)
Si(Li) #1	(111)	1100-1500	400-500
Si(Li) #2	(111)	1100-1500	400-500
Si(Li) #3	(111)	2300-2600	1500-1600

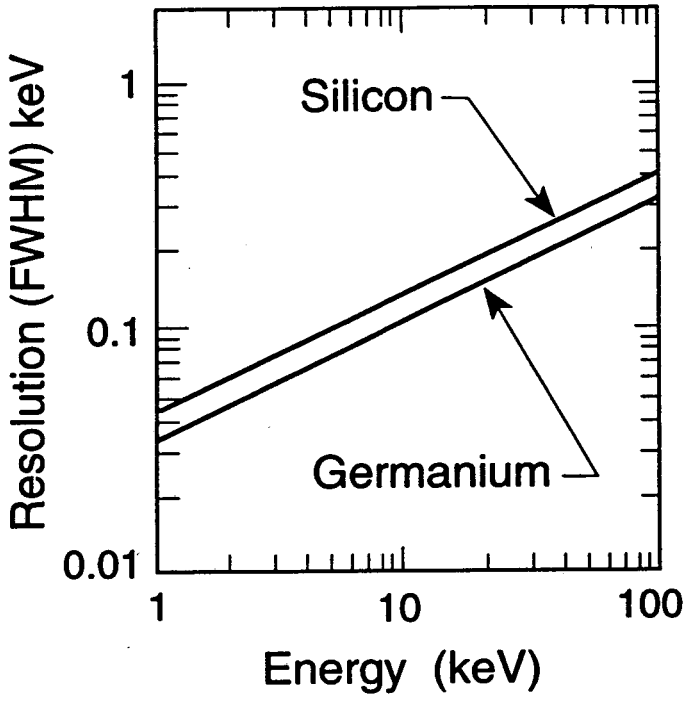
Table 2
Ge material used to fabricate detectors

Detector #	Orientation	Net impurity concentration $\lvert N_a\text{-}N_d\rvert$, cm^{-3}
Ge #1	(113)	3×10^{10}
Ge #2	(100)	3×10^{10}

Spectra were collected over a wide range of x-ray energies using a variety of sources: x-rays in the 1 – 2 keV range were produced with a Cu-anode x-ray tube in conjunction with a crystal monochromator [1]; 4 – 18 keV x-rays were produced using a Rh-anode x-ray tube to excite secondary characteristic x-rays from pure metal foils and from a multi-element thin film standard; an ^{241}Am source was used to obtain multi-energy spectra in the 8 – 60 keV range.

III. Energy Resolution

It is well known that Ge detectors exhibit superior energy resolution compared with Si detectors under equivalent conditions. The two factors which contribute to the superior energy resolution afforded by Ge detectors are the mean energy required for creating an electron-hole pair and the Fano factor, which is a correction term describing the departure of the charge production statistics from a Poisson distribution. The mean energy required to produce an electron-hole pair is 2.97 eV in Ge and 3.76 eV in Si, at 77 K [2]. Figure 3 shows detector energy resolution as a function of energy for Si and Ge, assuming typical Fano factors of 0.1 and 0.08, respectively [3]. The energy resolution of a Ge detector will be ~27% better than a Si detector, assuming the detector capacitance and the electronic contribution to the energy resolution are equivalent.



XBL918-7033

Fig. 3 Energy resolution as a function of energy for Si and Ge detectors, assuming Fano factors of 0.1 and 0.08, respectively. No account is taken of the amplifier noise contribution to resolution, which will dominate at low energies.

IV. Escape Peak Intensity

The intensities of the detector escape peaks were measured using the spectra acquired as a result of the excitation of characteristic x-rays from the metal foils. Examples of the metal foil spectra acquired with the Si(Li) and HPGe detectors are shown in Figs. 4 and 5, respectively. In Fig. 4, the Si escape peak is clearly visible at 1.74 keV below the Se K-α photopeak. The escape peak is a summation of the Si K-α and Si K-β escape peaks which cannot be resolved in energy. Similarly, the escape peak from the Se K-β cannot be resolved from the tailing background of the Se K-α photopeak. Escape peaks will be observable in spectra when the incident x-ray energy is greater than the absorption edge of the detector material; the relative intensity of the escape peak will decrease as the incident x-ray energy increases. In the case of a Si detector, escape peaks are observable when the incident photon energy is above the 1.84 keV absorption edge of Si. In Fig. 5, the Ge K-α and Ge K-β escape peaks from the Zr K-α and Zr K-β photopeaks are seen to comprise a significant fraction of the spectrum. The Ge K escape peaks will be observable when the incident photon energy is above the Ge K-absorption edge at 11.1 keV.

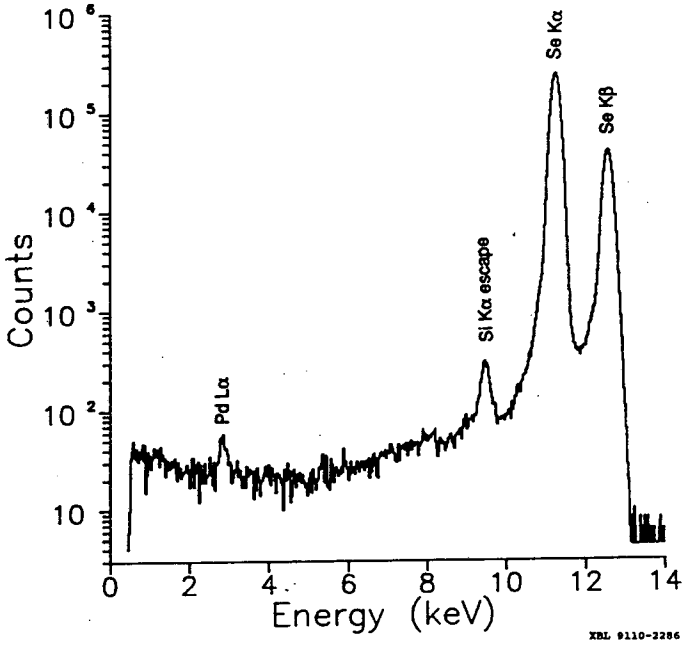


Fig. 4 X-ray spectrum from a Se metal foil using a Si(Li) detector. The Pd L photopeak is from the Pd surface barrier contact on the detector.

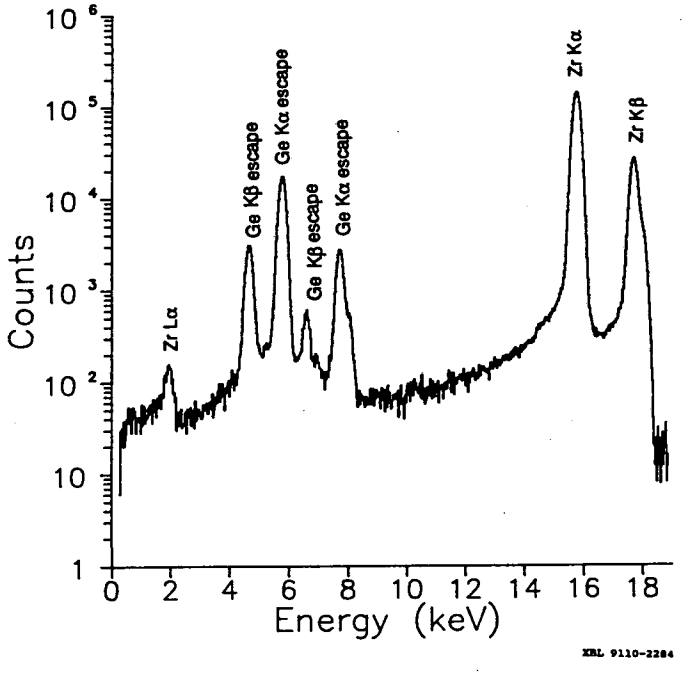


Fig. 5 X-ray spectrum from a Zr metal foil using an HPGe detector.

The experimentally measured ratios of escape peak-to-photopeak intensities are plotted with the theoretical ratios in Fig. 6, for the two types of detectors over the energy range 4.5 – 22 keV. The experimental intensities were calculated by integrating the areas under the K-α escape peak and the K-α photopeak and then subtracting the background. The measured curves closely fit the theoretical curves and are also comparable to previously published data [4,5]. The relative escape peak intensity is much larger in Ge detectors, compared with Si detectors, due to the higher x-ray fluorescence yield and larger linear absorption coefficients for Ge [6]. This represents a fundamental limitation to the use of Ge detectors in the analysis of complex x-ray spectra in the energy region above 11.1 keV.

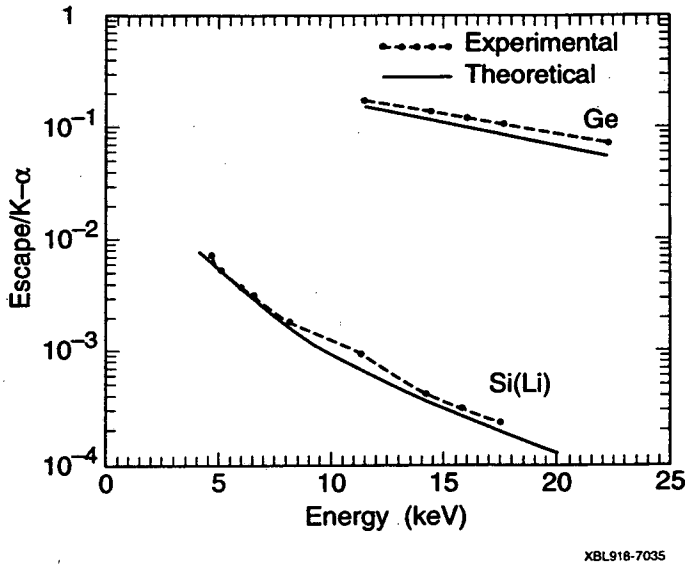


Fig. 6 Relative escape peak/K-α photopeak intensities for the Si(Li) and HPGe detectors used here. The theoretical curves are from references 4 and 5, for Si and Ge, respectively.

V. Detector Window Absorption

Figure 7 shows examples of the photopeak distortions which occur at energies just above the K-absorption edge of Si, and above the L-absorption edge of Ge. The shoulder on the low energy side of the photopeak has been the subject of numerous studies and is due to an incomplete charge collection (ICC) process occurring in a transition layer at the entrance window face of the detector. These data can be used to estimate the thicknesses of the ICC layers using a method described previously [7]. The results show that the ICC layers are of the order of 0.1 μm for the Si(Li) detectors and 0.2 μm for the HPGe detectors. These values are typical and have been reported in the literature previously [7-9]. It is emphasized that the ICC layer thicknesses were measured in detectors with surface barrier contacts, and may not necessarily be representative of detectors with other types of contacts (e.g. implanted contacts).

Two factors contribute to the more prominent peak distortion seen at low energies in HPGe detectors, compared to Si(Li) detectors: one factor is the larger linear absorption coefficients in Ge which result in a larger percentage of the photons being absorbed (and thus lost) in the surface ICC layer, and the second is what appears to be an inherently "thicker" ICC layer. The physical nature of the ICC layer is not well understood, but it is generally agreed that there are

several mechanisms that can contribute to charge loss at the entrance window contact surface. Surface and near surface defects in the contact region are sources of charge traps which can contribute to signal charge loss. Differences in contact and detector processing techniques will affect the nature and number of surface traps and thus will affect the ICC layer thickness. For example, Si(Li) detectors with Pd surface barrier contacts have thinner ICC layers compared to those with Au contacts [7]; very thin ICC layers have been reported in Ge detectors with low energy implanted contacts [10]; and variations in the annealing treatment of B-implanted contacts in Si have been shown to affect the thickness of the ICC layer [11]. The amount of charge lost via surface trapping and recombination is also determined by the number of minority charge carriers which can reach the surface through diffusion against the electric field; this is a direct function of the carrier mobility [12]. In addition, backscatter of photoelectrons from the bulk to the contact region [13], and the escape of photoelectrons and Auger electrons from the surface [14,15] are thought to contribute to charge loss and will affect the apparent thickness of the ICC layer.

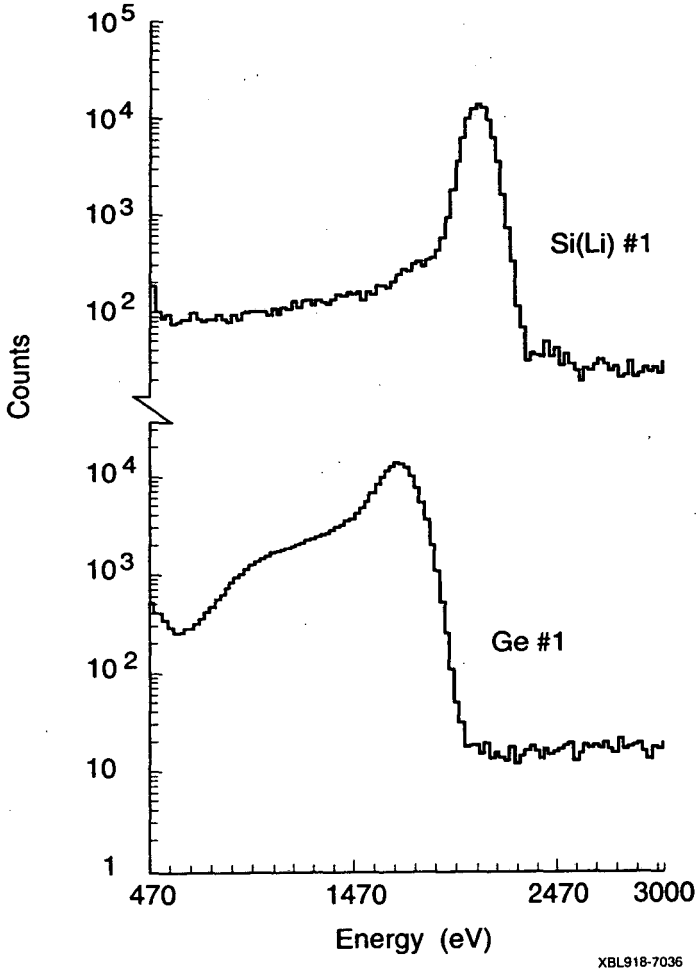


Fig. 7 (a) Spectrum from a Si(Li) detector taken just above the Si K-absorption edge; (b) Spectrum from an HPGe detector taken just above Ge L-absorption edge. (The electronic noise contributions to each of these spectra are not equivalent).

Although the details of the properties of surface traps for electrons on Si(Li)/Pd and HPGe/Pd surfaces are not known, it is possible that the explanation for the difference in ICC layer thickness in these detectors may lie in the difference in carrier mobility in Si and Ge. The mobility of electrons is approximately 1.7 times higher in Ge than in Si, at 77 K [2], which implies that a larger number of minority carriers can reach the p-type entrance window contact through diffusion against the drift field and recombine or be trapped there. The higher carrier mobility may account for the thicker ICC layers measured in the HPGe detectors compared with the Si(Li) detectors studied here.

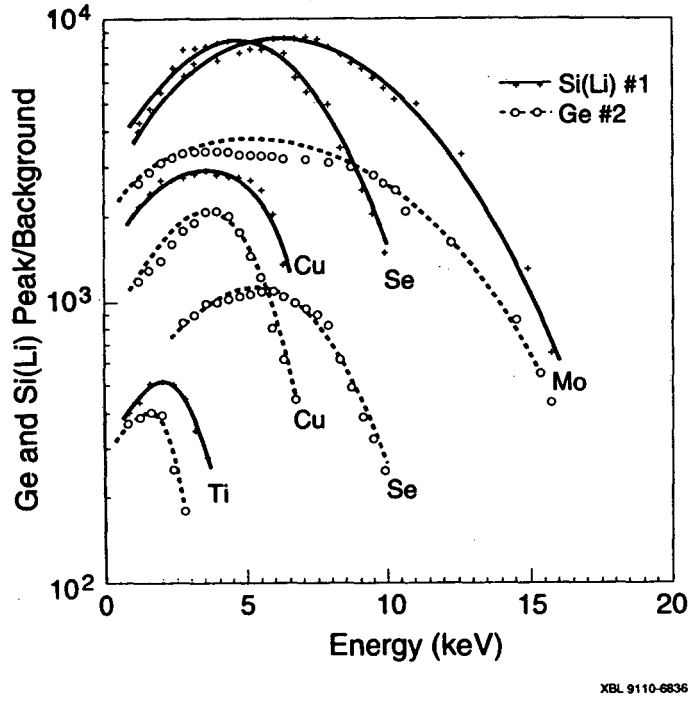


Fig. 8 Photopeak/background ratios from the metal foil spectra, for one representative Si(Li) detector and for one representative HPGe detector. The other detectors from each set exhibited essentially identical backgrounds, but were omitted to maintain graph clarity.

VI. Spectral Background

Continuum spectral backgrounds from the two types of detectors were measured and compared using the spectra produced by the pure metal foils (examples are shown in Figs. 4 and 5). Photopeak/background ratios were measured by taking the ratio of the integrated K-α photopeak to the integrated spectral background in ~400 eV segments, and then subtracting the escape peaks and the background produced by the Rh x-ray tube. Figure 8 shows the photopeak/background ratios for a representative Si(Li) detector and for a representative HPGe detector. (The other two Si(Li) detectors exhibited essentially identical backgrounds as the one shown, and likewise for the other HPGe detector, but were omitted to maintain graph clarity). It is clear from Fig. 8 that the Si(Li) detectors show higher peak/background ratios compared with

the HPGe detectors at equivalent photopeak energies. As an example, Fig. 9 shows the Cu foil spectra for a Si(Li) and an HPGe detector, normalized to the Cu K-α photopeak intensity. The higher background observed in the HPGe might be expected, due to the larger mass absorption coefficients in Ge for equivalent photon energies. However, even when comparing the detectors more fairly at equivalent linear absorption coefficients, the HPGe detectors still exhibit higher backgrounds. The percent background as a function of linear absorption coefficient is shown in Fig. 10 for each of the five detectors.

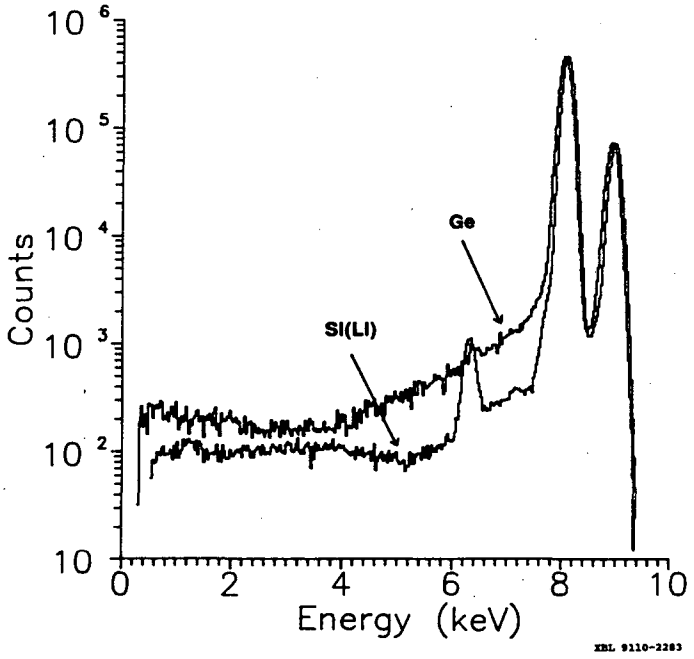


Fig. 9 Cu foil spectra from a Si(Li) and an HPGe detector, normalized to the Cu K-α photopeak. (The electronic noise contributions to each of these spectra are not equivalent).

It is tempting to attribute the larger spectral background observed in the HPGe detectors merely to the thicker ICC layer, which may indeed be the case, however there must be an additional charge loss mechanism present in both types of detectors, for the following reason: if the entire spectral background were assumed to be generated from the ICC layer, the proportion of background would decrease as the photons went deeper into the detector and were less influenced by surface charge loss. However, if one calculates an "equivalent" ICC layer thickness based on the total background according to:

$$d = -((\ln (1 - B/(B+P))/\mu\rho) \times 10^4 \quad (1)$$

where d is the ICC layer thickness in μm, B/(B+P) is the number of counts in the background relative to the total number in the photopeak plus background, and μρ is the linear absorption coefficient in cm^{-1}, then the ICC layer would appear to increase in thickness with decreasing photon absorption coefficient, as is shown in Fig. 11. This observation has been reported previously in Si(Li) detectors and has been attributed to charge loss due to trapping at bulk defect sites in addition to surface charge loss [16]. Computer models based only on surface charge loss mechanisms and photoelectron range considerations have underestimated the extent of the background [14,15,17] which lends additional support to the supposition that charge loss at bulk defect sites also contributes to the spectral background.

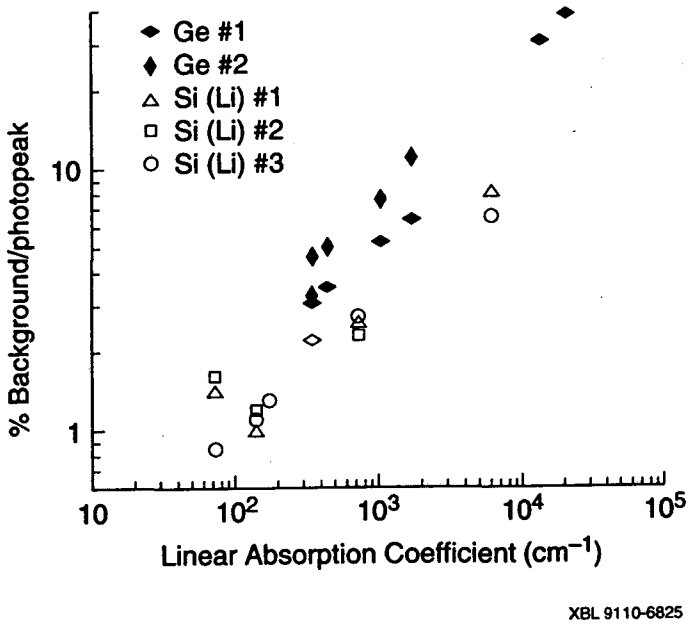


Fig. 10 Percent background, relative to the background plus photopeak as a function of linear absorption coefficient for the five detectors (escape peaks and x-ray tube background have been subtracted).

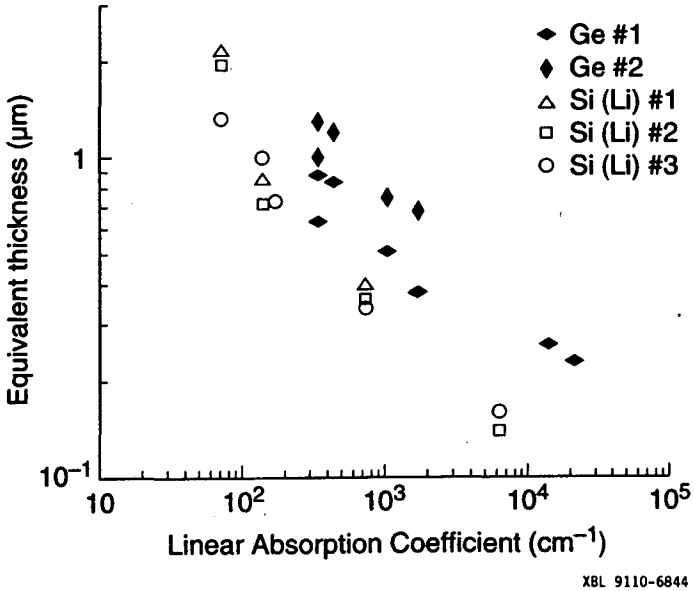


Fig. 11 Equivalent ICC layer thicknesses calculated from equation (1) in the text, as a function of linear absorption coefficient for the five detectors.

As previously stated, the above discussion on spectral backgrounds was based on data collected from the fluorescence of pure metal foils, in which there were only two main photopeaks. Spectral backgrounds are also compared in the multi-energy spectra of Figs. 12 and 13. Figure 12 is an ^{241}Am spectrum using a Si(Li) detector, normalized to Fig. 13 by the 14.0 keV peak of an equivalent spectrum using an HPGe detector. As is apparent from these figures, the relative spectral backgrounds of the two detectors in the 1 – 25 keV range is similar to that seen with the pure metal foils. The ^{241}Am spectrum of Fig. 13 also demonstrates the prominence of the Ge escape peaks.

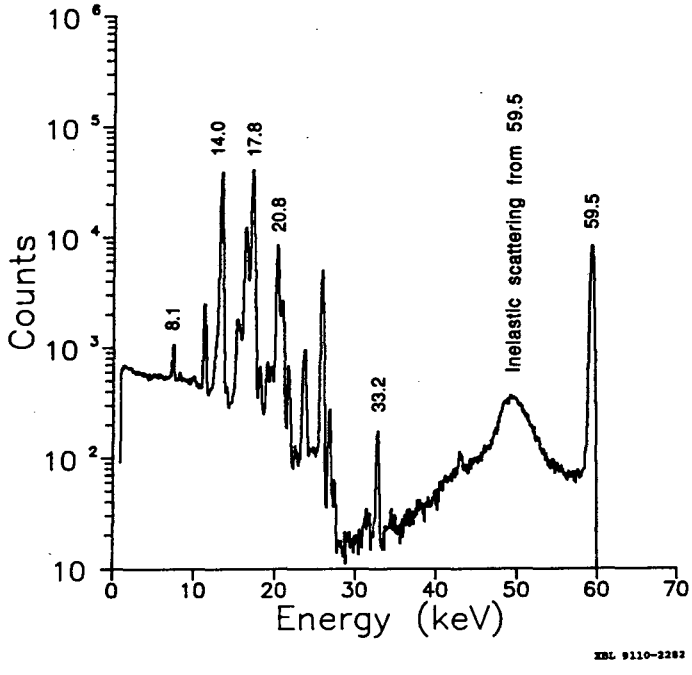


Fig. 12 ^{241}Am spectrum using a Si(Li) detector, normalized to the ^{241}Am spectrum in Fig. 13 by the 14.0 keV peak.

VII. Detector Sensitivity

The sensitivity of the detectors, as defined in terms of the relative photopeak efficiency, was compared between 4.5 – 17.4 keV by the excitation and detection of characteristic x-rays from a multielement thin film standard containing known concentrations of Ti, Fe, Zn, Rb and Mo. The concentrations of these elements were in the range 1 – 15 μg/cm^2. Figure 14 shows detector sensitivity as a function of photon energy, for the characteristic x-rays from elements in the thin-film standard. The detector sensitivity was calculated in terms of the integrated counts in the K-α photopeak of each element, per unit counting time, per microgram of each element. The two detector types are essentially equally sensitive in the 4.5 – 17.4 keV range. This would be expected, since the detector efficiency is essentially 100% in this energy range for the thicknesses of Si and Ge used here. The detector sensitivity increases with increasing photon energy as both the Rh x-ray photoelectric cross-section of the foils and the fluorescence yield increase. The difference in spectral background observed between the HPGe and Si(Li) detectors was not large enough to affect the measurement of the detector sensitivity in the energy range and concentration range studied here. However, at lower x-ray energies, in the 1.2 – 2 keV range, a decrease in sensitivity would be expected in HPGe devices due to the large photopeak distortions occurring just above the Ge L-edge.

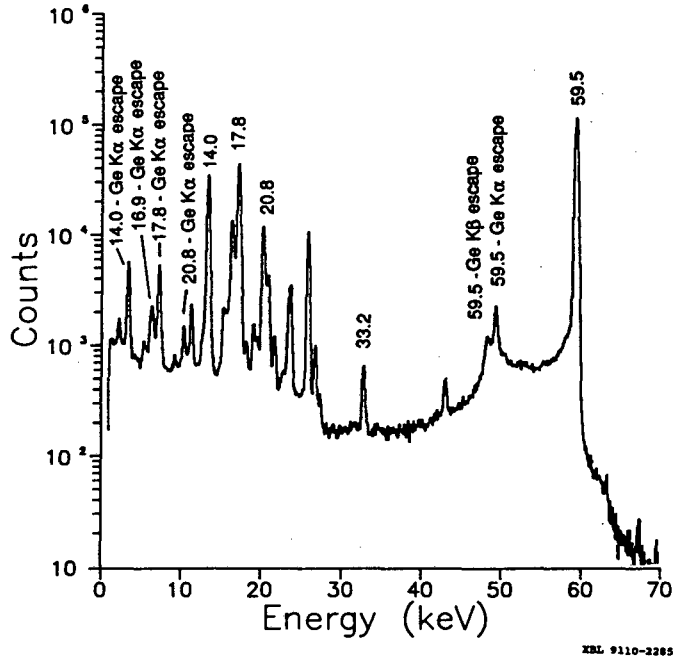


Fig. 13 ^{241}Am spectrum using an HPGe detector, normalized to the ^{241}Am spectrum in Fig. 12 by the 14.0 keV peak.

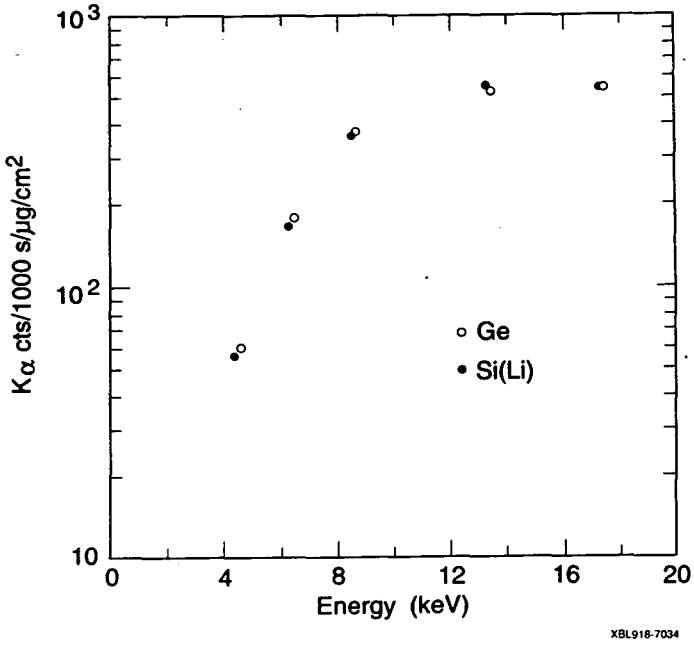


Fig. 14 HPGe and Si(Li) detector sensitivity in terms of K-α photopeak counts, per 1000 seconds of counting time, per microgram-cm^{-2}, as a function of photon energy.

VIII. DISCUSSION AND CONCLUSIONS

When choosing a detector for low-noise, high resolution x-ray spectroscopy applications, several factors must be taken into consideration. To facilitate the selection of such detectors, we have compared small, high resolution Si(Li) and HPGe detectors of equivalent size and geometry in the 2 – 17 keV x-ray range with regard to energy resolution, escape peaks, detector window absorption, detector sensitivity and spectral background. As is well known, Ge offers approximately 27% better energy resolution compared with Si, for detectors of equivalent capacitance, and may be the detector of choice if maximum energy resolution is a requirement. In addition to its inherent superior energy resolution, it is possible to fabricate thicker detectors from HPGe compared with Si(Li), which translates directly into a lower capacitive device with lower noise and higher energy resolution. However, there are other characteristics of Ge that may make its superior energy resolution of secondary importance. For spectroscopy applications in the low energy x-ray range, below approximately 3 keV, the photopeak distortion and higher spectral background resulting from the thicker entrance windows of HPGe might make Si(Li) a better choice. The detector entrance window thickness is a direct function of the entrance window contact processing technique and thus it is possible that contacts other than the surface barrier contacts studied here would yield thinner windows.

In the medium energy x-ray range, detector window absorption is not as critical an issue as it is at low energies, but the presence of escape peaks may be of consideration. Ge detectors produce intense escape peaks when the incident photon energy is above the Ge K-absorption edge of 11.1 keV, and these may obscure other photopeaks of interest. The escape peaks in Si are observed at lower energies (>1.84 keV) than in Ge, but are much less intense and would obscure only weak photopeaks. For the detection of x-rays higher than approximately 20 keV, Ge would likely be the material of choice, as it is a much more efficient absorber of high energy photons; the efficiency of 5 mm thick Si(Li) starts to decrease above ~20 keV.

IX. ACKNOWLEDGMENT

This work was supported by the Director's Office of Energy Research, Office of Health and Environmental Research, U. S. Department of Energy under Contract No. DE-AC03-76F00098.

X. REFERENCES

[1] J.M. Jaklevic, J.T. Walton, R.E. McMurray, Jr., N.W. Madden and F.S. Goulding, "Semiconductor performance for low-energy x-rays," *Nucl. Instr. Meth.*, vol. A266, pp. 598-601, April 1988.

[2] G. Bertolini and A. Coche (eds.), *Semiconductor Detectors*, Amsterdam: Elsevier-North Holland, 1968.

[3] F. Goulding and Y. Stone, "Semiconductor radiation detectors," *Science*, vol. 170, pp. 280-289, Oct. 1970.

[4] G. I. Johansson, "Modifications of the HEX program for fast automatic resolution of PIXE-spectra," *X-Ray Spectrom.*, vol. 11, pp. 194-200, Oct. 1982.

[5] J.M. Palms, P. Venugopala Rao and R.E. Wood, "An ultra-high resolution Ge(Li) spectrometer for singles and coincidence x-ray and gamma-ray studies," *Nucl. Instr. Meth.*, vol. 64, pp. 310-316, Oct. 1968.

[6] B. Crasemann (ed.), Atomic Inner Shell Processes: II. Experimental Approaches and Applications, New York: Academic Press, 1975, pp. 3-7.

[7] C.S. Rossington, J.T. Walton and J.M. Jaklevic, "Si(Li) detectors with thin dead layers for low energy x-ray detection," *IEEE Trans. Nucl. Sci.*, vol. 38, pp. 239-243, April 1991.

[8] K. Shima, S. Nagai and T. Mikumo, "Measurement of the low energy tail spectra adjacent to the x-ray photopeak in Si(Li) x-ray detectors," *Nucl. Instr. Meth.*, vol. 217, pp. 515-519, Dec. 1983.

[9] C.E. Cox, B.G. Lowe and R.A. Sareen, "Small area high purity germanium detectors for use in the energy range 100 eV to 100 keV," *IEEE Trans. Nucl. Sci.*, vol. 35, pp. 28-32, Feb. 1988.

[10] M. Slapa, J. Chawaszczewska, J. Jurkowski, A. Latuszynski, G. C. Huth and A. Dabrowski, "Preliminary study of the behavior of HPGe detectors with ion-implanted contacts in the ultralow-energy x-ray region," *Adv. X-Ray Anal.*, vol. 25, J.C. Russ, C.S. Barrett, P.K. Predecki and D.E. Leyden (eds.), New York: Plenum Press, 1982, pp. 23-30.

[11] C. Tassin, Y. Thenoz and J. Chabbal, "Thinned backside illuminated CCD's for ultraviolet imaging," *Proceedings of the SPIE Technical Symposium Southeast on Optics*, Orlando, FL, April 1988.

[12] F.S. Goulding, "Some aspects of detectors and electronics for x-ray fluorescence analysis," *Nucl. Instr. Meth.*, vol. 142, pp. 213-223, April 1977.

[13] J.L. Campbell and J.-X. Wang, "Improved model for the intensity of low-energy tailing in Si(Li) x-ray spectra," *X-Ray Spectrom.*, to be published in vol. 20, 1991.

[14] H.J. He, T.W. Zhang, R.C. Shang and S.D. Xu, "A detailed study of the interaction mechanisms for Si(Li) detector response function by the direct Monte Carlo approach," *Nucl. Instr. Meth.*, vol. A272, pp. 847-854, Nov. 1988.

[15] R.P. Gardner, A.M. Yacout, J. Zhang and K. Verghese, "An investigation of the possible interaction mechanisms for Si(Li) and Ge detector response function by Monte Carlo simulation," *Nucl. Instr. Meth.*, vol. A242, pp. 399-495, Jan. 1986.

[16] M. Geretschlager, "Monte Carlo simulation of the response of Si(Li) x-ray detectors to proton induced K x-rays of light elements ($12 < Z < 32$)," *Nucl. Instr. Meth.*, vol. B28, pp. 289-298, Sept. 1987.

[17] J.-X. Wang and J.L. Campbell, "Monte Carlo simulation of the response of Si(Li) detectors to monoenergetic x-rays," *Nucl. Instr. Meth.*, B54, 499-506, March 1991.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720