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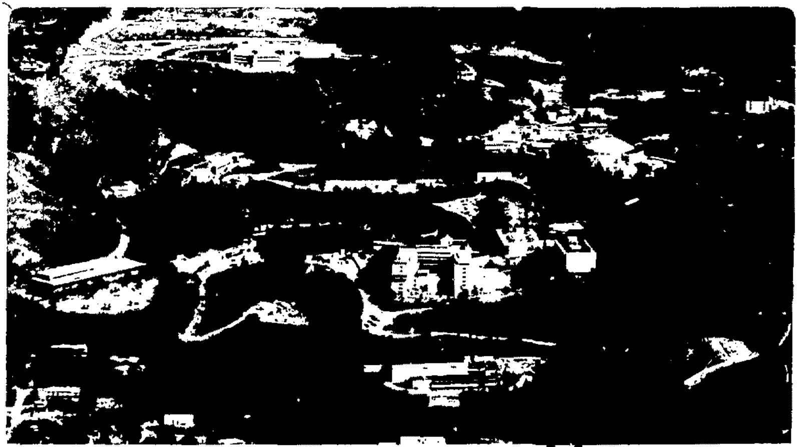

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SEMICONDUCTOR DETECTOR PERFORMANCE FOR LOW-ENERGY X-RAYS

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Abstract

Factors that limit the capabilities of semiconductor detectors at photon energies below 5 keV include energy resolution, detector efficiency, and detector-related continuum background. These properties can be controlled to a certain extent by optimal detector design and fabrication techniques. We describe measurements on the low energy response of Si(Li) detectors obtained using a tunable, low-energy monochromatic source. Window thicknesses have been measured for a number of devices using different materials for the entry contact. The interpretation of these results in terms of existing detector window models is discussed. Results obtained using a new contact structure demonstrate that a dramatic reduction in window-related absorption in Si(Li) detectors can be achieved.

Introduction

Semiconductor radiation detectors are widely used for the measurement of x-ray spectra acquired in synchrotron radiation experiments. Their energy resolution is superior to most other types of detectors and they operate efficiently over an energy range which overlaps the output spectra from typical synchrotron sources. The upper limit of this energy range is determined primarily by the maximium thickness which can be depleted using a reverse bias voltage across the diode structure. This thickness is typically 3 - 5 mm for Si(Li) detectors and 5 - 10 mm for high-purity Ge diodes, corresponding to practical upper limits of 20 and 100 keV respectively.

In the low energy region, the minimum practical energy is established by the absorption of the incident x-rays in the materials which are interposed between the source and the active volume of the detector. In the limiting case where the detector and source are in a common vacuum enclosure with a clear path between, the minimum window thickness is established by the thickness of the metalized film or implanted layer required to maintain an electrical contact to the semiconductor and by the properties of the semiconductor material at the boundary between the depleted detector volume and the contact. The details of this window structure can be varied according to choice of methods employed in the fabrication of the contact structure. The present study is an effort to coordinate the detailed characterization of x-ray detectors with the fabrication process in order to understand those factors which determine the intrinsic window thickness and to optimize the detector performance for low energy photon detection.

1. Background

Figure 1 is a schematic diagram of a typical semiconductor detector diode. The device is fabricated from semiconductor material characterized by a low density of free charge carriers in the bulk of the material. This is achieved by lithium ion compensation in the case of Si(Li) detectors and by the use of high purity starting material in the case of high-purity germanium devices. The depleted detection volume is formed by constructing p^+ and n^+ contacts on the respective faces of the device and reverse biasing the diode structure. The ionizing radiation is incident on the sensitive volume through one of the contacts.

In the figure shown, the p^+ contact is enlarged to indicate the simplified model which is used to describe the entry window to the detector. It consists of a thin Schottky barrier contact together with an idealized layer of semiconductor material which constitutes the "dead region" of the device. The contact is typically formed by evaporation of a thin metal film although ion-implanted contacts with or without metalization can also be employed.

X-ray absorption in the metalized layer can be minimized by choosing an appropriate metal and limiting the evaporated thickness to a value just sufficient to provide a low resistivity contact, typically 0.01 microns. Curves a) and b) of Figure 2 show the calculated x-ray transmissions for such layers for the cases of Al and Au. X-ray absorption associated with ion-implanted contacts structures can be estimated from the calculated range for low-energy implanted ions and the associated silicon absorption coefficients assuming that incomplete charge collection occurs from the implanted layer. These estimates indicate that absorption in the contact layer can be even lower than that for metalized contacts at least in this simplified model.

A second limitation to low energy detector efficiency which is of more fundamental importance is that due to the intrinsic "dead layer" associated with the semiconductor material itself. Various investigators have proposed that there exists a region of Si or Ge at the boundary between the depleted region and the rectifying contact from which radiation-induced electron-hole pairs are inefficiently collected during the signal integration interval and do not contribute to the photopeak signals. Measurements based on alpha particle energy loss and x-ray attenuation have indicated that the thickness of this layer is typically about 0.2 microns. Curves c) and d) of Figure 2 show calculated transmission coefficients for idealized layers of this thickness in Si and Ge. It is clear that the effect of this layer on x-ray transmission is a significant limitation in the low energy performance of semiconductor detectors.

A number of explanations for the existence of this dead layer have been proposed. The simplest descriptions involve the presence of a thin layer of damaged material at the surface caused by the processing steps involved in forming the contact. More sophisticated models are based on detailed consideration of the charge transport properties of the electrons and holes across an interface.[2,3,4] These models predict the existence of a region near the surface of the depleted volume from which incomplete charge collection will occur independent of the structure of the adjacent rectifying contact. Quantitative estimates acquired with the models are consistent with previously observed "dead layer" thicknesses of 0.2 microns.

We have studied the low energy detection efficiency of a number of Si(Li) detectors fabricated using a series of different metallic contacts and ion-implanted structures. The purpose of the study is to determine the extent of the validity of existing window models and to ascertain whether improvements in low-energy detection capabilities can be achieved.

Experimental Procedures

Since we are most interested in studying the properties of the window absorption due to the semiconductor material itself, we have used the detector response above and below the silicon K absorption edge as an indicator of window thickness. A laboratory x-ray source consisting of an 800 watt thin-window Cu anode tube in conjunction with a (200) penta-erythritol (PET) crystal was used for obtaining tunable x-rays in the 1.8 keV region. The x-ray tube is a modified version of a standard tube with provisions for a 0.002 " Be window and continuous pumping. The system is unique in that the PET crystal and x-ray tube are mounted on the theta-2 theta motions of the goniometer which allows a fixed geometry for the detector system and cryostat as the energy is tuned. A plastic enclosure maintains a He path from the x-ray source to the exit window of the 0.3° Soller slits. The range of energies accessible with the PET monochromator is approximately 1.6 to 2.5 keV with a nominal energy resolution of 10 eV. Due to contamination of the Cu anode with material evaporated from the filament, the energy ranges surrounding the tungsten M x-rays at 1.77 and 1.84 keV were excluded from the scans. Figure 3 is a diagram of the monochromator system.

The Si(Li) detectors studied were fabricated at LBL using the standard lithium drifting process on p-type single crystal silicon.[5] The wafers were nominally 2 cm diameter and 3 - 5 mm thick with the (111) crystal direction normal to the planar contacts. To ensure that residual effects of the lithium ion compensation process did not influence the measured window properties, the Au contact used during the drifting process was removed from the entry side of the detector and replaced by the metal contact to be studied. This was achieved by lapping off the Au contact, masking the sides of the device, and etching to remove approximately 80 microns of silicon from the window surface. The metal contacts were then evaporated onto the entry window surface.

For the boron-implanted contacts, the implantation was performed prior to the lithium drift process. Typical processing parameters were 1 x $10^{14}/cm^2$ at 25 keV followed by annealing for 30 min at 465°C. This sequence was necessary since the required high-temperature boron annealing step would disrupt the lithium compensation if performed following the drift process.

Figure 4 is an example of a typical spectrum acquired in the study. The multiple harmonic peaks reflect the response of the PET monochromator to the continuum spectrum generated on the Cu anode. The attenuation of the first order reflection relative to the second due to the 25 cm He path was estimated to be 4%. Due to uncertainties regarding the stability of the incident intensity as the energy was tuned above and below the edge, it was not possible to determine the change in x-ray transmission directly to a precision adequate to allow comparisons among detector structures.

Consequently, indirect measurements of the window thicknesses were obtained by comparing the peak shape of the detector response above and below the Si K absorption edge. The low energy tailing observed above the edge is interpreted as due to partial charge collection associated with incident x-rays which were photoelectrically absorbed in the window region. Figure 5 is an example of two photopeaks obtained on a Au contact detector for incident energies of 1.701 and 1.894 keV respectively. The asymmetric shape caused by the low energy tailing is apparent in the peak for the energy above the Si K edge at 1.838 keV. By fitting the high energy sides of each peak to a Gaussian shape, the fraction of events contained in the tail was determined and related to an effective window thickness using the literature values for the photoelectric cross section jump ratio at the Si edge.[1] In the case of the Al contact, an additional correction was required to remove the contribution at 1.49 keV due to the Al k-alpha fluorescence radiation produced by photoelectric absorption in the contact.

Results and Conclusions

The effective windows observed for the representative detectors are summarized in Table 1. The measured windows for Au and Ni surface barriers are consistent with earlier literature values in the 0.1 to 0.2 micron region. The boron implanted window exhibits an effective thickness of 0.4 microns which is the largest of the group. This large value is thought to be anomalous and is probably due to problems in the fabrication and storage of this particular device. A previous study on Ge detectors has indicated that ion-implanted detectors can yield windows which are comparable to or thinner than equivalent metalized structures.[6]

Of particular interest is the value of 0.02 observed for the n^+ Al contact. This detector was unique among the devices studied in that the normal structure employing a p^+ contact for the entry window was reversed. The detector face from which the lithium was drifted and which is normally the n^+ contact was lapped off and coated with Au to form the p^+ contact. The Al contact was then formed on the entry side and the detector bias reversed. This configuration resulted in the thinnest window which we have observed to date.

In addition to providing encouragement in terms of the future thin window technology, this result also indicates that theoretical models involving charge transport calculations will need to be extended to include the dependence of the effective window on the barrier height of the contact. The fact that Al is also the lightest metal studied is particularly fortuitous since Figure 1 shows it exhibits the least absorption for low energy x-rays. Since a secondary consideration in the use of semiconductor detectors in synchrotron applications is the detection of low energy x-rays in the presence of large fluxes of UV or optical photons, the use of thicker, optically opaque windows again favors Al metalizations.

The wide variation in window thickness which has been observed in the limited sample set considered in the present study indicates that more extensive, systematic studies are required before a definitive optimization is achieved. Of particular importance will be a more comprehensive understanding of the properties of implanted contacts. One of the immediate goals of a continuing study will be a re-evaluation of the theoretical understanding of the mechanism producing window effects in the semiconductor material. Finally, the window effects which limit the performance of silicon devices have an even greater detrimental effect on the performance of Ge detectors due to the increased photoelectric absorption cross sections. Equivalent studies using the L-absorption edges of Ge are planned.

Acknowledgments

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Contact Structure	Measured Si Dead Layer (μm)
Boron Implanted (p^+)	0.46
Gold (p^+)	0.09
Nickel (p^+)	0.08
Aluminum (n^+)	0.02

Table I. Thickness of dead layer in Si(Li) detector for various contact types.

Figure Captions

1. Schematic diagram of a typical Si(Li) detector geometry indicating the entry window model used for interpreting low energy efficiency measurements.

2. Calculated low x-ray transmission coefficients for several thin layers relevant to semiconductor spectrometer performance.

3. Schematic diagram of the tunable low-energy x-ray source. The PET crystal and thin-window Cu anode tube are mounted on the rotating stages of a theta-2 theta goniometer.

4. Typical spectrum obtained using a Si(Li) detector. Multiple harmonics of the continuum spectrum are visible. The x-ray source was operated at 20 keV and 5 ma. The Fe and Cu lines are due to fluorescence of the anode and surrounding materials.

5. Representative spectra showing difference in photopeak for incident energies below and above the Si k-absorption edge respectively. Peak tailing is attributed to partial charge collection in the silicon material at the detector entry window.

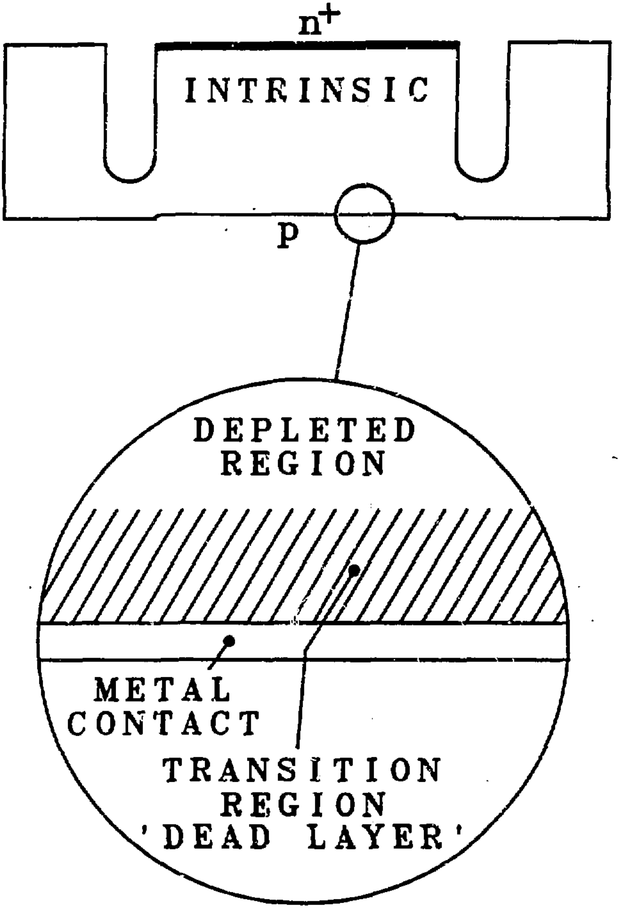

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Fig. 1.

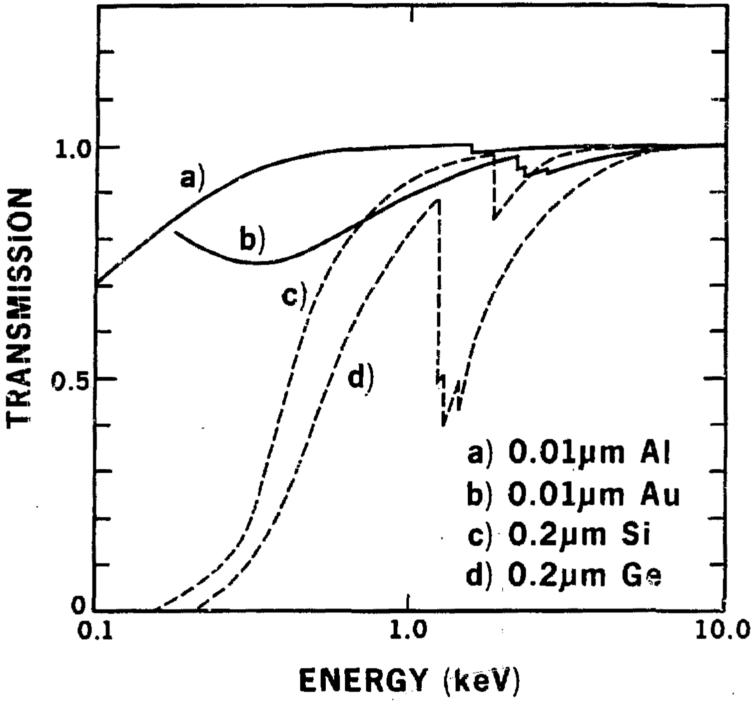

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Fig. 2.

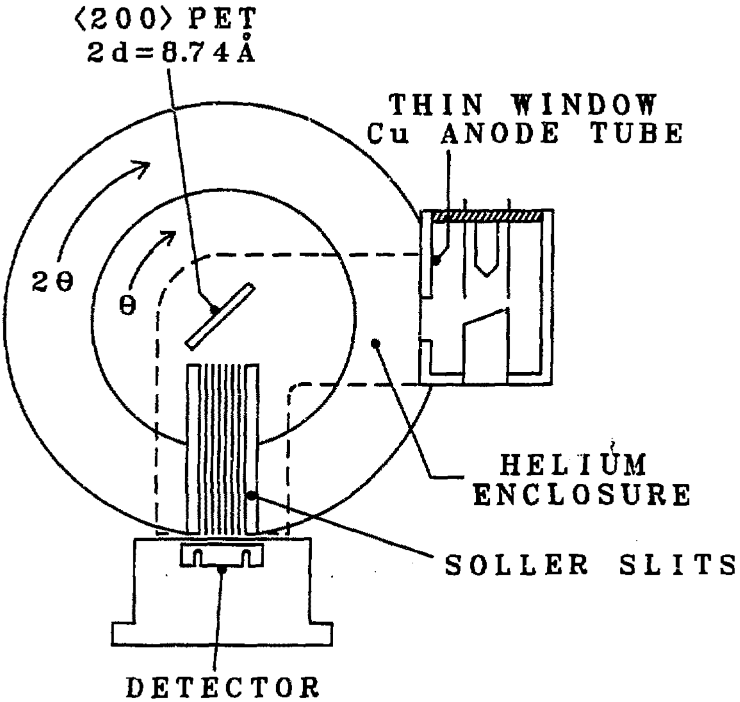

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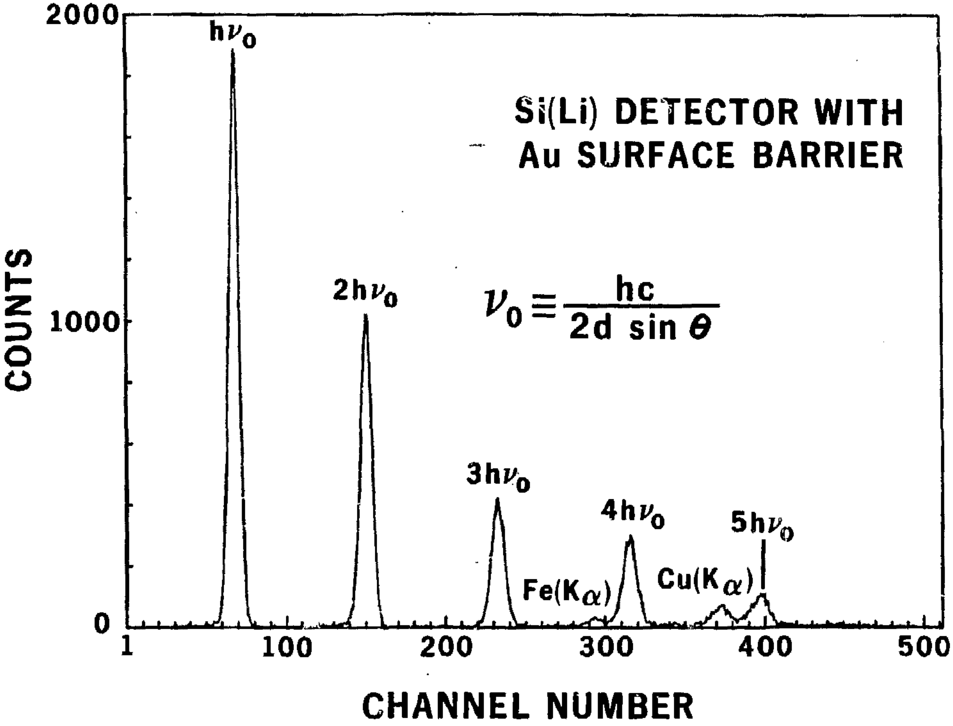
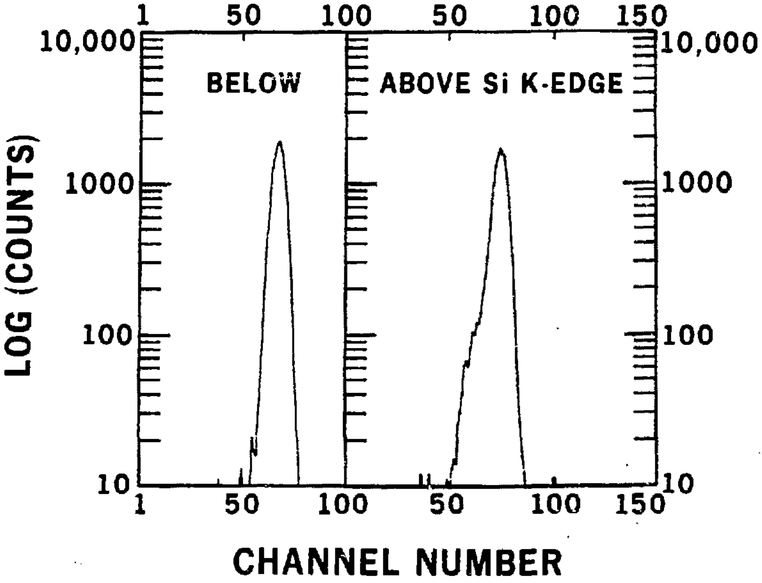
Fig. 3.



XBL 876-2837

Fig. 4.



XBL 876-2839

Fig. 5.