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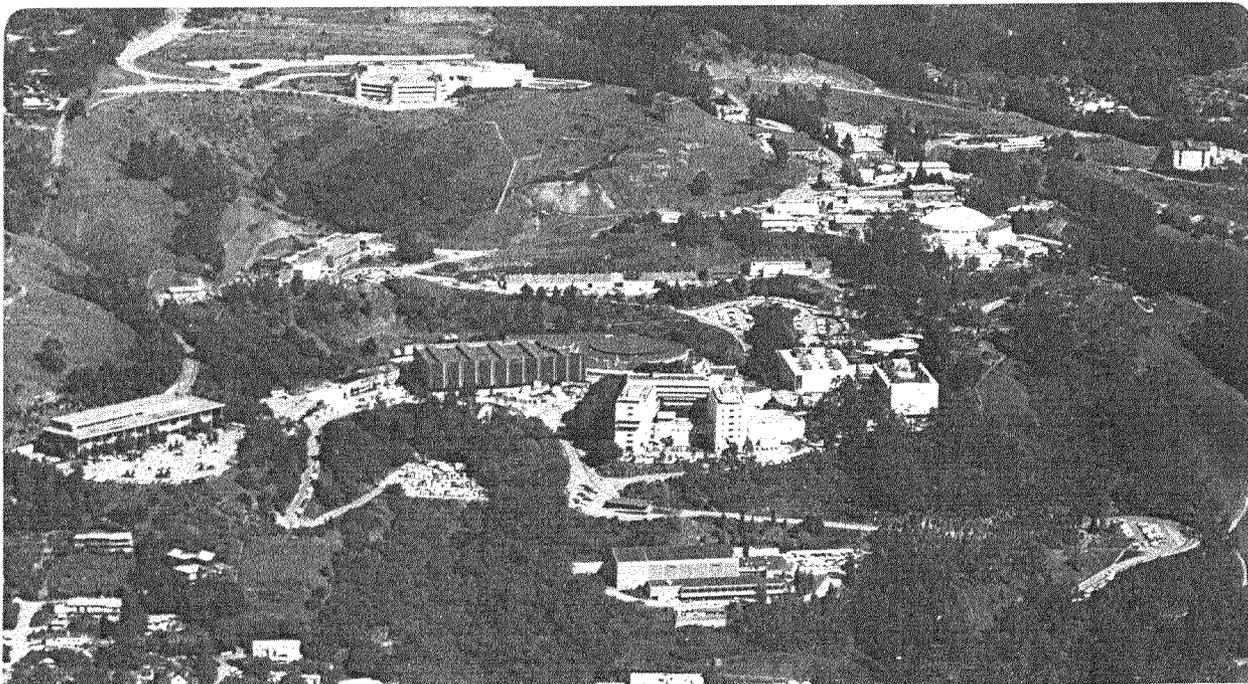
Si(Li) Detectors with Thin Dead Layers for Low Energy X-Ray Detection

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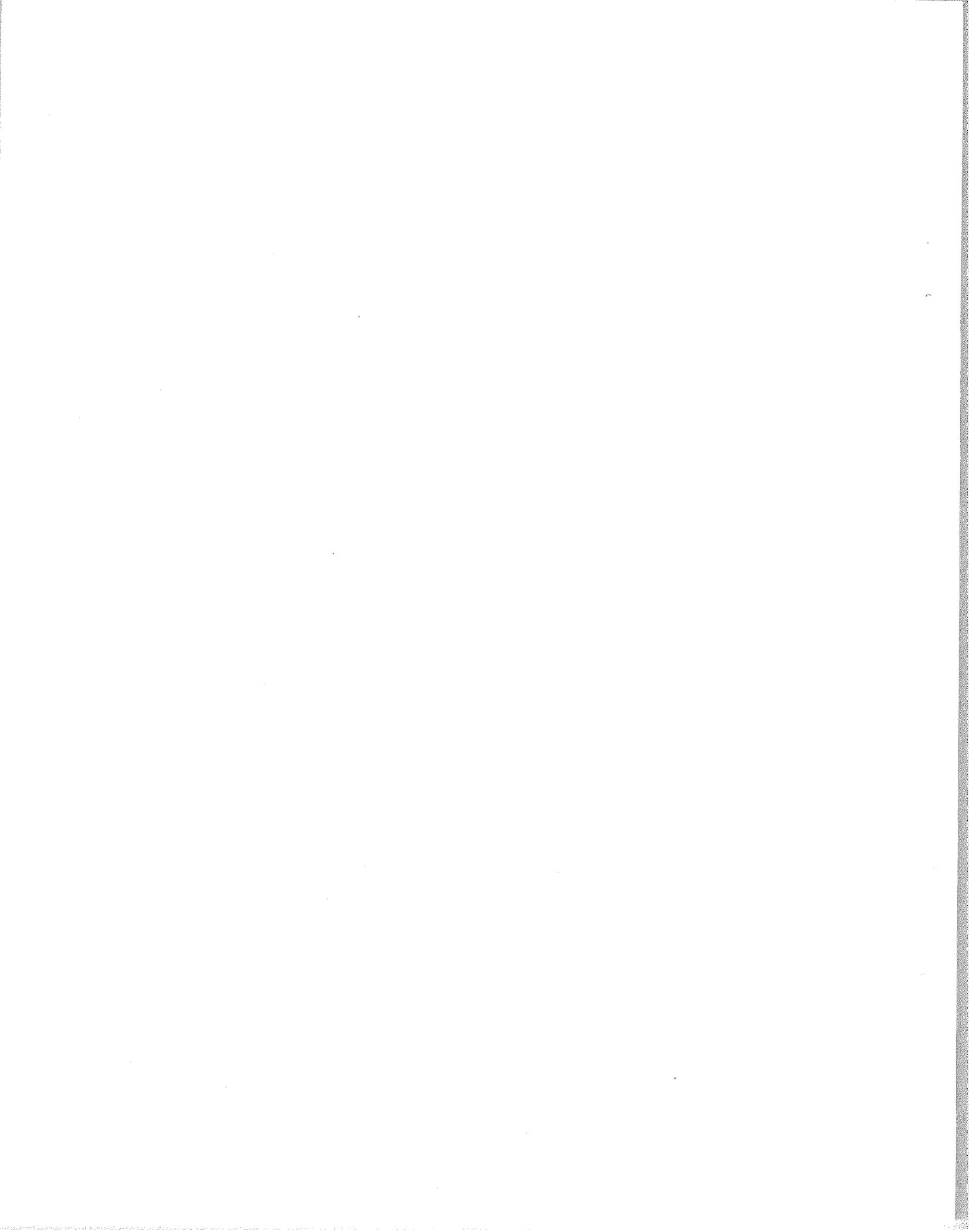
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**Si(Li) DETECTORS WITH THIN DEAD LAYERS
FOR LOW ENERGY X-RAY DETECTION**

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Si(Li) Detectors with Thin Dead Layers for Low Energy X-Ray Detection

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Abstract

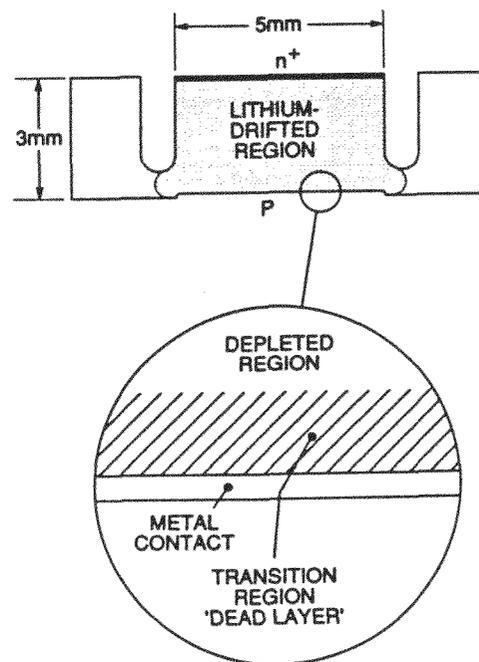
Regions of incomplete charge collection, or "dead layers", are compared for Si(Li) detectors fabricated with Au and Pd entrance window electrodes. The dead layers were measured by characterizing the detector spectral response to x-ray energies above and below the Si $K\alpha$ absorption edge. It was found that Si(Li) detectors with Pd electrodes exhibit consistently thinner effective Si dead layers than those with Au electrodes. Furthermore, it is demonstrated that the minimum thickness required for low resistivity Pd electrodes is thinner than that required for low resistivity Au electrodes, which further reduces the signal attenuation in Pd/Si(Li) detectors. A model, based on Pd compensation of oxygen vacancies in the SiO_2 at the entrance window Si(Li) surface, is proposed to explain the observed differences in detector dead layer thickness. Electrode structures for optimum Si(Li) detector performance at low x-ray energies are discussed.

I. INTRODUCTION

Silicon and germanium radiation detectors are widely used in x-ray and gamma-ray spectroscopy applications in many diverse fields such as medicine, astrophysics, chemistry and materials science. The high energy detection limit for these devices is determined by the detector material and depletion thickness - typically on the order of 0.5 mm for high purity silicon, 5 mm for lithium-drifted silicon (Si(Li)) and 10 mm for high purity germanium. For these thicknesses, the detector efficiencies rapidly decrease above 10, 30, and 150 keV, respectively. The lower detection limit is determined by the thickness and composition of materials that the radiation must pass through prior to reaching the active volume of the detector. This path includes a vacuum-tight Be (or other material) cryostat window, a metal or implanted detector electrode and a transition layer between the contact and depleted detector volume in which incomplete charge collection can take place. (From here on this transition layer will be referred to using the more common phrase "dead layer"). If a Be cryostat window is present, it will set the lower energy detection limit to approximately 1.5 keV, but in situations where the detector and source are in a common vacuum without a cryostat window, the electrode and detector dead layer will be the limiting factors for low energy detection. This configuration is of potential importance in applications where specialized x-ray sources, such as synchrotrons, are employed. For a conventional Au electrode thickness of 500 Å and a corresponding Si dead layer thickness of 0.2 μm , the practical lower energy detection limit is of the order of 800 eV. To increase the detector efficiency below 800 eV, the electrode and

semiconductor dead layer must be minimized to reduce absorption in these layers.

Semiconductor detector dead layers have been measured in the past in high purity silicon [1-3], lithium-drifted silicon [4-7] and high purity germanium [8-10] using a variety of techniques. The most detailed studies of dead layers performed to date were carried out on high purity silicon surface barrier detectors with Au and Al electrodes [2], and with Cr, Ni and Pd electrodes [3]. The thinnest dead layers observed were in those detectors with very thin Pd electrodes, but the authors offered no explanation for their results. In addition, very thin dead layers have been observed in "reverse polarity" Si(Li) detectors with Al electrodes [6]. These studies suggested that there might exist alternatives to the conventional Au electrode that would yield Si(Li) detectors with superior entrance window thicknesses in Si(Li) detectors fabricated with Au and Pd electrodes is reported, and a model to explain the dead layer dependence on electrode composition is proposed. A discussion of optimum Si(Li) detector electrode structures for low energy x-ray detection will be given.



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Fig. 1 Schematic of the Si(Li) detector geometry used for this work, with a detailed schematic of the entrance window contact. The shaded area is the lithium-drifted (intrinsic) region.

II. EXPERIMENTAL

Figure 1 is a schematic of the Si(Li) detector geometry used for this work. High resistivity p-type silicon material was machined and etched to the shape shown and then compensated via the lithium-drifting technique [11]. The n⁺ contact was a ~150 μm thick diffused Li layer, while the metal p⁺ contact was a vacuum-evaporated metal, normally 500 Å of Au. The p⁺ electrode was reprocessed after drift by lapping off 0.1-0.2 mm of material from the p⁺ window face, re-etching the Si surface with a polish etch and then depositing a new layer of either Pd or Au. The data of Fig. 2 show that the Si dead layers were significantly thinner (at low to moderate biases) when the original electrode was reprocessed after drift in this manner. Subsequent p⁺ window reprocessing substituted the lapping step with etching of the metal electrode. All of the dead layer measurements were performed using two detectors, each of which was reprocessed several times with both Pd and Au electrodes, in random order. The results reported here were independent of the specific detector and were also independent of the number of times the detector had been reprocessed.

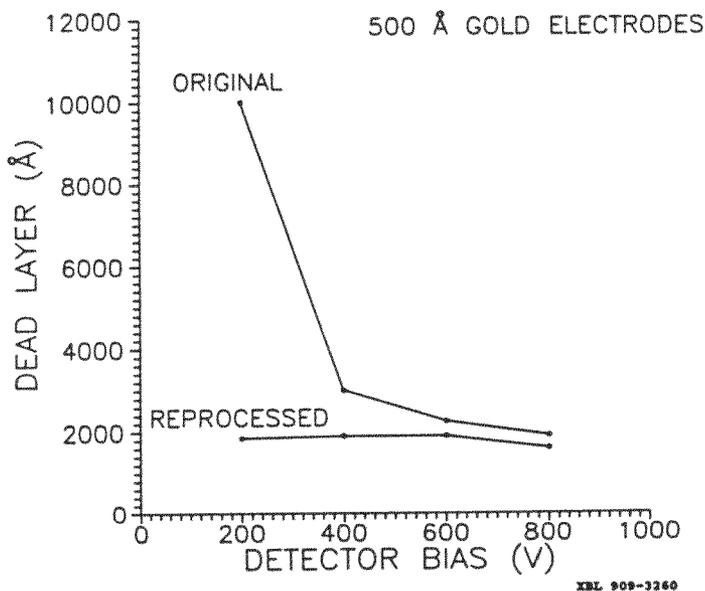


Fig. 2 Dead layer thickness as a function of detector bias for a Au electrode used during the lithium-drift process and for a reprocessed Au electrode on the same detector.

The detector dead layers were measured by characterizing the detector response with 2 keV x-rays that penetrate only the first few microns of the Si surface. A laboratory x-ray source consisting of an x-ray tube with a (200) pentaerythritol (PET) monochromator crystal was used to obtain tuneable x-rays in the 2 keV region. The experimental x-ray setup has been described in detail elsewhere [6]. Figure 3 is an example of a Si(Li) detector response to 2.05 keV x-rays. The partial charge collection due to events occurring in or near the dead layer results in a low energy shoulder on the Gaussian x-ray peak.

The ratio of the number of events occurring in the low energy shoulder relative to the total number of events can be directly related to an absorption depth according to [8]:

$$A = 1 - \exp(-(u/\rho) \rho d) \quad (1)$$

where A is the fraction of events occurring in the low energy shoulder, u/ρ is the mass absorption coefficient for silicon at 2.0 keV in cm²/g, ρ is the density of silicon in g/cm³, and d is the absorption depth in cm which is taken to equal the dead layer thickness. The low energy shoulder on the response peak shown in Figure 3 represents ~10% of the total number of events, which corresponds to a dead layer depth of ~1700 Å.

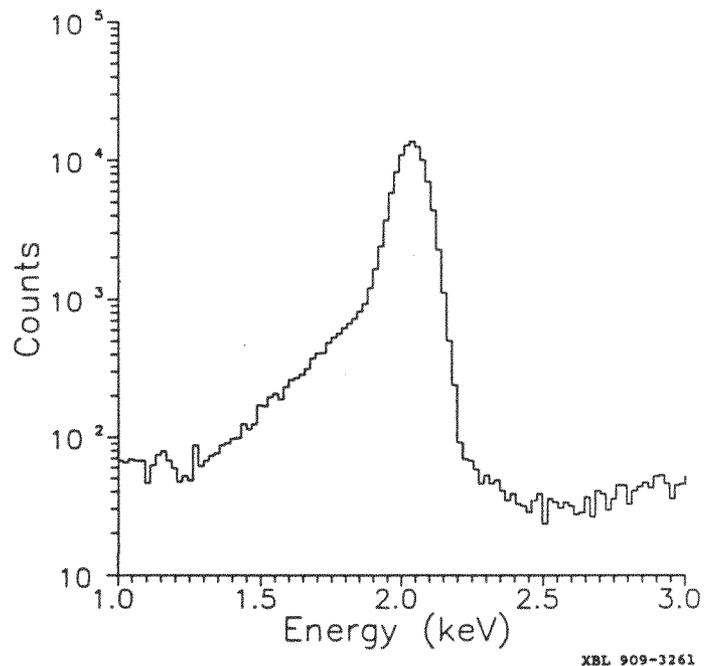


Fig. 3 Au/Si(Li) detector response to 2.05 keV x-rays, showing the low energy shoulder on the Gaussian peak corresponding to a 1700 Å thick dead layer.

III. RESULTS AND DISCUSSION

Figures 4 and 5 show dead layer thickness as a function of detector bias for detectors with a range of Au and Pd electrode thicknesses. The dead layers tended to decrease in thickness as the detector bias increased. This trend has been documented previously in high resistivity surface barrier detectors [1-3] and in Si(Li) detectors [4]. The dead layer dependence on bias can be explained by a combination of two effects. As the bias increases, the detector volume rapidly depletes until the intrinsic region is fully depleted. As the bias increases further, the narrow regions of high density space charge near the contacts are depleted. Thus, the transition regions between the contacts and intrinsic volume become thinner, decreasing the effective dead layer thickness. The second effect contributing to the dead layer dependence on detector bias is described by the

model from reference 12. That model equates the dead layer thickness with the distance over which charge carriers diffuse against the electric field and are trapped at the surface, before their motion in the electric field removes them from the region of the surface. For example, in a Si(Li) detector with a p⁺ entrance window contact, such as that shown in Figure 1, the electrons created from photon events near the p⁺ window should be collected at the n⁺ contact, but some electrons can diffuse against the drift field and can be trapped at the p⁺ window contact, resulting in loss of signal charge. The diffusion distance, or dead layer thickness, is an inverse function of the electric field, until the carrier saturation velocity is reached.

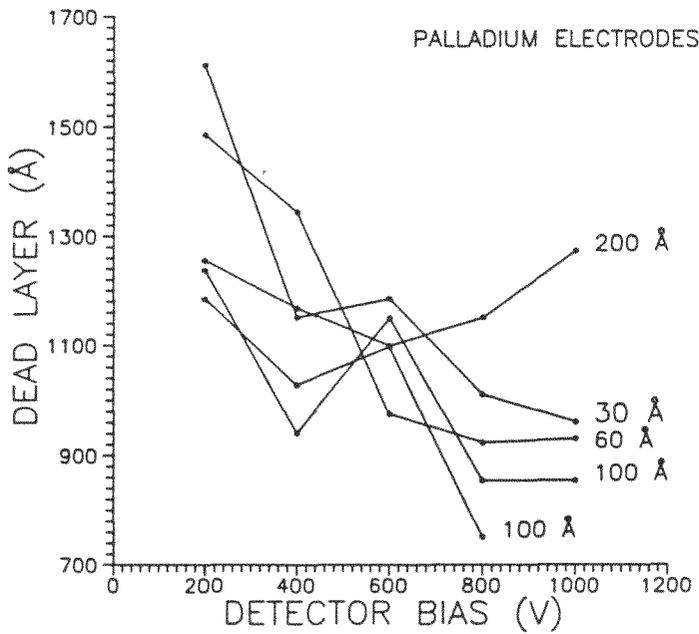


Fig. 4 Dead layer thickness as a function of detector bias for detectors with Pd electrodes of various thicknesses.

The model described above assumes that all the charge carriers diffusing against the field and reaching the surface will be trapped at the surface, which in effect assumes an infinite surface recombination velocity. In reality, the surface recombination velocity is sensitively dependent on surface and contact preparation techniques [13-16]. It seems probable that the surface recombination velocity would vary among Si(Li) detectors depending on the contact type and preparation procedure, and hence the effective dead layer thickness would also vary. Figures 4 and 5 show that the detectors with Pd electrodes had significantly thinner dead layers than those with Au electrodes, as summarized in Table 1.

Table 1
Measured Dead Layers

Pd/Si(Li)	Au/Si(Li)
800-1100 Å	1200-2000 Å

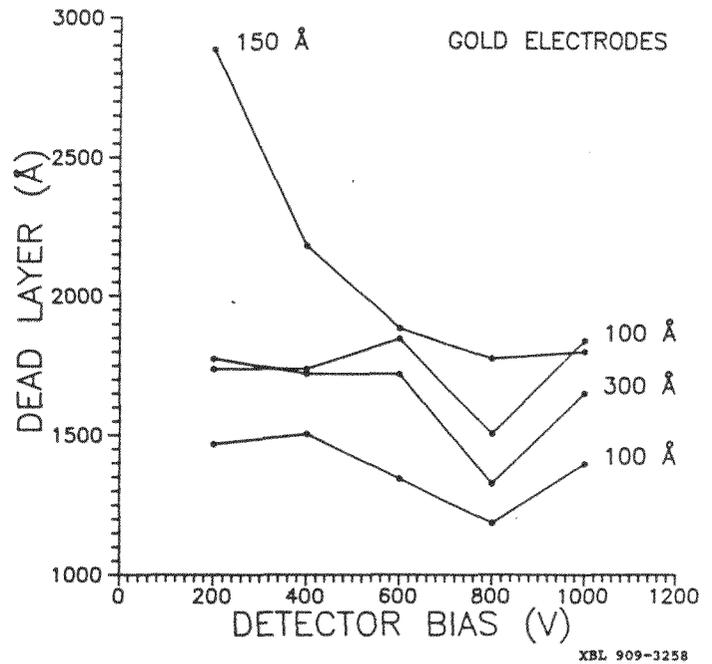


Fig. 5 Dead layer thickness as a function of detector bias for detectors with Au electrodes of various thicknesses.

In order to obtain information about the physical nature of Pd/Si(Li) and Au/Si(Li) surfaces, x-ray photoelectron spectroscopy (XPS) measurements were performed. The photoemission spectra produced by Mg K α x-rays revealed nothing unusual about the bulk Pd and Au layers, but did reveal differences in the SiO₂ beneath the metals, as shown in Figure 6. (It should be noted that the SiO₂ was the native oxide on the Si(Li) material, which was not removed prior to deposition of the metal). Figure 6 shows the Si 2p photopeak arising from the SiO₂ on (a) an oxidized Si surface, (b) a Au/Si(Li) surface, and (c) a Pd/Si(Li) surface. The Si 2p photoelectron produced by the Mg K α x-ray has an energy of 99.5 eV, but will be shifted in energy by ~4 eV if the Si is bound to oxygen [17]. The Si 2p photopeaks from the SiO₂ in Figure 6 (a) through (c) are shifted by 3.5, 3.7 and 2.6 eV, respectively. Schleich, et. al. [18] performed extensive studies of the Pd/SiO₂/Si surface using XPS and other techniques, and formulated a model to explain the reduced shift in the SiO₂ peak observed in the Pd/SiO₂/Si system compared with the SiO₂/Si system. They proposed that the weaker SiO₂ shift is due to a decrease in the number of oxygen vacancies resulting from compensation by Pd atoms that diffused into the SiO₂ layer. Pd diffusion occurred in their samples at temperatures as low as 100 K. In addition, they observed no shift in the Pd 3d₅ photopeak at temperatures <400 K, indicating that there was no Pd-silicide formation at those temperatures. Our XPS measurements confirm the lack of a Pd-silicide in the Pd layers deposited at room temperature. We propose that it is the compensation of the oxygen vacancies by Pd in the native SiO₂ on the Si(Li) surface that decreases the charge trapping at the Pd/Si(Li) interface. The reduction in charge trapping decreases the surface recombination rate and effectively decreases the dead layer thickness in the Pd/Si(Li) detectors.

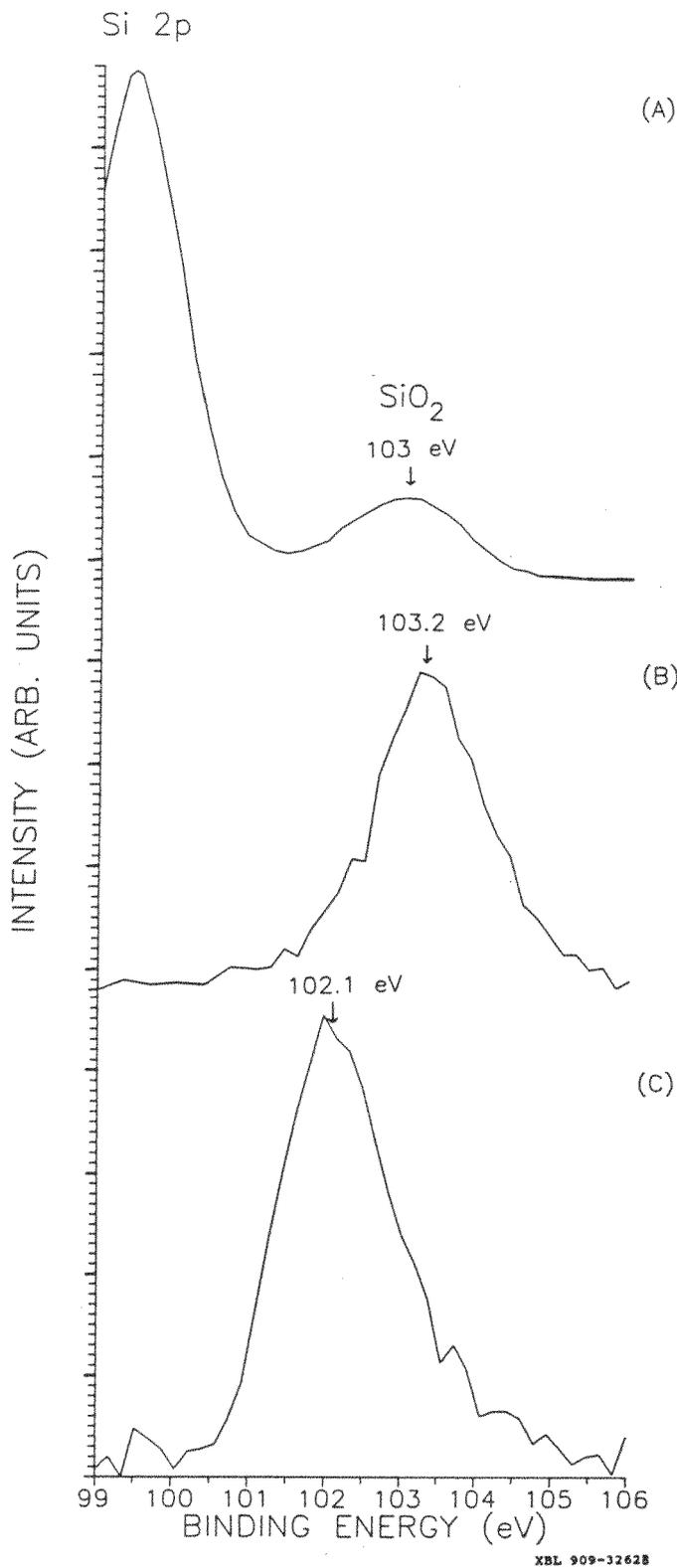
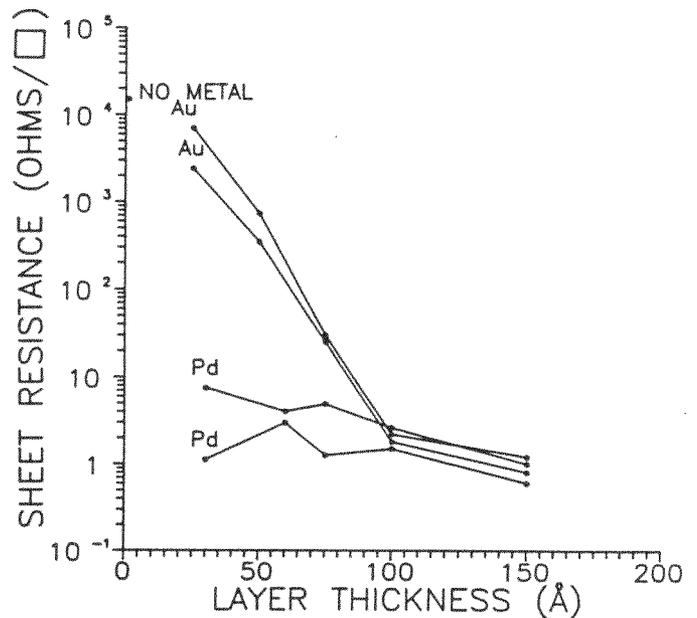


Fig. 6 X-ray photoemission spectra using Mg $K\alpha$ x-rays: (a) Si and SiO_2 photopeaks from a SiO_2/Si sample, (b) SiO_2 photopeak from a Au layer on Si(Li), (c) SiO_2 photopeak from a Pd layer on Si(Li).

Our XPS measurements on Al/Si(Li) surfaces showed an almost identical shift in the SiO_2 peak to that seen on the Pd/Si(Li) surfaces. This implies that the same metal diffusion model as discussed above for Pd could in part explain the very thin dead layers in Al/Si(Li) detectors observed by the authors of reference 6. If charge trapping at detector entrance window interfaces could be eliminated, this would translate into a negligible surface recombination velocity and an immeasurable dead layer.

For optimum detector performance the metal electrodes must be of low resistance so as not to contribute to the series noise of the detector. To determine the minimum thicknesses required for low resistance Au and Pd electrodes, sheet resistances were measured as a function of metal thickness, as shown in Figure 7. The metal films were deposited on Si(Li) surfaces that had been processed in the same manner as the detectors. Figure 7 shows that low resistance Pd layers can be fabricated with as little as 30 Å of Pd, whereas a minimum of 100 Å of Au is required. (However, these results may be specific to the metal deposition technique employed here).



XBL 909-3256A

Fig. 7 Sheet resistance as a function of layer thickness for Pd and Au layers on Si(Li) material.

Three characteristics of Si(Li) detectors with Pd electrodes, compared to those with Au electrodes, translate directly into an increase in window transmission: (1) thinner metal layer required for a low resistance electrode, (2) lower absorption coefficients for Pd, and (3) thinner detector dead layers. Figure 8 compares the calculated transmission for three different electrode configurations at low energies: (1) a conventional 500 Å Au electrode in conjunction with its nominal 2000 Å thick Si dead layer, (2) a 150 Å Au electrode with its thin Si dead layer of ~1300 Å, and (3) a 60 Å Pd electrode with its corresponding ~900 Å Si dead layer. Figure 8 clearly

illustrates the calculated superiority of a thin Pd contact to the conventional Au contact for low energy x-ray detection.

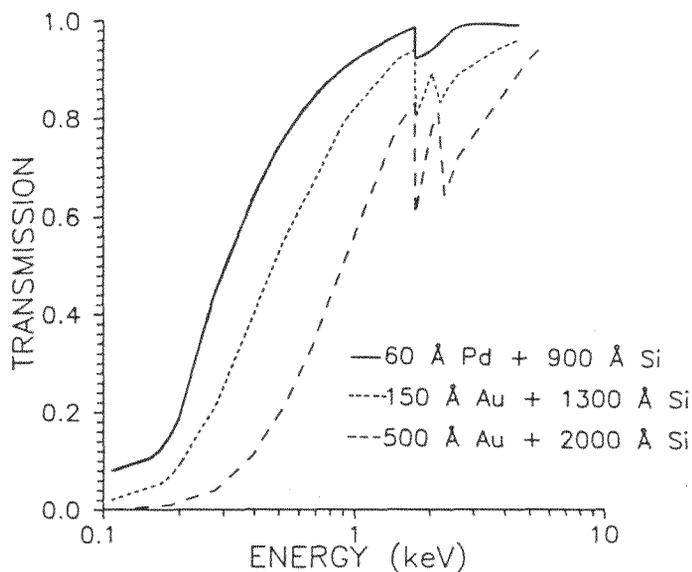


Fig. 8 Calculated transmission as a function of energy for three different Si(Li) electrode structures: (1) 60 Å Pd in conjunction with its ~900 Å Si dead layer, (2) 150 Å Au with its ~1300 Å dead layer, and (3) 500 Å Au with its ~2000 Å dead layer.

IV. SUMMARY

Detector dead layers have been measured in Si(Li) detectors with Pd and Au entrance window electrodes. X-ray photoemission measurements show that the thinner dead layers observed in the Si(Li) detectors with Pd electrodes, compared to those with Au electrodes, are due to Pd diffusion into the SiO₂ layer on the Si surface, which compensates oxygen vacancies and reduces the charge trapping at the entrance window interface. XPS measurements on Al/Si(Li) surfaces show that the same metal diffusion model could explain the thin dead layers observed in Al/Si(Li) detectors. If charge trapping at the detector entrance window interface could be eliminated, this would translate into a negligible surface recombination velocity and no measurable dead layer. Surface recombination velocity measurements on Pd/Si(Li), Au/Si(Li) and Al/Si(Li) surfaces are planned for the near future.

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VI. ACKNOWLEDGMENT

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