

were connected to a separate power supply and biased at half the bias across the detector. Then, the resolution as a function of the detector bias was measured. We found that the detectors can be overbiased by approximately 20 V (about half as much as for a complete guard ring). Despite the decrease in active surface we decided to run strips 1 and 28 as "guard strips" during future runs.

The observation that the events in the "ghost locus" are central hits on the face of the detectors has an explanation: according to the manufacturer (Ref. 4), the resistivity of the raw silicon material is often lower in the interior region of the crystal and thus across the wafer from which the detector is manufactured. As a consequence, the central region of the detector depletes fully at a higher bias, which in turn leads to the "ghost locus" if the detector is run at or slightly below its nominal depletion voltage.

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## TEMPERATURE SENSITIVITY OF SURFACE CHANNELS ON HIGH-PURITY GERMANIUM DETECTORS

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### Introduction

Problems relating to the intrinsic surface of germanium detectors have been recognized from the beginning of their use. Surface states invariably lead to the nominal intrinsic surface having some degree of n- or p-typeness; this slightly conducting layer is called a "surface channel".<sup>1-4</sup> The typeness of the surface channel is not related to the typeness of the bulk germanium from which the detector is fabricated. These surface channels cause distortions in the electric field near the surface. Some of the charge from photon interactions occurring in these affected regions reaches the surface, then slowly migrates to a contact. When the charge movement is sufficiently slow, the charge will not reach an electrical contact within the integration time of the amplifier. Consequently, only a partial signal, whose magnitude depends on the location of the photon interaction, will be observed. The depth of the affected region usually varies greatly from one electrical contact to the other, and is on the order of 1 mm from the surface.<sup>3,4</sup> The presence and

magnitude of surface channels can be greatly affected by the environment in the cryostat and by prior chemistry of the surface.

The primary cause of resolution degradation resulting from radiation damage in germanium detectors is the trapping of the holes created by the incident gamma rays before these holes are fully collected at the  $p^+$  contact of the detector.<sup>5</sup> Since the cross section of the traps created by radiation damage is inversely proportional to the electric field, and since the electric field in part of the detector is decreased by the presence of a surface channel, this type of surface problem could, in principle, compound the degrading effect radiation damage has on the resolution. In particular, this effect should be more noticeable in detectors having a relatively large surface-area to volume ratio, such as thick planar detectors with a small diameter.

### Motivation

The LBL/IUCF experimental program to study the effects of radiation damage on high-purity germanium detectors and the subsequent annealing of these detectors has been maintained since 1986. Highly controlled and monitored beams of both protons and neutrons have been used to irradiate a number of germanium detectors to various fluences. In February, 1992, nine detectors contained in five variable-temperature cryostats were irradiated with 183-MeV neutrons to various fluences.<sup>6</sup> The same nine detectors were fully recovered with high-temperature annealing (up to 140 C) and irradiated again with 183-MeV neutrons to the same respective fluences in March, 1993. Measuring the energy resolution of high-energy gamma rays (usually the 1332-keV gamma ray from  $^{60}\text{Co}$ ) as a function of temperature has always been a central part of this radiation damage study. After the second irradiation, some of the planar detectors showed significantly more degradation over time with bias on at elevated temperatures than after the first irradiation, whereas other planar detectors, as well as the coaxial detector, were about the same. All the detectors should have exhibited the same behavior after each irradiation based on radiation damage considerations. The likely explanation is that some of the detectors acquired different surface channel characteristics sometime between the two experiments. As all the cryostats underwent modifications and repairs between the two irradiations, the detectors were exposed at different times and for different periods of time to air and the general environment. Exposure of detectors to various gases, including air, can alter surface channel characteristics.<sup>3</sup>

In addition, there is a very significant hysteresis characteristic observed in all our radiation-damaged planar detectors that supports a correlation between the energy resolution of these detectors and surface effects. When a planar detector is maintained at an elevated temperature for a number of hours with the bias on and then cooled back to 83 K (nominal  $\text{LN}_2$ ), the resolution at 83 K will be worse than it was before the elevated temperature cycle. The magnitude of this hysteresis effect increases with the temperature reached and the time spent at that temperature, becoming measurable around 90 K and increasing rapidly with temperature thereafter. Bias-off temperature cycles in the 90-110 K region also cause this effect, although to a considerably smaller degree. Bias-off temperature cycles reduce the degradation caused by previous bias-on temperature cycles. In fact, bias-off temperature cycles in the 120-145 K region completely remove resolution degradation caused by previous elevated temperature cycles. For example, before any

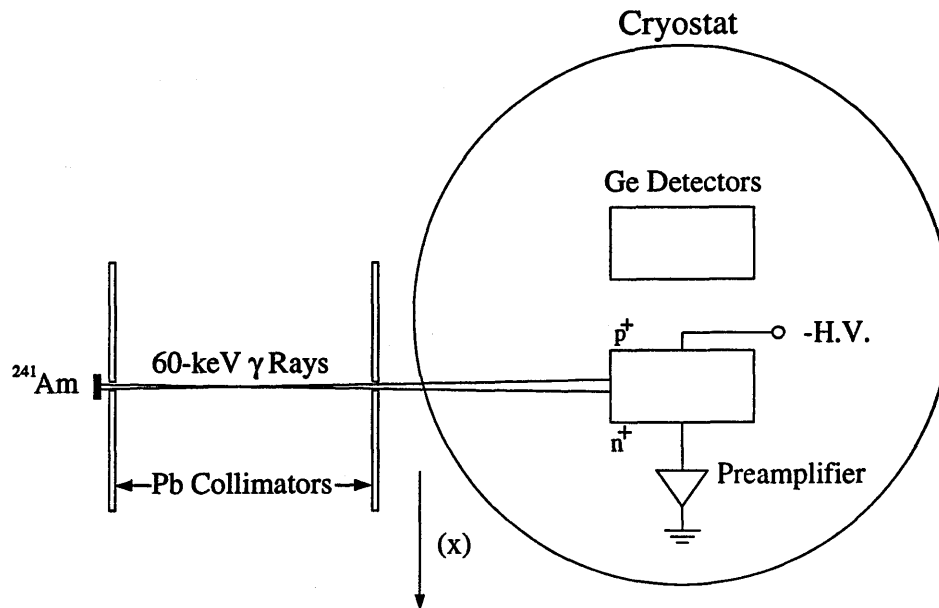


Figure 1. Apparatus used to perform the 60-keV scan measurements. The gamma rays are horizontally collimated by lead slabs to produce a beam spot on the detector surface about 1.5 mm wide. The position of the collimator can be varied in the  $x$ -direction in a controlled manner.

temperature cycles, the 1332-keV gamma-ray resolution of detector 644-1.5 was 2.4 keV at 83 K. After 35 hrs at 104 K with bias on, the resolution at 83 K degraded to 3.7 keV. After a subsequent cycle to 125 K for 24 hrs with the bias off, the resolution was again 2.4 keV. During our study, this pattern was repeatedly observed in all the planar detectors. However, this effect was not seen to any significant degree in our radiation-damaged large coaxial detector. Our planar detectors have a much higher surface-area to volume ratio than the coaxial detector; therefore, it is plausible that surface effects might be responsible for the hysteresis characteristic associated with the planar detectors.

To complement and aid our basic program of measuring the radiation damage effects on germanium detectors, an attempt was made to correlate the surface channel behavior with this anomalous gamma-ray resolution degradation. Since measuring the temperature dependence of the resolution degradation of radiation-damaged germanium detectors is a prime goal of our program, the temperature sensitivity of the surface channel within the operating range (70-120 K) was also measured.

#### Experimental Setup

The surface channel characteristics of the planar detectors were measured with techniques similar to those published.<sup>3,4</sup> As shown in Fig. 1, the 60-keV gamma rays from an  $^{241}\text{Am}$  source are collimated by slots between lead slabs to provide a vertical fan beam about 1.5 mm wide at the detector. These collimated gamma rays pass through a thin aluminum cryostat window and impinge on the surface of the detector. The detectors studied are all about 10-mm thick with diameters ranging from 20 to 24 mm. The horizontal position ( $x$ ) can be well maintained and repeated to better than 1 mm. In a typical

scan, the horizontal position of the source-collimator assembly is varied and the 60-keV peak efficiency, defined as the number of 60-keV full-energy peak events divided by the total number of events in the spectrum, is measured. The attenuation length ( $1/e$ ) of 60-keV gamma rays in germanium, 1.1 mm, is on the order of the depth over which some of the charge created is collected on the surface.<sup>3</sup> This depth can vary significantly from contact to contact. Depending on the horizontal position and depth of the interactions occurring within this affected region, some of the charge created travels a variable distance within the detector before reaching the surface. The longer this distance, the more the contribution to the signal. Gamma rays that interact beyond the region where some of the charge created is collected on the surface give a full-energy signal because all the charge is collected directly on the electrical contacts. Consequently, the 60-keV peak efficiency will vary as the beam of gamma rays moves from contact to contact.

To complement the 60-keV efficiency measurements, the 1332-keV count rate was monitored as a measure of the peak efficiency of the detector. For this measurement, two 10  $\mu\text{Ci}$   $^{60}\text{Co}$  sources were symmetrically placed about 3 cm from the detectors. Uniform charge deposition is assumed throughout the volume of the detectors, essentially a perfect assumption considering the gamma-ray energy, detector dimensions, and source-detector geometry used.

Eight planar detectors were studied as a function of temperature. For this presentation, attention is focused on five detectors that give representative results. All these detectors were fabricated from crystals grown in the  $\langle 113 \rangle$  crystal axis direction and have a boron-implanted  $p^+$  contact and a lithium-diffused  $n^+$  contact. The intrinsic surfaces on all these planar detectors had been passivated with amorphous germanium; subsequently, these detectors were subjected to multiple high-temperature annealing cycles. What effect, if any, this had on the nature of these surface channels is unknown.

Surface channels often also affect the I-V characteristic of the diode. As will be discussed in the following section, most of the planar detectors studied had significant surface channel characteristics. Nevertheless, all these detectors displayed consistently excellent diode characteristics, i.e., these surface channels do not cause excessive leakage current. During most of this study, the detectors were operated at a bias voltage of  $-2000$  V, well above their depletion voltages. Most of the detectors could be fully biased at temperatures as high as 120 K.

### Results and Conclusions

Figure 2 illustrates how a p-type surface channel affects the electric field, and thus the efficiency, near the surface of planar detector 475-3.0. A p-type surface channel causes poor efficiency for gamma rays impinging on the detector near the  $n^+$  contact because most of these gamma rays create holes that travel only a short distance through the detector before reaching the surface. Since these holes induce little if any usable signal while moving along the surface to the  $p^+$  contact, only a fraction of the total full-energy signal from these gamma rays is recorded. The two spectra shown in figure 2 demonstrate the dramatic change in the 60-keV efficiency as a function of position. For analogous reasons, an n-type surface channel causes poor efficiency for gamma rays impinging near the  $p^+$  contact because most of the electrons created travel only a short distance through the detector before reaching the surface.

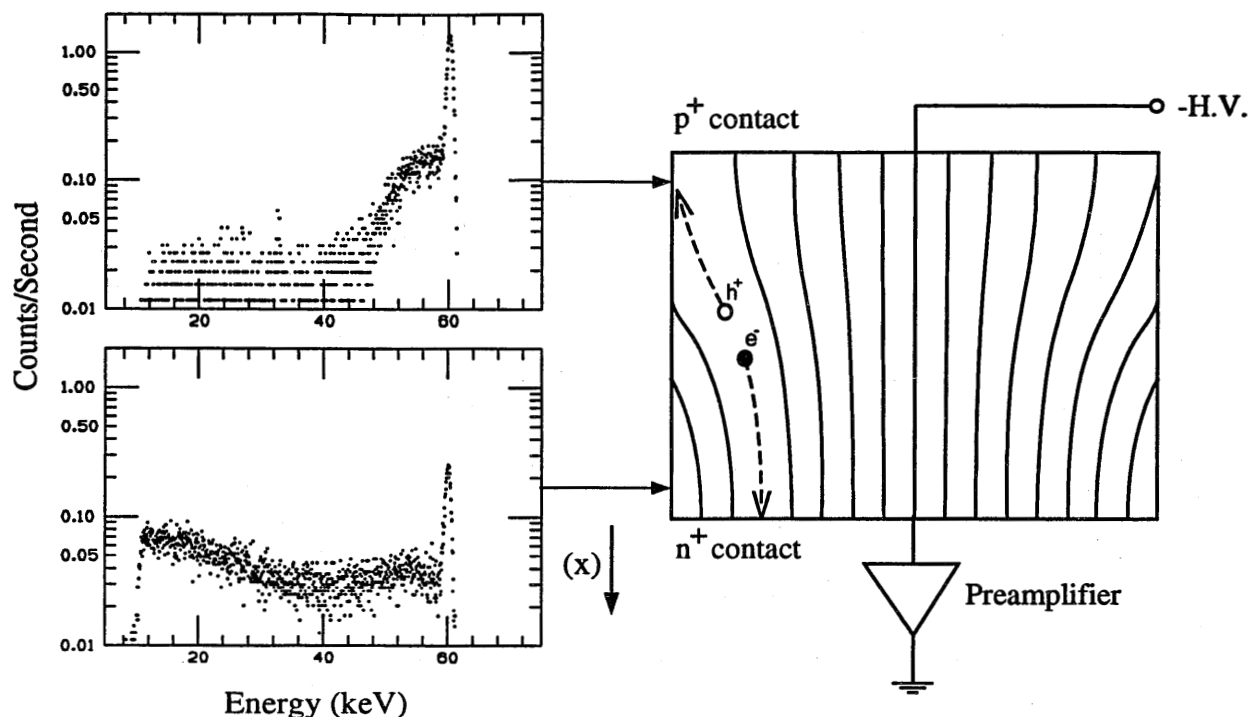


Figure 2.  $^{241}\text{Am}$  spectra observed when gamma rays impinge at the indicated positions on planar detector 475-3.0. Also shown is a schematic presentation of the electric field lines in this detector, which has a p-type surface channel. Note that the field lines meet the contacts orthogonally, as they must. This and other details have been overlooked in prior representations of this situation. The spectrum obtained when the photon interactions occur near the  $\text{p}^+$  contact shows good 60-keV full-energy peak efficiency because most of the signal is induced by electron flow to the  $\text{n}^+$  contact. The corresponding spectrum obtained when the photon interactions occur near the  $\text{n}^+$  contact shows much lower efficiency because many of the holes created reach the surface before being collected at the  $\text{p}^+$  contact.

Figure 3 presents the 60-keV scan results for four detectors at various temperatures in the 70-120 K region. Figure 3a shows the 60-keV scan for detector 475-3.0. The 60-keV efficiency of this detector clearly decreases in a monotonic fashion when scanning from the  $\text{p}^+$  contact to the  $\text{n}^+$  contact, the classic signature of a p-type surface channel. The efficiency in the 72-95 K region exhibits extreme temperature dependence. Figure 3b shows the same result for detector 486-2.3, except the monotonic increase in the efficiency from the  $\text{p}^+$  to the  $\text{n}^+$  contact is the classic signature of an n-type surface channel. Figure 3c shows the scan results for detector 642-1.5. This detector displays little surface channel character at 75 K, but acquires both n- and p-type surface channel characteristics at higher temperatures. Again, the effect of the surface channels increased dramatically with temperature. Figure 3d shows the scan results for a detector, 508-3.9, that exhibits a p-type surface channel, but one with relatively little temperature sensitivity.

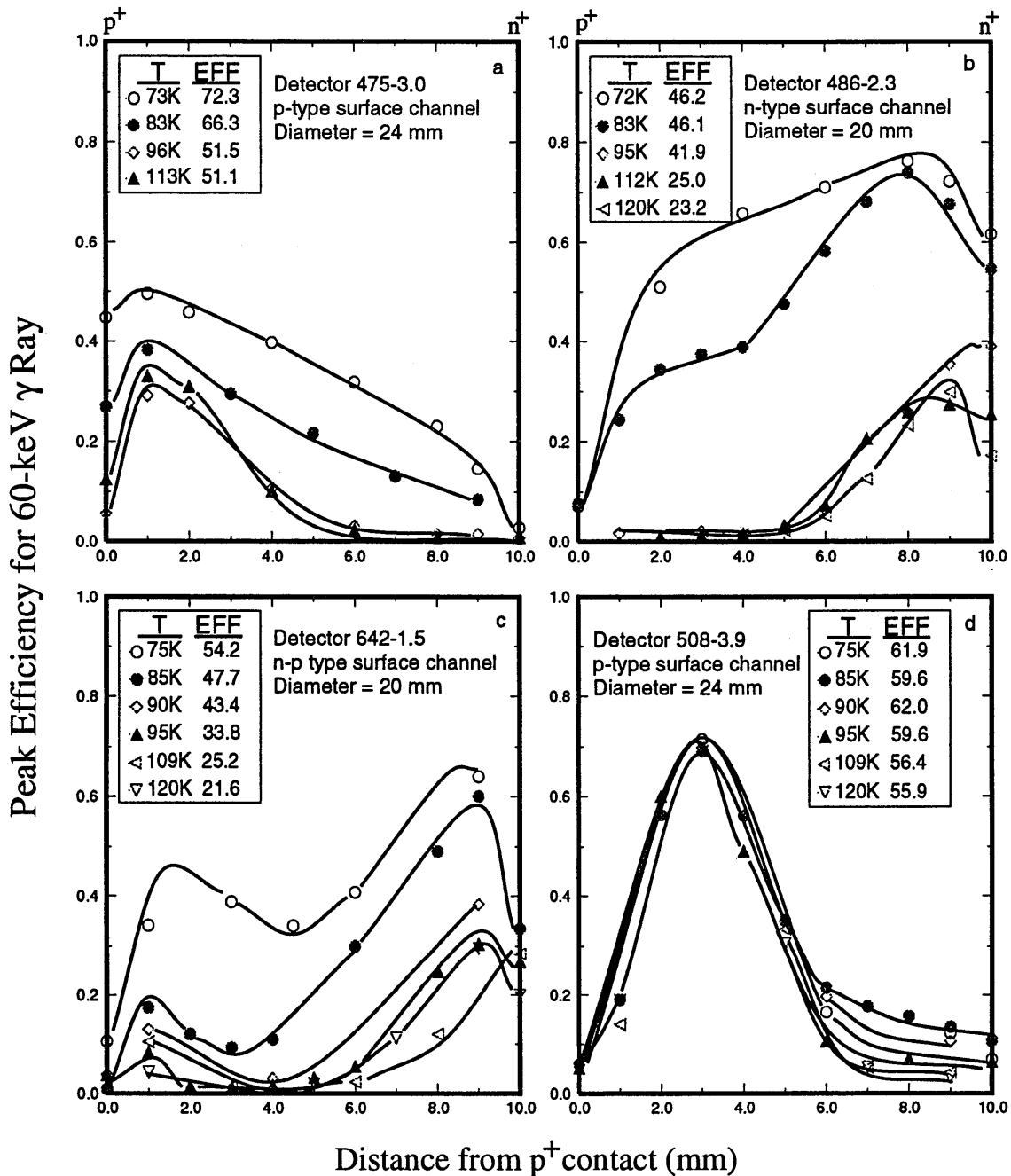


Figure 3. Efficiency data obtained using the 60-keV scan that illustrates the various types of surface channels and their temperature dependence. Some detectors showed p-type surface channels (a), n-type surface channels (b), or signs of both p- and n-type surface channels (c). These three detectors all exhibited extreme temperature sensitivity in the 72-95 K region. Another detector showed surface channel characteristics but almost no temperature sensitivity (d). As indicated in the legends the count rate in the 1332-keV peak (EFF) continued to decrease with temperature even at temperatures higher than 95 K.

The 60-keV scans show a strong general trend of decreasing efficiency with increasing temperature in the 72-95 K region for all detectors except 508-3.9. Although these relatively low-energy gamma rays probe only the region near the surface, one would expect the full-energy peak efficiency of the 1332-keV gamma ray, which causes interactions almost uniformly throughout the entire detector, to also decrease with increasing temperature. In the legends accompanying Fig. 3, the count rate in the 1332-keV peak is listed for the temperatures at which a measurement was made. There is a definite correlation between changes in the scan results and the 1332-keV peak efficiencies of the detectors. The count rates in the full-energy 1332-keV peaks are plotted against temperature in Fig. 4. Both 20-mm diameter detectors lost more than a factor of 2 in peak efficiency over the temperature range measured, whereas both 24-mm diameter detectors lost less than a factor of 1.4 in peak efficiency. This comparison demonstrates that a considerably larger fraction of the volume is affected by the surface channel in a smaller diameter detector. The 1332-keV count rate showed sensitivity over the entire temperature range measured, whereas the 60-keV scan showed sensitivity only in the 72-95 K range. This is almost certainly due to strong attenuation of the 60-keV gamma rays. We believe the effects of the surface channel continue to increase with temperature; however, the affected region is sufficiently thick by 95 K that practically all the 60-keV gamma rays interact within this region, eliminating sensitivity of the scan to further changes. The worsening of surface channel effects with increased temperature is another compelling reason to operate planar detectors as cold as possible.

Measurements of the current due to gamma-ray interactions were made over the temperature range where the surface channel was extremely temperature sensitive by placing two 10  $\mu\text{Ci}$   $^{60}\text{Co}$  sources a fixed distance from detector 644-1.5 and varying the temperature. These measurements, after adjusting for thermally generated current, indicated that the total charge reaching the electrical contacts of the detector was the same, to the one percent level, throughout the temperature range studied even though the 1332-keV peak efficiency decreased greatly with increased temperature. As the temperature increases, apparently a larger fraction of the charge created reaches the surface where movement is slow and/or charge movement on the surface is further slowed. When charge movement is too slow, little or no signal is induced within the pulse processing time, causing a deficit in the signal amplitude that excludes these events from being counted in the peak efficiency because they fall below the 1332-keV peak. In fact, these events appear as additional background in the spectrum. For example, although the total counts in full  $^{60}\text{Co}$  spectra observed with detector 475-3.0 at 83 K and 101 K were the same, the 1332-keV peak efficiency at 101 K was lower by a factor of 1.4.

The effect of radiation damage on the  $^{241}\text{Am}$  spectra is a shift in the 60-keV peak position. The probability of charge being trapped is proportional to the distance the holes must travel within the detector to reach the  $p^+$  contact because radiation damage causes predominantly hole trapping in germanium detectors. For this reason, more holes are lost to trapping when the photon interaction occurs near the  $n^+$  contact than when the interaction occurs near the  $p^+$  contact. This loss of charge causes the position of the 60-keV peak to shift down as the scan moves from the  $p^+$  contact to the  $n^+$  contact. Figure 5 presents examples of this effect, which is very small compared to the charge

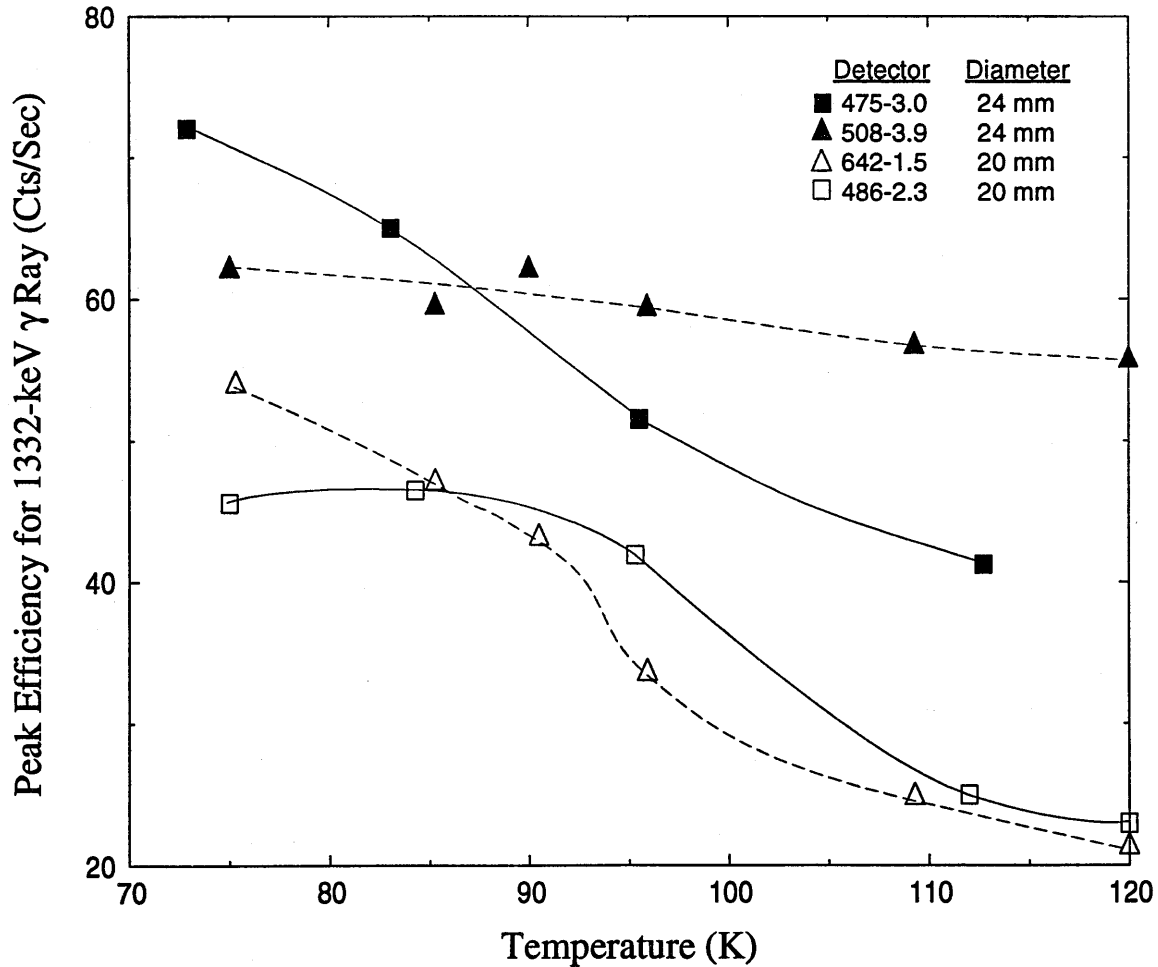


Figure 4. Relationship between the position where the 60-keV gamma rays impinge on the detector and the corresponding peak position. The 60-keV peak shifts downward as a function of distance from the  $p^+$  contact because of the hole trapping caused by neutron damage. There is a striking difference between detector 475-3.0 before (a) and after (b) being fully annealed. Detector 644-1.5 (c) received about twice the fluence of 475-3.0 and shows a significantly larger peak shift. The shift for the damaged detectors (a and c) shows a strong temperature dependence; the charge trapping effect of radiation damage is known to be highly temperature sensitive.

losses due to the surface channel. Figure 5a shows the 60-keV peak position as a function of collimator position at different temperatures after detector 475-3.0 was irradiated to a fluence of  $3.6 \times 10^8$  n/cm<sup>2</sup>. The charge trapping that occurs in radiation damaged detectors is known to be extremely temperature sensitive.<sup>6</sup> Figure 5b shows results from the same measurement after this detector was fully annealed. Clearly, annealing removes the effect of radiation damage. However, the annealing does not necessarily change the 60-keV scan and 1332-keV efficiency measurements. We are led to the conclusion that radiation damage does not affect the surface channel characteristics. Figure 5c shows results from the same measurement on detector 644-1.5, which had been irradiated to a fluence of  $7.2 \times 10^8$



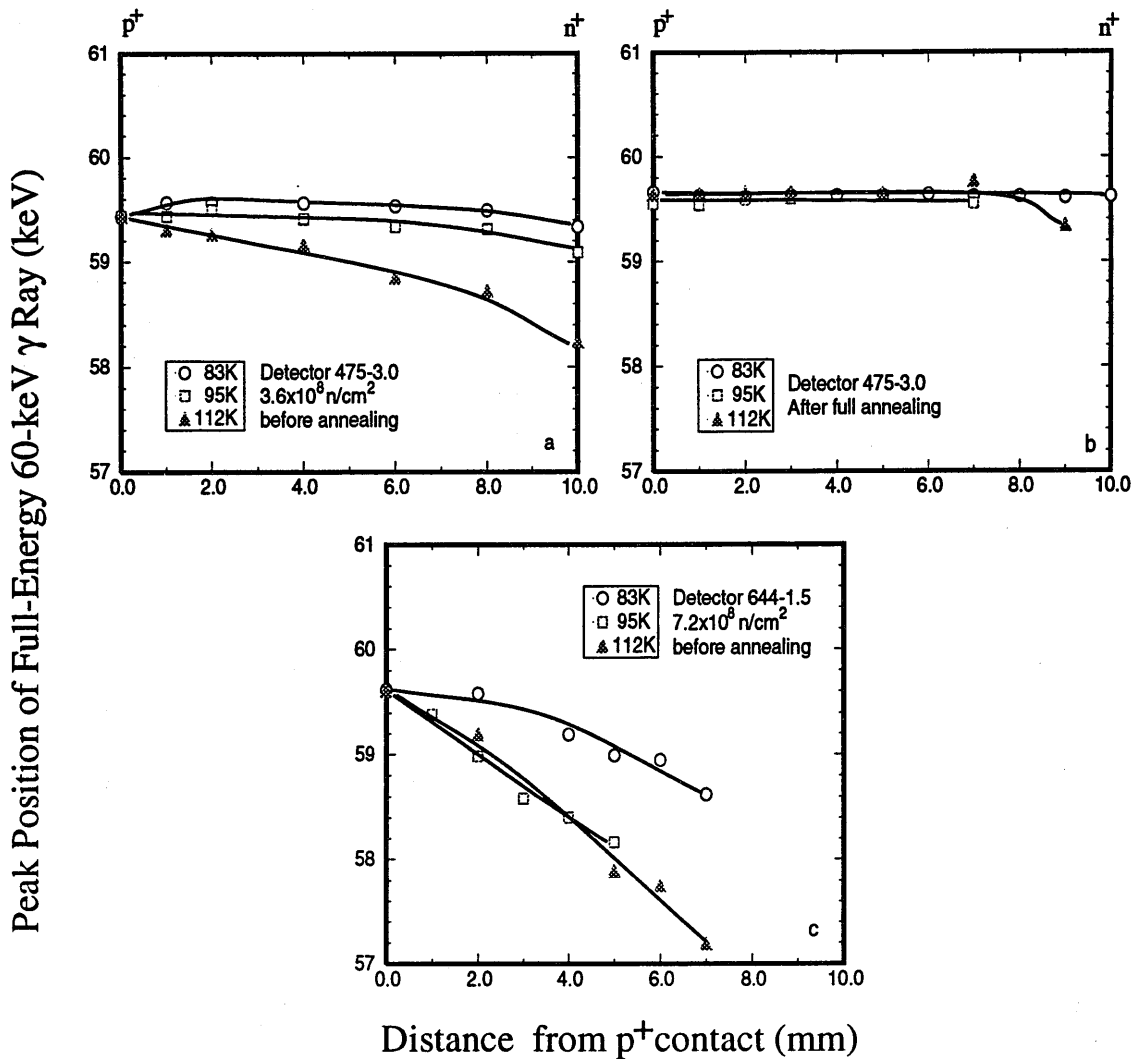


Figure 5. Relationship between the position where the 60-keV (59.6-keV) gamma rays impinge on the detector and the corresponding peak position. The 60-keV peak shifts downward as a function of distance from the p<sup>+</sup> contact because of the hole trapping caused by neutron damage. There is a striking difference between detector 475-3.0 before (a) and after (b) being fully annealed. Detector 644-1.5 (c) received about twice the fluence of detector 475-3.0 and shows a significantly larger peak shift. The peak shift for the radiation damaged detectors (a and c) shows a strong temperature dependence; the charge trapping effect of radiation damage is known to be highly temperature sensitive.

n/cm<sup>2</sup>. As expected, the higher fluence causes a more pronounced peak shift. To ensure a clean measurement of the surface channel effect during the 60-keV scans, the peak shift caused by radiation damage was noted and adjusted for. As shown in Fig. 5a, a peak shift was observed when detectors were irradiated to a fluence of  $3.6 \times 10^8$  n/cm<sup>2</sup>. However, detectors irradiated to a fluence of only  $1.5 \times 10^8$  n/cm<sup>2</sup> did not show a measurable peak shift. Somewhere between the two fluences the peak shift becomes measurable.

Different detector environments and temperatures were found to cause changes in the surface channel effects. In a fully annealed detector, 475-3.0, temperature cycles to 120 C caused the effects of the surface channel observed at 83 K to become worse. The original detector characteristics could be repeatedly restored by filling the cryostat with argon or simply letting the molecular sieve outgas at room temperature.

Although great effort was made to find a correlation between the surface channel measurements and the anomalous degradation in the energy resolution of high-energy gamma rays, no positive correlation was established. Bias-on temperature cycles in the 90-120 K region significantly degraded the resolution measured when the detectors were cooled back to 83 K, whereas the 60-keV scan results and the 1332-keV peak efficiencies were not measurably changed. Resolution degradation is caused by charge trapping occurring on the one percent level. On the other hand, surface channel effects nearly always cause a much larger fraction of the charge created to not contribute to the signal amplitude. Although the signal amplitude of these events is too low to affect the resolution of the full-energy peak, the peak efficiency measurement is obviously affected because these events are not in the full-energy peak. Since the resolution degradation and the surface channel results reported here are measurements of effects acting on totally different levels, there need not be an observable correlation between the two measurements. If the anomalous resolution degradation observed at elevated temperatures in these radiation-damaged planar detectors is caused by surface channel effects, grounded guard-ring planar detectors will eliminate this problem because such detectors effectively have no surface. To prove this point, we plan to include some grounded guard-ring detectors in our continuing radiation damage study. A fairly thick guard-ring, probably on the order of 5 mm, will be required to eliminate surface channel effects over the entire temperature range studied in our radiation damage program.

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