Submitted to Physics Today

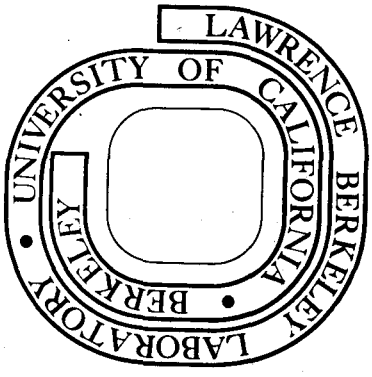
LBL-7212
Preprint

GERMANIUM GAMMA-RAY DETECTORS

Richard H. Pehl

November 1977

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48



DISCLAIMER

Germanium gamma-ray detectors

Devices either of lithium-drifted germanium or the more recently developed high-purity type find uses in such fields as nuclear and exotic-atom studies, nuclear medicine and activation analysis.

Richard H. Pehl

Reprinted from Physics Today

Germanium gamma-ray detectors

Devices either of lithium-drifted germanium or the more recently developed high-purity type find uses in such fields as nuclear and exotic-atom studies, nuclear medicine and activation analysis.

Richard H. Pehl

Semiconductor gamma-ray detectors consist essentially of a piece of solid material in which electrons and holes are produced when a gamma ray is absorbed. These electrons and holes are then collected by an electric field in the material to provide an electric signal that is a direct measure of the energy of the gamma ray. This simple statement implies detector-material characteristics that are by no means easy to achieve, and much of this article will be concerned with these characteristics.

After a brief survey of the desired properties of the detector material—germanium or silicon—and the manner in which it is used, we will compare the use of lithium-drifted germanium with the more recently developed high-purity germanium. This latter development has made possible applications such as the nine-detector array at Vanderbilt University Medical Center shown in figure 1. Following a discussion of this and other applications, the article ends with a summary of some recent work on radiation damage in gamma-ray detectors caused by fast neutrons and charged particles.

Detector characteristics

An important characteristic of any material used for a detector pertains to the production of charge carriers in it. When a gamma ray is absorbed, the number of carriers produced by ionization should be linearly related to the energy absorbed. Furthermore, the best materials require only a small amount of energy to produce a hole–electron pair; so the number of carriers produced for a given energy absorption is large, and the statistical fluctuations in that number are small when expressed as a percentage of the total number.

Production of charge carriers is not enough. To obtain an electrical signal in the external circuit, the carriers must move readily through the material in response to an externally applied electric field. Furthermore, if the total output charge is to be directly related to the energy absorbed, the carriers must not be lost before they reach the external electrodes of the detector. This means that both holes and electrons must have high mobility, and neither type of carrier should be trapped to a significant degree during transit through the detector. These conditions are difficult to satisfy to the extent necessary for high-resolution gamma-ray spectroscopy; at present only germanium and silicon possess the required properties. While considerable effort has been expended on a number of compound semiconductor materials, such as CdTe, GaAs and HgI_2, none of these deserve serious consideration alongside germanium in a discussion that reflects the present state of the art of high-resolution gamma-ray spectroscopy.

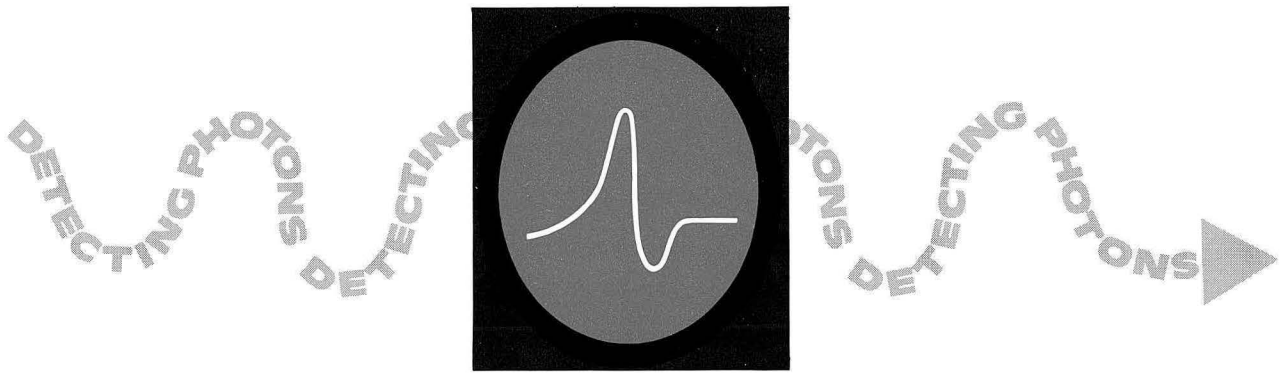
To obtain charge collection from the whole of a detector, sufficient electric field (~1000 V/cm) must be obtained across the material by application of a voltage to electrodes on its opposite faces. Furthermore, the leakage current flowing through the material must be very small so that the signal arising from the gamma-ray is detectable. Operation of germanium detectors at room temperature is impossible, due to the large thermal generation rate of hole–electron pairs by excitation of electrons across the 0.7-eV band gap. Consequently, low-temperature operation (usually achieved by liquid-nitrogen cooling) is essential.

Since the photoelectric effect exhibits almost a Z^5 dependence on the atomic number Z of the detector material, only germanium meets the requirement for high-energy gamma-ray spectroscopy, the Z of silicon being too low for the use of silicon detectors above about 30 keV. Even higher-Z materials would be desirable, but none meets the other requirements for high-resolution gamma-ray spectroscopy. Materials of high atomic number used as scintillators give better absorption efficiency than germanium, but inefficient processes are unfortunately involved both in the conversion of free electrons into light quanta by the scintillator and in the conversion of light quanta into electrons by the electron-multiplier tube. Statistical fluctuations are very large, and the energy resolution suffers accordingly. Germanium detectors usually exhibit improvement in energy resolution of one to two orders of magnitude compared with scintillators.

The concept of a slab of material with electrodes bonded to the opposite faces requires further elaboration. If such contacts provide a free exchange of holes and electrons between the semiconductor and the electrodes, large currents will flow through the detector when voltage is applied across it. To overcome this, "blocking" contacts must be used—that is, the positive contact must not inject holes, nor the negative contact inject electrons into the material. This can be achieved either by careful choice and application of the metals used for the contacts, or by forming heavily doped n and p regions by high-temperature diffusion or by ion implantation into the detector surfaces. The n^+ surface is used as the positive detector electrode, and the p^+ surface as the negative electrode.

The need for blocking contacts is illustrated by considering the electrical properties of a hypothetical detector made from a 10-cm^2 area, 1-cm-thick

Richard H. Pehl is a staff senior scientist at Lawrence Berkeley Laboratory.

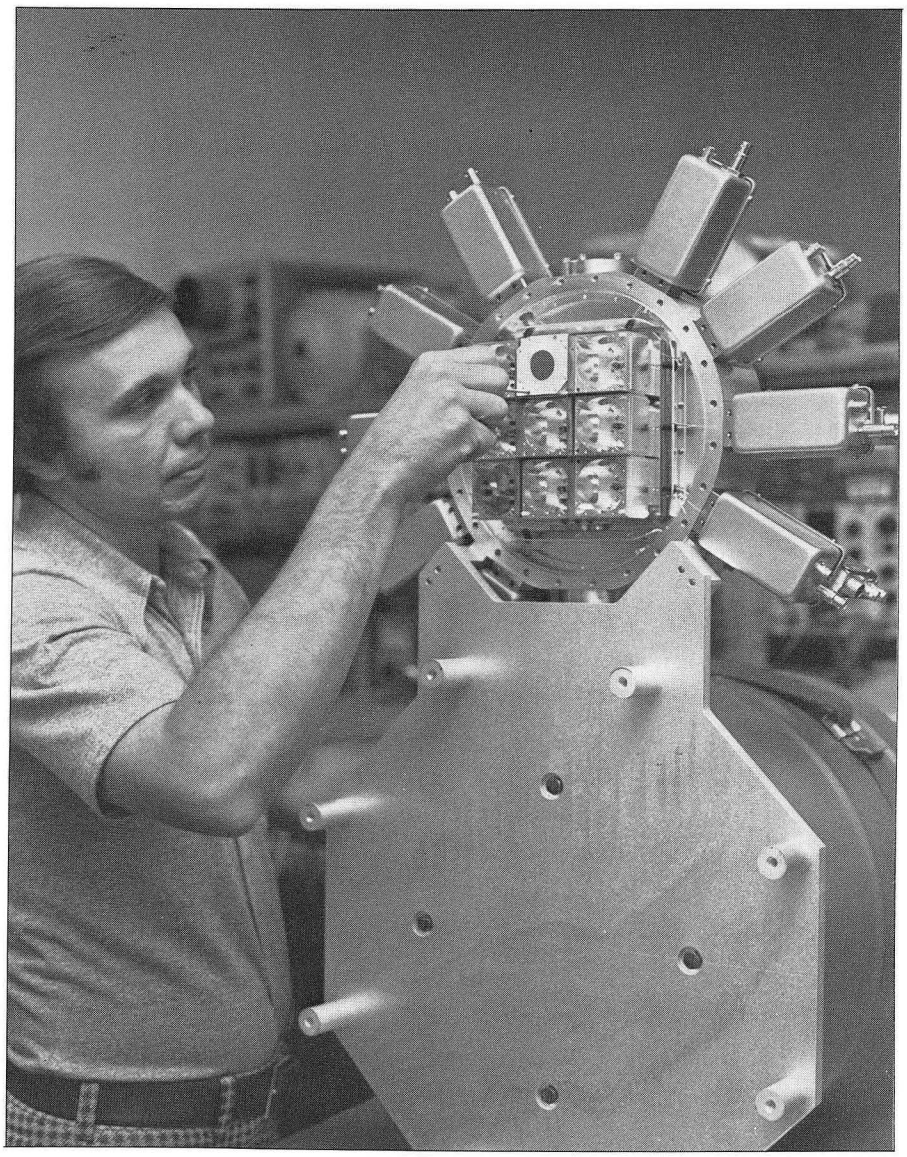


piece of germanium having a net electrical impurity concentration of 10^{10} atoms/cm^3 and being operated at 85 K. This example applies to both p and n type germanium because the mobility of holes and electrons in germanium is nearly equal in this temperature region. If ohmic contacts (which permit free exchange of both types of carriers at the contacts) are made to its faces the germanium slice behaves as a resistor between the contacts. Its resistance is only about 2000 ohms, so if 2000 volts (a reasonable bias for this sized detector) is applied across the contacts a current of one amp will flow. For high-resolution gamma-ray spectroscopy significant resolution degradation occurs when the leakage current exceeds about 4×10^{-9} amps.

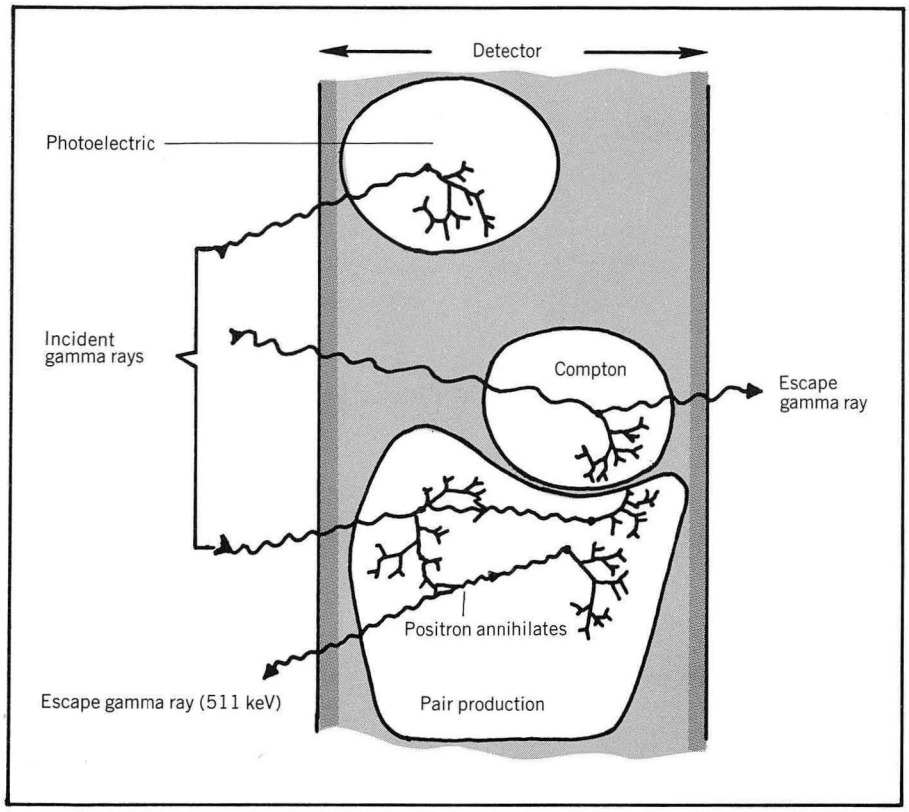
Another very important aspect of the fabrication of detectors relates to the problem of surface leakage current. The surface itself represents a major disturbing effect penetrating well into the germanium, and the absorption of various chemical species on the surface modifies the electrical effect of the surface. Very severe leakage and breakdown problems can result from these surface effects. Therefore, proper chemical treatment of the surface, and suitable methods of protecting the surface from ambient changes, are essential considerations in detector fabrication.

Charge production and collection

When gamma rays enter a detector, any of three primary interactions may take place between the gamma rays and electrons: a photoelectric interaction, a Compton collision, or pair production (see figure 2). Whereas a photoelectric event produces an amount of ionization corresponding directly to the gamma-ray energy, Compton events produce a variable amount of ionization. Only if the de-



Mounting one of the germanium detectors in the nine-detector array now being used as a gamma-ray scanner at the Vanderbilt University Medical Center. Figure 1



Three primary interaction mechanisms between gamma rays and the electrons in a detector. In the photoelectric process nearly all the gamma-ray energy is transferred to the electron, which then produces a hole–electron shower. In the Compton process only a portion of the gamma-ray energy is given to the electron. Pair-production requires the expenditure of 1022 keV to produce an electron–positron pair; this energy reappears as a pair of 511-keV gamma rays when the positron annihilates. One or both of these 511-keV gamma rays may escape from the detector; the ionization signal will therefore depend on whether single or double escape occurs. Figure 2

graded (less energetic) secondary gamma ray is fully absorbed is useful information about the distribution of gamma-ray energies obtained from Compton interactions. As a result of this process a general "Compton background" is observed in gamma-ray spectra.

These interactions produce one or more electrons having considerably more energy than the thermal energy of electrons in the germanium. These "primary" electrons rapidly achieve thermal equilibrium with other electrons, losing their energy by several processes, one of which is the production of energetic holes and electrons that themselves produce further ionization. The expenditure of energy in creating hole–electron pairs, together with that lost in competing processes, is expressed in terms of the parameter ϵ, the average energy required to produce a hole–electron pair. However, for a given energy absorbed in the primary interaction, the total number of hole–electron pairs created is subject to statistical fluctuations due to the random energy-loss division between the ionization process and competing processes. Any process that consumes energy without producing ionization is worthless from the point of view of electrical signal production. This sharing is described in terms of the Fano factor F, a smoothing factor applied to Poisson statistics to obtain the value of the fluctuations in the ionization produced. If the average number of charge carriers produced is E/ϵ, where E is the energy absorbed in the detector, the standard deviation in that number is

$$\sigma = \left(F\frac{E}{\epsilon}\right)^{1/2}$$

If no competing energy loss processes occurred, the total absorbed energy would be used in producing ionization, and no statistical fluctuations would occur in the signal. This corresponds to $F = 0$. Conversely, if ionization processes were rare compared with other energy-loss processes, normal Poisson statistics would prevail, corresponding to $F = 1$. The actual situation lies between these extremes. Small germanium detectors (<1 cm^3) have exhibited measured Fano factors as low as 0.08[1], but larger detectors tend to exhibit values nearer 0.13.

The dependence of the energy band gap on temperature is reflected in a change in ϵ with temperature. This is illustrated in figure 3, which shows the behavior of ϵ for germanium over a wide temperature range.[2]

Trapping effects

Despite the extreme perfection of the germanium crystals grown for detector fabrication, the presence of centers capable of trapping holes or electrons constitutes a major problem in producing detectors for high-resolution gamma-ray spectroscopy. Possible trapping centers include impurities and crystal imperfections (for example, vacancies). The depth of a trap determines the "detrapping time," the average time a carrier remains trapped before being released by thermal excitation. If the detrapping time in a detector is very short compared with the pulse-shaping times used in the amplifier, trapped carriers will be released quickly enough to contribute to the total signal and are not lost. However, if the detrapping time is comparable to, or larger than, the pulse-shaping times, the trapped carriers are partially or completely lost so the output signal is deficient of these carriers. Because the location of the initial charge production and variations in the concentration of traps at different points in the detector cause the loss of signal to change from one event to another, a fluctuation in output signal results. Frequently these signal fluctuations are dominant in determining the energy resolution of a detector. Consequently, considerable effort must be devoted to selecting crystals relatively free of trapping.

Since the amount of charge lost by trapping is almost proportional to the total charge produced, the effect on the spectral line width increases as the gamma-ray energy increases. Consequently, trapping becomes a relatively more serious problem at high energies. A detector that is acceptable for 100-keV measurements may perform very poorly when measuring 5-MeV gamma rays.

The first germanium gamma-ray spectrometer was made in 1962.[3] At that time the highest-purity germanium produced by standard zone-leveling and crystal-growing techniques contained about 10^{12} impurities (either acceptors or donors) per cubic centimeter. Application of reasonable voltages to a detector made from this material produces a depletion layer only 0.5 to 2 mm thick; consequently such detectors have low efficiency for absorbing gamma rays.

The inherent limitations of this material were circumvented by "lithium drifting," a process for compensating acceptor impurities with an interstitial donor (lithium). By this method germanium (and silicon) can be produced with thick regions that exhibit extremely low net impurity concentrations; less than 10^9 net impurities per cubic centimeter are routinely obtained.

To make lithium-drifted detectors, lithium is evaporated onto and diffused into the face of a piece of p-type germanium at about 400°C to produce an n–p junction; then with the temperature held high enough for the lithium ions to be reasonably mobile (20° to 50°C), a positive voltage (around 500 volts) is applied

to the lithium-doped side of the junction. Lithium ions drift in the electric field in such a way that they almost exactly compensate the acceptor impurities in the material; in a week or two, a compensated region about a centimeter thick is produced.

Germanium detectors having very large volumes can be made by means of the coaxial-drift technique, whereby lithium is drifted from the outer surface of a cylindrical block of germanium towards the middle of the crystal. The drift process is terminated when a suitable (typically 7-mm diameter) core of the original p-type material remains. This core provides the p contact for the detector. The large sensitive volume (up to about 150 cm^3 is fairly common, and up to about 200 cm^3 has been fabricated occasionally) obtainable in the coaxial configuration increases the probability of high-energy γ-ray absorption by one or more Compton-scattering interactions followed by photoelectric events. (Germanium detector manufacturers generally express the full-energy peak efficiency of their detectors relative to the efficiency of a 3-by-3-inch NaI (Tl) crystal. A Co^{60} source having a known disintegration rate is placed 25 cm from the face of the germanium detector, and the count rate in the 1.33-MeV peak is measured. The absolute efficiency determined from this measurement is then divided by 1.2×10^{-3}, which is the calculated absolute efficiency of a NaI(Tl) crystal 25 cm from the source.[4]) Furthermore, the surface-to-volume ratio is small, thereby reducing the relative effect of surfaces on charge collection and leakage current.

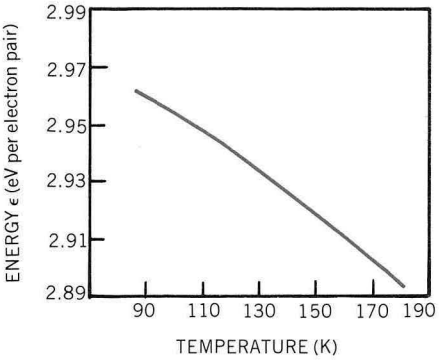
In spite of the value of lithium for compensating impurities there was great interest in producing germanium pure enough to make lithium-drifting unnecessary. A major change in germanium detector technology occurred, and is still occurring, as a result of the development of high-purity germanium.[5,6] (Detectors made from this material are often incorrectly called "intrinsic" germanium detectors. At the low temperature required for detector operation even the extremely high-purity germanium now available is extrinsic, not intrinsic. Thus detectors made from this material are more appropriately called "high-purity".) Germanium with net electrically active impurity concentrations in the 10^{10} atoms/cm^3 range (note that this corresponds to an impurity of only 1 part in 10^{13}) became available; thus thick detectors could be fabricated without requiring lithium compensation. The depletion-layer thicknesses achieved when a reverse bias is applied to planar diodes made from germanium of various impurity concentrations are presented in figure 4. For example, the application of 600 volts to a diode made from germanium having a concentration of 10^{10} acceptors or donors/cm^3 produces a 1-cm depletion thickness. Of course one would like to be able to apply sufficient overvoltage that the elective field at the back contact is high enough for good charge collection. Normally about 500 volts overvoltage on a 1-cm-thick detector is desired. From this figure you see that germanium having impurity concentrations less than about 3×10^{10} atoms/cm^3 is required for detectors 1-cm thick when reasonable voltages are applied.

Several significant advantages result from the avoidance of lithium drifting. The lengthy drift process with all its attendant problems is not required. This simplifies the fabrication procedure, but a much more important advantage is that the detector can be manipulated at room temperature with far fewer problems. The movement of lithium, which occurs in germanium at room temperature, makes the logistics of manipulating lithium-drifted germanium detectors a major problem. The availability of high-purity germanium has opened up the possibility of employing arrays of detectors to provide large-area coverage and increased detection efficiency. Although the cost of high-purity germanium is still significantly higher than germanium appropriate for lithium drifting, high-purity germanium detectors are rapidly replacing lithium-drifted germanium detectors in many applications.

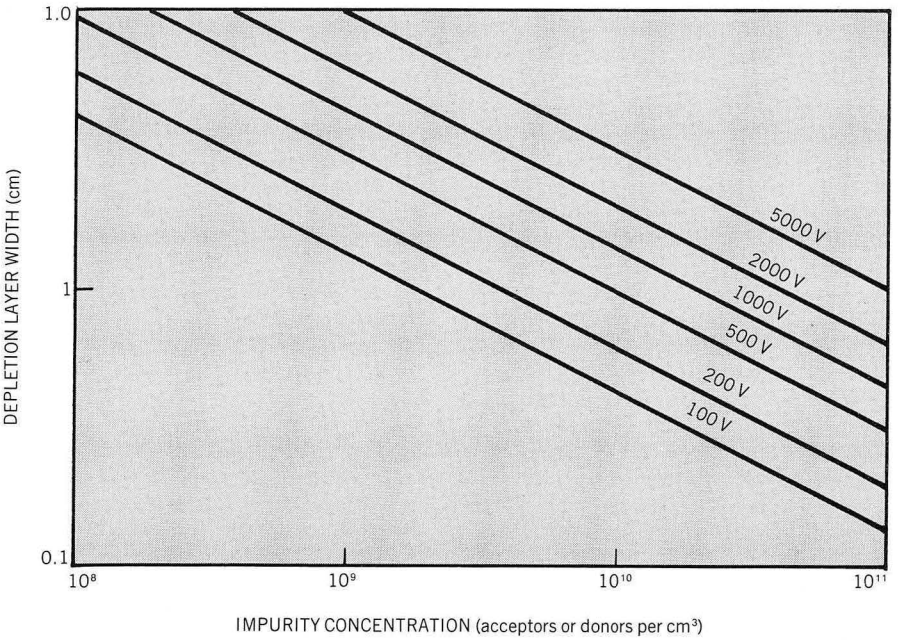
The fabrication methods for high-purity germanium detectors are similar to those used for lithium-drifted detectors except for the lithium-drifting step. A lithium-diffused n^+ surface layer is the simplest and most rugged n^+ contact. Excessive diffusion temperatures must be avoided to prevent diffusion of copper (always present in the surrounding environment) into the germanium with consequent charge trapping. Experience shows that diffusion temperatures as low as 180°C can be employed successfully, although 280°C is more typical. The contrast with the diffusion temperature required prior to lithium drifting is presumably due to the reduced demand for lithium in high-purity detectors, where it merely provides the n^+ contact, and does not act as a source for the drift-compensation process.

No deterioration of the lithium contact due to lithium precipitation in detectors that have been stored at room temperature for several years has been discernible. The only negative aspect of the lithium contact is its thickness, a few hundred microns. This effective dead layer prevents the optimum stacking of detectors for charged-particle counter telescopes, but causes no problem for detectors used for gamma-ray spectroscopy.

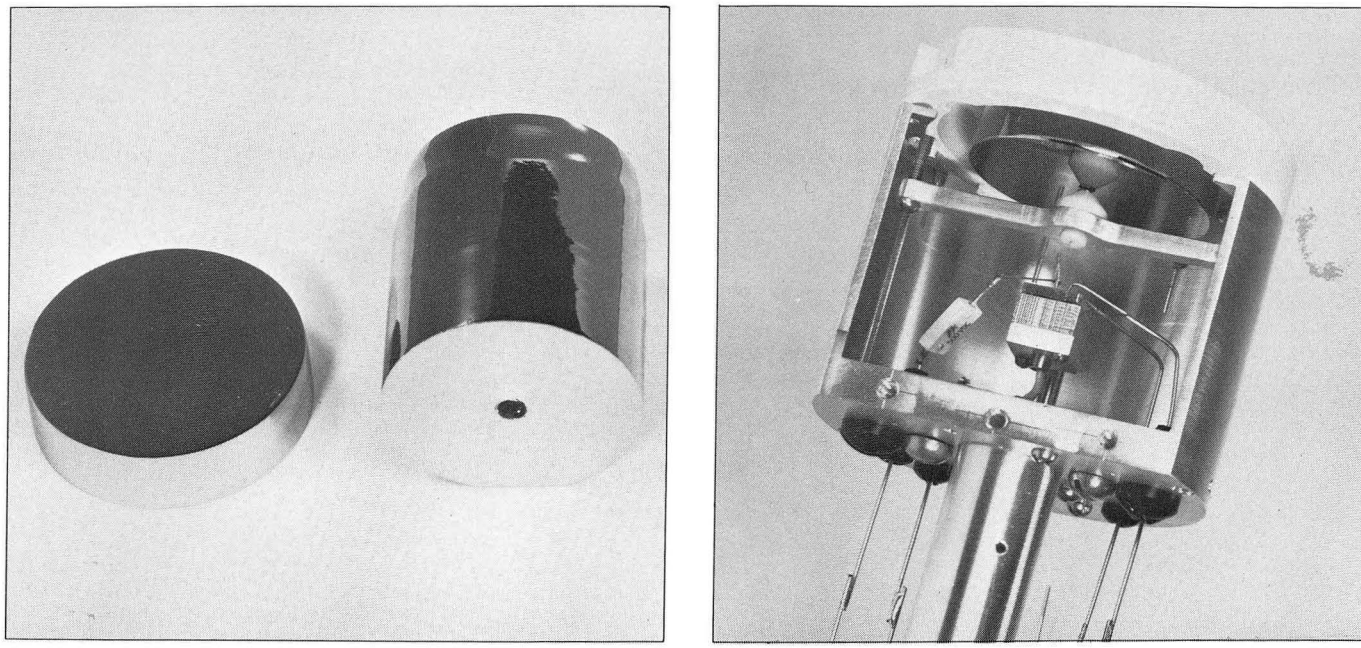
High-purity germanium detectors are



Variation of ϵ, the average energy required to produce a hole–electron pair, with temperature for germanium. Figure 3



Depletion-layer width as a function of applied voltage and impurity concentration for planar diodes made from high-purity germanium. Figure 4



High-purity germanium detectors. The left photograph shows two common detector geometries; on the left is a planar detector that uses the full area of the germanium wafer, and a coaxial detector is on the right. The right photograph shows the heart of a germanium gamma-ray spectrometer. A part of the aluminum heat shield has been removed to expose a planar detector and the electronic components that make up the cooled first stage of a pulsed optical feedback preamplifier. Within the small aluminum block visible in the center of the picture (to which the wires are attached) can be seen a field-effect transistor and a light-emitting diode. Figure 5

normally used in a totally depleted condition with a considerable overvoltage applied to achieve a high electric field throughout the detector. A good blocking contact is therefore required for the face opposite the n^+ side of the detector. Although good blocking contacts have been achieved by using a number of metal surface barriers, a boron implanted p^+ contact has proven to be most reliable.

These fabrication methods work equally well on both p and n type germanium.

While the planar geometry is the most convenient one to use, the geometrical advantages of the coaxial structure are important just as in lithium-drifted detectors. However, the equivalent of the undrifted central core of lithium-drifted coaxial detectors does not exist in a coaxial detector made from high-purity germanium. Consequently, a central core of material must be removed, and a contact put on the inside surface of the detector. Although this is not easy to achieve, successful coaxial detectors have been fabricated from both p and n type material. With p type material the lithium-diffused n^+ contact is put on the outside and a metal surface barrier in the core. For n type material the lithium-diffused contact is in the core while the metal surface barrier or boron-implanted p^+ contact is put on the outside. Figure 5 shows two common high-purity germanium detector geometries and the internal construction of a germanium gamma-ray spectrometer.

High-purity germanium crystals are now available up to 6 cm in diameter. Thus coaxial detectors up to almost 200 cm^3 are feasible. However, for many applications coaxial detectors made from smaller diameter crystals are preferable because charge carriers then move a shorter distance on the average.

Some illustrative detector applications

Germanium gamma-ray detectors are now applied to a very wide range of problems. The combination of relatively low cost, excellent energy resolution, and simultaneous broad energy-spectrum analysis is uniquely suited to many applications in both basic and applied physics. A comprehensive review of these applications is far beyond the scope of this article. Instead, a few applications that illustrate the present and future potential of germanium detectors will be presented.

Although the use of semiconductor detectors in x-ray spectrometers has revolutionized, and to a large extent created, the field of x-ray fluorescence analysis in recent years, these spectrometers normally employ lithium-drifted silicon detectors, and this general application will not be discussed here. Germanium detectors provide slightly better energy resolution than silicon detectors because ϵ is about 26% larger in silicon, and the measured Fano factor is typically smaller in germanium. However, the fairly intense germanium x-ray escape peaks severely limit the usefulness of germanium spectrometers as analytical tools if photons in the energy region from 11.1 to about 30 keV are present. Furthermore, the entrance windows on germanium detectors severely degrade the performance of germanium spectrometers at x-ray energies under about 3 keV.[7]

Since the development of the first germanium detectors they have been extensively used for nuclear decay-scheme studies. In the analysis of complex gamma-ray spectra with a single germanium detector, the Compton background can often significantly diminish the ability to analyze peaks corresponding to relatively low-intensity low-energy gamma rays. This Compton continuum can be drastically reduced by surrounding the germanium detector by plastic or NaI(Tl) scintillators operated in anticoincidence with the germanium detector. This technique is also very important for many studies requiring low background counting.[8]

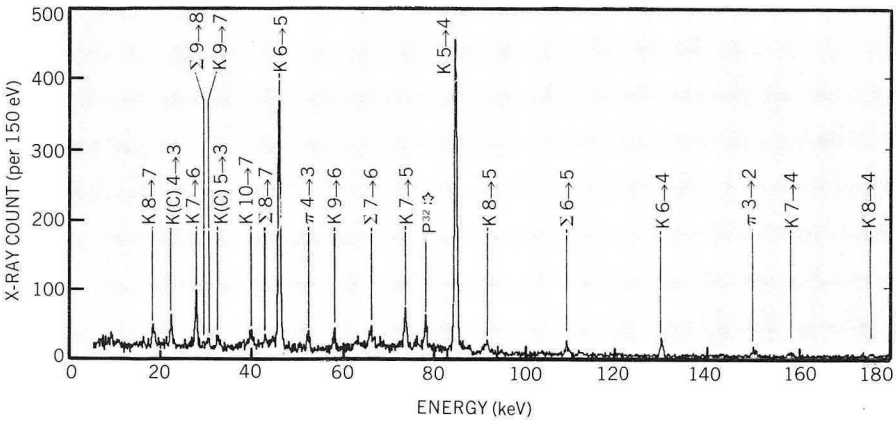
At high gamma-ray energies the spectra are further complicated by the presence of single—and double—escape peaks along with the full-energy peak. The use of a pair-spectrometer simplifies these spectra by enhancing the double-escape peak relative to the other peaks and the Compton background. The germanium detector is surrounded by one or more pair of NaI(Tl) scintillators, and the spectrometer counts only those events that result in pulses in coincidence with the positron annihilation gamma rays detected by the scintillators.

The availability of large-volume germanium detectors permits coincidence measurements between these detectors. A true-to-random coincidence ratio that would be impossible for scintillators is easily attained because of the excellent energy resolution.

Exotic-atom x rays

An exotic atom is formed when one of the electrons is replaced with a different negatively charged particle. Seven neg-

ative particles are capable of substituting for the electron, and so far five of them have been successfully used—muons, pions, kaons, sigma hyperons, and antiprotons. Because these particles are much heavier than electrons their orbits are so small that they may overlap the nucleus itself, acting as a sensitive probe of the fields close to the nucleus and of the nuclear surface. Germanium spectrometers have made a great contribution to this field by providing the energy resolution necessary to observe the x-ray spectrum generated as these particles cascade inward, from orbit to orbit, toward the nucleus.[9] Figure 6 shows a spectrum from the first significant physics experiment to use a high-purity germanium detector. It is also the first spectrum to show a kaonic induced nuclear gamma ray; in addition x-ray transitions from three different types of exotic atoms can be seen. The data were accumulated during three consecutive days of continuous running of the Bevatron.



Kaonic x-ray spectrum of chlorine, with some x rays from pionic and sigma hyperonic atoms shown also. The star labels a kaonic induced nuclear gamma ray. The numbers indicate which orbits were involved in each transition: K 8 → 7, for example, means that the transition was made by a kaon jumping from its $n = 8$ orbit to its $n = 7$ orbit. Figure 6

Exotic atoms are expensive to make, especially those other than muonic and pionic atoms. Consequently, there is considerable benefit in obtaining a high detection efficiency for the emitted x rays. We have provided two arrays of high-purity germanium detectors to be used for these studies; one array consists of three, the other of four, planar detectors. Multiple-detector arrays in the same cryostat allow more detectors near the target than would be possible with each detector in a separate cryostat.

Multiple-detector arrays

As mentioned previously the availability of high-purity germanium has opened up the possibility of employing arrays of detectors to provide large-area coverage and increased detection efficiency as we have done for exotic-atom x-ray spectroscopy. The effort to mount arrays of lithium-drifted germanium detectors in the same cryostat is vastly greater than that required for high-purity germanium detectors. In fact, arrays of lithium-drifted germanium detectors could never be considered a standard instrument. Fabrication and application of these multiple-detector arrays is probably the major change in the germanium-detector field recently, and is expected to play an ever increasing role in the years ahead. The increased detection efficiency afforded by arrays allows germanium detectors to be used for applications that were previously not practical.

For example, we fabricated an array (figure 1) of nine planar detectors, each 3.5 cm in diameter and 1.0 cm thick, to be used as a γ-ray scanner at the Vanderbilt University Medical Center.[10] Although there has been considerable discussion concerning the merit of germanium gamma-ray detectors for use in nuclear medicine, little clinical application has occurred, largely because the detection efficiency of available systems was insufficient to provide a practical instrument. Our nine-detector array should provide a good clinical test.

Two large arrays of high-purity germanium coaxial detectors have been fabricated by Princeton Gamma Tech for use by a group at the Naval Research Laboratory.[11] The first array consisted of twelve 7% efficient detectors and the second has fifteen 10% efficient detectors. Each detector is mounted in its own vacuum enclosure although all the detectors in an array are connected to a common cold plate attached to a single Dewar. The amplified signals from each detector are fed to a commercially available multiplexer. This kind of operation avoids summing the noise from the detectors and therefore preserves the energy resolution. Each of the twelve individual detectors in the first array has a resolution of better than 2.0 keV at 1332 keV, and when the signals are summed via the multiplexer the resolution is 2.07 keV at 1332 keV. The summed resolution is approximately 1.0 keV in the region 60–120 keV.

Two arrays of four planar detectors for monitoring plutonium in the lungs have been fabricated by ORTEC for use at Rocky Flats. Each of the eight individual detectors is 3.6 cm in diameter and 1.0 cm thick, and has a resolution of better than 650 eV at 60 keV. For measurement of plutonium via the 59.54-keV gamma ray of Am^{241}, the detection capability of the germanium system is about a factor of three better than the detectability of the phoswich system at Rocky Flats. Although pessimism has been expressed concerning the feasibility of using this system for measuring plutonium via L x rays in the presence of Am^{241} or for quantities of Pu^{239} less than one or two Maximum Permissible Lung Burdens (16 or 32 nCi),[12] the overall results have been sufficiently promising that two additional four-detector arrays have been ordered. To increase the detection sensitivity, each detector in the new arrays will have an area of 15 cm^2.

An array of ten planar detectors, each 3.6 cm in diameter and 1.0 cm thick, to be used for measuring plutonium contamination in environmental samples and to grade waste as permanently disposable or retrievable, has been fabricated by ORTEC for use at Hanford. Since easy field serviceability of the system was considered to be more important than packing density each detector is mounted in its own vacuum enclosure, although all are connected to a common cold plate attached to a single Dewar.

Activation analysis

For many years nuclear reactors have been used to "activate" materials. After capturing slow neutrons from the reactors, these materials can be analyzed by observing the γ-rays emitted upon decay of excited nuclear states. This analysis usually involves the evaluation of complex gamma-ray spectra. Consequently, the excellent energy resolution of germanium detectors has proven very profitable to this field of applied gamma-ray spectroscopy.

Among the potential applications of germanium gamma-ray detectors in space is another activation-analysis technique. The surface of an airless planetary object emits gamma rays directly into space. These gamma rays are generated in two ways. First, the naturally radioactive elements thorium, potassium and uranium emit gamma rays either directly or in the course of decay chains. The second source of gamma rays is the interaction of surface material with cosmic rays. These high-energy nuclear particles cause nuclear reactions that result in gamma rays characteristic of the target nucleus. Detection of these characteristic gamma rays by a germanium spectrometer in an orbiting spacecraft provides a measurement of the concentration of many elements in the planetary surface. Spectrometers that are being developed may be used in

possible future missions such as Lunar Polar Orbiter, a Mars orbiter, a Mercury orbiter, outer-planet satellite missions, and rendezvous with asteroids and comet nuclei.

Often in space applications, and sometimes elsewhere, maintenance of germanium detectors near liquid-nitrogen temperature is difficult. Consequently, the energy resolution at higher temperatures is of considerable interest. Figure 7 shows the energy resolution of Co^{60} 1.17-MeV gamma rays measured by a germanium detector over a wide temperature range.[14] A serious degradation of resolution is seen to occur at temperatures above 150 K due to the rapid rise of detector leakage current. This temperature represents a good estimate of the maximum operating temperature of germanium detectors, although a recent study indicates that slightly higher temperatures are possible.[15] However, there is a great advantage in operating germanium spectrometers that will be exposed to significant radiation damage as cold as possible—at least down to liquid-nitrogen temperature.

Radiation damage

Energetic particles can produce interstitial-vacancy pairs (a Frenkel defect) in a crystal by knocking the atoms from their normal positions. Detectors are unique among semiconductor devices in depending on very low concentrations of electrically active impurities, and also on efficient transport of holes and electrons over relatively large distances. Because the dense regions of damage produced by energetic particles may result in donors and/or acceptors, and also provide trapping sites for holes and electrons, detectors are very sensitive to radiation damage. (Compared to fast neutrons and charged particles, the damage caused by electrons and gamma rays is negligible and will not be discussed here.) In addition to these effects occurring within the detector, radiation may also change the characteristics of the exposed surfaces causing unpredictable effects on the detector leakage current. Fortunately, radiation-induced surface degradation has rarely, if ever, been observed for germanium detectors.

Fast neutrons

Although several studies of the radiation-damage effects of fast neutrons on germanium detectors have developed considerable empirical information, little physical interpretation of the electronic effects can be given in terms of microscopic detail due to the limited knowledge of the dynamics of collision-produced vacancies and their coagulation and recombination. The following discussion summarizes our picture.

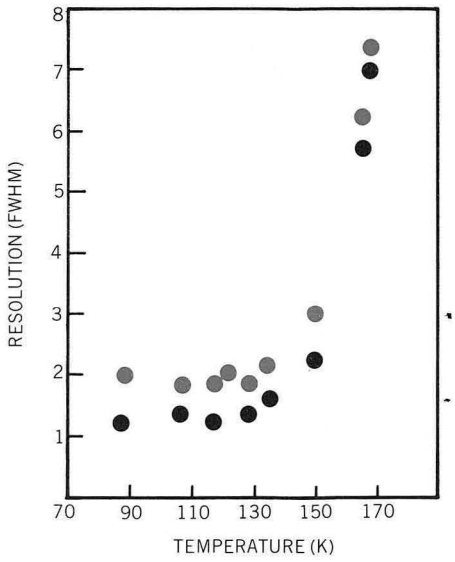
Significant energy-resolution degradation in 1-cm thick planar germanium detectors, both lithium-drifted and high-purity, occurs after irradiation by between 10^9 and 10^{10} n/cm^2 of 5-MeV neutrons.[16] A wide range of damage sensitivities (a factor of about ten) exists among high-quality detectors made from different germanium crystals. Unfortunately, the crystal parameter (or parameters) that is (or are) responsible for this wide range is not presently known.

Small changes in the energy resolution take place after irradiation while the detectors remain near liquid-nitrogen temperature. This is not inconsistent with the fact that some vacancy mobility exists at this temperature. Therefore, spectral degradation resulting from irradiation may exhibit a dependence on neutron dose-rate as well as fluence, although in most situations this will not be an important factor.

Complete collapse of the energy resolution occurs when high-purity germanium detectors are annealed at 200 K, dry-ice temperature. The acceptor concentration is greatly increased after the dry-ice anneal and decreases with further high-temperature anneals. From a practical viewpoint, it is obvious that if a germanium detector has been exposed to a significant flux of fast neutrons it would be imprudent to allow the unit to go through a room-temperature thermal cycle, even though the detector had exhibited no resolution degradation while being maintained near liquid-nitrogen temperature.

Annealing high-purity germanium at 100°C for periods of hours produces a very large portion of recovery. Thus *in situ* annealing of high-purity germanium spectrometers is possible. (To diminish the risk of contaminating the detector surface during *in situ* annealing, the cryostat should be connected to a good, clean external vacuum system. Unfortunately, this step invalidates the warranty on commercial germanium spectrometers. Nevertheless to take full advantage of the attributes of high-purity germanium detectors, properly equipped users must seriously consider the merit of occasionally "repairing" their own detectors.) Although complete recovery may not be obtainable with 100°C annealing the performance should be acceptable for nearly all applications. Complete recovery can be achieved at somewhat higher temperatures, not more than 150°C being necessary.

Hole trapping predominates as the degrading effect on energy resolution. This fact leads to a consideration of the possibility of minimizing hole trapping in charge collection by the use of a high-purity germanium coaxial detector configured with the p^+ contact on the coaxial periphery. The holes then make only a short traversal from the outer portions of the detector (where most interactions occur) to the contact of collection. To establish high fields at the periphery one would want to use n type germanium. A



Energy resolution of a high-purity germanium gamma-ray spectrometer as a function of temperature. Data for the 1.17-MeV cobalt-60 gamma-ray line are in color; black dots are for the pulser. The detector is 3.2 cm diameter, 1 cm thick, at a bias of 1000 volts. Figure 7

recent experiment by L. S. Varnell, R. H. Parker, B. D. Wilkins, L. Finnin, M. Fong, A. E. Metzger and myself with high-energy protons has provided a strong indication that such a coaxial configuration is very beneficial for detectors that will be radiation damaged. Unfortunately, standard lithium-drifted coaxial detectors and all commercial high-purity coaxial detectors are configured with the n^+ contact on the coaxial periphery. Consequently, they are extremely vulnerable to radiation damage.[17]

Charged particles

Until recently no radiation-damage measurements of germanium detectors comparable to those made with fast neutrons had been made with charged particles. Motivated by the possible use of germanium gamma-ray spectrometers for astronomical and planetological observations on extended space missions we have undertaken a program to study the radiation-damage effects of high-energy charged particles. This program has been initiated by the exposure of six high-purity germanium planar detectors and one high-purity germanium coaxial detector to a flux of 6-GeV/c protons.

These protons caused about 60 times more damage than did 16.4-MeV neutrons;[18] the degradation observed at 3×10^9 n/cm^2 was equal to the degradation observed at 5×10^7 p/cm^2. This difference is roughly consistent with the calculated number of defects expected.

Although the spectrometer performance of the detectors was considerably worse following the proton irradiations than it was following the neutron irradiations, the detectors annealed far more easily (lower temperature and/or shorter time), indicating a different damage

mechanism for much of the damage.

The energy resolution of the coaxial detector, configured with the p^+ contact on the coaxial periphery, degraded considerably less than did the energy resolution of a planar detector fabricated from the same germanium crystal when the high-energy proton beam passed through both detectors. If the n^+ contact had been on the coaxial periphery we would have anticipated the energy resolution of the coaxial detector degrading much more than the energy resolution of the planar detector. Although additional experiments must be done, it now appears that coaxial germanium detectors having the n^+ contact on the coaxial periphery should not be used on extended space missions, or in any situation subject to radiation damage.

* * *

This work was performed under the auspices of the US Department of Energy.

References

1. R. H. Pehl, F. S. Goulding, Nuc. Inst. Meth. **81,** 329 (1970).
2. R. H. Pehl, F. S. Goulding, D. A. Landis, M. Lenslinger, Nuc. Inst. Meth. **59,** 45 (1968).
3. D. W. Freck, J. Wakefield, Nature **4816,** 669 (1962).
4. R. L. Heath, *Scintillation Spectrometry Gamma-Ray Spectrum Catalogue,* 2nd ed., Vol. I, IDO-16880-1, AEC R & D Rep. Phys. TID-4500, 31st ed. (1964).
5. R. N. Hall, T. J. Soltys, IEEE Trans. Nuc. Sci. **NS-18,** 160 (1971).
6. W. L. Hansen, Nuc. Inst. Meth. **94,** 377 (1971).
7. J. Llacer, E. E. Haller, R. C. Cordi, IEEE Trans. Nuc. Sci. **NS-24,** 53 (1977).
8. N. A. Wogman, IEEE Trans. Nuc. Sci. **NS-23,** 1214 (1976).
9. C. E. Wiegand, Scientific American, May 1972, page 102.
10. J. A. Patton, R. R. Price, F. D. Rollo, A. B. Brill, R. H. Pehl, to be published in IEEE Trans. Nuc. Sci. **NS-25,** No. 1 (1978).
11. K. W. Marlow, G. W. Phillips, F. C. Young, Proceedings of ERDA Symposium on X- and Gamma-Ray Sources and Applications, CONF-760539, 94 (1976).
12. R. B. Falk, Proceedings of the Workshop on Measurement of Heavy Elements In-Vivo, BNWL-2088, 229 (1976).
13. E. L. Haines, J. R. Arnold, A. E. Metzger, IEEE Trans. Geoscience Electronics, **GE-14,** 141 (1976).
14. R. H. Pehl, E. E. Haller, R. C. Cordi, IEEE Trans. Nuc. Sci. **NS-20,** 494 (1973).
15. G. H. Nakano, D. A. Simpson, W. L. Imhof, IEEE Trans. Nuc. Sci. **NS-24,** 68 (1977).
16. H. W. Kraner, R. H. Pehl, E. E. Haller, IEEE Trans. Nuc. Sci. **NS-22,** 149 (1975).
17. P. H. Stelson, A. K. Dickens, S. Raman, R. C. Trammell, Nucl. Inst. Meth. **98,** 481 (1972).
18. R. H. Pehl, L. S. Varnell, A. E. Metzger, to be published in IEEE Trans. Nuc. Sci. **NS-25,** No. 1 (1978). □

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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