Presented at:
1981 Nuclear Science Symposium
21-23 October 1981, San Francisco, CA

BNL 30616

CONF-811012--56

MASTER

RADIATION DAMAGE IN SEMICONDUCTOR DETECTORS*

H. W. Kraner

Brookhaven National Laboratory
Upton, New York 11973

December, 1981

---

*This research was supported by the U. S. Department of Energy: Contract No. DE-AC02-76CH00016.

BNL--30616

DE82 010248

RADIATION DAMAGE IN SEMICONDUCTOR DETECTORS*

H. W. Kraner

Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

A survey is presented of the important damage-producing interactions in semiconductor detectors and estimates of defect numbers are made for MeV protons, neutrons and electrons. Damage effects of fast neutrons in germanium gamma ray spectrometers are given in some detail. General effects in silicon detectors are discussed and damage constants and their relationship to leakage current is introduced.

INTRODUCTION

It is difficult in a short article to deal comprehensively with radiation damage in semiconductor detectors. A considerable number of specific, largely empirical studies have been reported on several detector types and radiations.[1-5] The interpretation of these results must be based on a familiarity with the mature field of radiation effects in semiconductors.[6] In addition, a large body of literature[7] represents the experience of a variety of semiconductor devices in the several radiation fields of interest ("radiation effects"). The science common to these many facets of radiation effects is the interactions of radiation with matter, specifically silicon and germanium.

Descriptions of the interactions and energy loss mechanisms are found in early texts[8-11] and are seldom reviewed in current articles. It may therefore be instructive to briefly review some concepts of important interactions in order to better appreciate the comparison of the effects of several different radiations.

Of the radiation fields one might consider, ranging in specific ionization, or energy loss, from photons to fission fragments, the most common, damaging radiations might be considered to be heavy, swift charged particles such as protons and alpha particles in the MeV range and fast neutrons. To be sure, damage problems arise for more and less heavily ionizing radiations, but not with the frequency of these often encountered fluences. Heavy charged particles are often a primary source and fast neutrons are a common background. The effects of slower heavy ions at the low energies and high fluences pertinent to ion implantation constitute an entirely separate area of radiation damage which is not pertinent to detector damage. Some mention will be made about the interaction and effects of fast electrons which are often encountered but seldom seriously affect radiation detectors. Electrons are useful, however, to introduce "light" damage (individual isolated defects) in damage studies.

Radiation damage refers to the effect of a radiation which produces atomic displacements in the crystal lattice. An isolated, "Frenkel defect" consists of a displaced atom, now an interstitial, and its vacancy. Further, a wide spectrum of relatively stable defect structures such as vacancy-impurity pairs, vacancy-vacancy pairs, interstitial-impurity atom pairs and multiple vacancy "clusters" are known which produce anomalous electronic states characterized by specific levels in the band gap. The changes in the electronic properties of the semiconductor are interpreted by the defect levels in the band gap which are often deep levels with behavior unlike the more common shallow dopant levels which are mostly ionized (active) and contribute to either the properties of a junction on the degree of compensation of the device. Deep defect levels behave as carrier traps, which can reduce the charge collection efficiency (energy resolution), the carrier mobility or can change the majority carrier concentration and affect the apparent material resistivity. Certainly the great variety of defect structures will produce a wide range of electronic defect levels with a wide range of effects on the device. Because of the extreme variety of irradiation fluences, energies and effective annealing conditions, the particular defect levels in band gaps (which are often still controversial) will not be discussed.

INTERACTIONS

The simplest parameters to be considered in a collision between an incident particle of mass M_1 and energy E_o with a lightly bound atom of mass M_2 is the maximum energy T_M that can be transferred kinematically. In this case, the incident particle is "back scattered" in the direction from which it came.

$$T_M = \frac{4M_1M_2}{(M_1+M_2)^2} E_o \quad .$$

If M_1 is a swift electron, $M_1 = m << M_2$

$$T_M = \frac{4m}{M_2} E_o$$

and if relativistic ($E_o \geqslant mc^2$):

$$T_m = \frac{2(E_o+2mc^2)}{Mc^2} E_o \quad .$$

Listed below are several maximum energy transfers for 1 MeV particles:

Incident Particle, M_1	$T_m(M_2=28,Si)$ (keV)	$T_m(M_2=72,Ge)$ (keV)
electrons	0.155	0.121
1 {protons neutrons}	133	54
16 (oxygen)	926	694

A radiation effect would be expected to have some proportionality to the number of defects produced per incident particle. In a single interaction in which an energy T is transferred, the number of defects ν might be estimated as

$$\nu \sim T/E_d$$

DISTRIBUTION OF TH

---

*This research was supported by the U. S. Department of Energy. Contract No. DE-AC02-76CH00016.

where E_d is an average displacement energy per defect. E_d lies in the range of 15 to 45 eV is often taken as 25 eV (3-4 times a lattice binding energy) for semiconductors.[12]

The distribution of energy transfers T from Rutherford scattering, the elastic collisions to be expected from heavy charged particles is given by

$d\sigma = C\, dT/T^2$ where $E_d < T < T_m$ and

C is $E_d T_m \sigma_o/(T_m - E_d)$. ($\sigma_o$ is a total cross section)

Non-relativistic electrons also undergo essentially elastic, coulombic scattering with

$$d\sigma = C' dT/T^2$$

but C' contains a cross section, σ_o', which is $\sim M_1c^2/2$ less than σ_o, above.

Elastic scattering of fast neutrons, if regarded as isotropic in the center of mass system, transfer energy uniformly

$$d\sigma = C'' dT \text{ where } C'' = \sigma_o''/T_m - E_d \; .$$

It is illustrative to consider the average value of the energy transfer, $\bar{T}$, to an atom of the lattice, the "primary knock-on" (often referred to as PKA) in order to estimate the density of subsequent defects which will result from the PKA:

$$\bar{T} = 1/\sigma_o \int_{E_d}^{T_m} T d\sigma \quad .$$

Thus, we have

$$\bar{T} \text{ (Rutherford, protons)} = E_d \ln(T_m/E_d)$$

$$\bar{T} \text{ (Hard sphere-isotropic fast neutrons)} = T_m/2 \quad .$$

The average value of defects per PKA might then be simply $\bar{T}/E_d$, except that several other effects must be considered. The first and most obvious is that fast neutron elastic scattering is not isotropic, even for energies as low as 2 MeV on light elements such as Si.[13,14] Inelastic events also play a role in the collision process which reduce T by the energy absorbed within the nucleus; inelastic events are better approximated by isotropic scattering, however. A comparison of the energies of primary recoils is made schematically in Fig. 1 for an incident particle energy of 1 MeV and E_d = 25 eV. The very large energy transfer in hard sphere (fast neutron) scattering is evident and the mitigating effects of forward-directed, non-isotropic elastic and inelastic scatterings are sketched in. The relative cross sections of coulombic, Rutherford scattering to the hard sphere value as sketched are not exact but suggests a hard-sphere cross section of 1 barn and a Rutherford cross section for photons on silicon which is cut off for scattering angles of less than ~ 4° which amounts to ~ 5×10^3b. The electron cross section saturates at a value $M_1c^2/2$ less than the heavy particle value.[15]

A third reservation to a simple relationship of number of defects to $\bar{T}$ and E_d lies in the fact that not all the energy given to a recoil or PKA will be used to produce further defects; some fraction will produce ionization leaving the lattice undisturbed. In fact most of the energy of swift energetic particles goes into ionization as we measure the full energy of charged particles in semiconductor detectors linearly with very little "pulse height defect". Kinchin and Pease[15] thoroughly described the energy loss in cascade processes (interactions proceeding from and including the PKA), by placing a firm upper limit (E_i) to the energy for which nuclear, displacement-producing collisions could occur, above which all energy loss was by ionization and would not be included in defect production. Additionally, they noted that the integration of defect production should start from $2E_d$ and not E_d because in the case of identical particles energy transfers between E_d and $2E_d$ result in a free recoil and bound incident particle indistinguishable from before the collision. Finally, Kinchin and Pease showed that for hard-sphere elastic, isotropically-distributed collisions, the total number of defects produced was exactly

$$\bar{\nu} = \frac{\bar{T}}{2E_d}$$

which has strongly influenced the form of subsequent calculations of ν. In more recent calculations the parameter $\bar{T}$ above is usually replaced by an effective energy available to create defects.[16]

The strict upper limit to energy loss by nuclear collisions suggested by Kinchin and Pease has been replaced by a variable factor derived from better understanding of the partition of energy loss between ionization and nuclear collisions developed in several papers by Lindhard *et al.*[17,18] The nuclear $(\bar{\nu})$ and ionization stopping $(\bar{\eta})$ powers have proven to be separately calculable[19] and the fractional energy loss into each as a function of an effective energy parameter ε is shown in Fig. 2. These values represent the case for identical particles (Si recoils in Si or Ge recoils in Ge) and the recoil energies are given along the lower axis. Thus the number of defects to be expected might result from

$$\bar{\nu}(E) = \frac{\bar{E}}{2E_d} = \frac{1}{2E_d} \cdot \frac{1}{\sigma_T} \int_{2E_d}^{T_M} T \cdot L(T) \cdot \frac{d\sigma}{dT}(E,T) \cdot dT$$

where L(T) is the Lindhard-derived fraction of energy available for nuclear collisions and the particular differential cross sections for energy transfer between T and T+dT really may be expanded to contain an angular distribution and kinematic factor.

The number of defects as a function of fast neutron energy has been calculated at 2, 5 and 16 MeV[20] in germanium using optical model-based differential cross sections for elastic scattering and calculated isotropic inelastic cross sections. The details of these calculations are found in the reference; the results are reproduced in tables I and II below.

TABLE I

Neutron Energy (MeV)	Total Cross Section (barns)	$\sigma_{e\ell}$-E_D (b-keV)	σ_{inel}-E_D (b-keV)	$\bar{E}_D$ (keV)
2	3.54	42.6	31.3	20.9
5	3.96	60.59	106.3	42.14
16	3.05	70.45	337.6	133.6

TABLE II

E_o MeV	$\bar{E}_D$ (keV)	$\bar{\nu}=\frac{\bar{E}_D}{2E}$	$\bar{\nu}/N\sigma$ Def./n-cm^{-1}	T (keV)	$\bar{R}$ (Å)*	$\bar{\nu}/\bar{R}$
2	20.9	417	66	29.5	222	1.88
5	42.1	843	146	61.3	390	2.16
16	133.6	2672	361	225.6	1160	2.30

*Ranges from Schiott[21]

The energy available for defects is shown for both elastic and inelastic scattering in Table I which emphasizes the importance of inelastic scattering, heretofore neglected, which is most probably isotropic. Elastic scattering in this case is decidedly not isotropic with greatly reduced energy transfer.

Having given $\bar{\nu}$ for these several fast neutron energies in Ge, Table II offers two possible interpretations to a radiation effect which may occur through either the fourth column, the number of defects per *neutron per cm*, or the last column, which suggests the linear defect density which is little changed with neutron energy.

The calculations can be simply made for 2 MeV neutrons in silicon using the comparatively slight variation (compared with Ge) from isotropicity in cross section found in Ref. 13. The scattering is primarily elastic and one finds, neglecting inelastic events, a damage energy of 33 keV resulting in 1320 defects. Taking an average recoil range of 1360 Å at 120 keV,[21] a defect density of ~ 1/Å is found, comparable to that for Ge in Table II.

In order to make some comparison between radiation types it is convenient to reproduce the calculations of Bulgakov et al.[22] carried out in a similar manner for MeV protons in silicon. Figure 3 illustrates the calculated number of defects per proton per cm as a function of proton ranges for 6.3 MeV protons. Because all protons are identical when viewed from the end of their range,[23] N_d is available for incident proton energies below this value as drawn in by the vertical flags. For 2 MeV protons an integral of this curve gives ~ 20 defects per 50 μm of range considerably fewer and of lesser density than in the case of 2 MeV neutrons in silicon or germanium.

For completeness, 2 MeV electrons should also be considered. The maximum energy transfer T_m in silicon is 155 eV, not much greater than E_d = 25 eV. In fact, E_d is often measured by a threshold effect in some parameter as a function of incident electron energy[9,15] and the threshold is often found to be ~ 600 keV suggesting E_d = 25 eV. The average number of defects from $\nu = T/E_d$ for this value of T_m is thus about 2, still of the order of that for heavy charged particles but given the range of 2 MeV electrons in Si (~ 1 gm/cm^2) one gets only 5 x 10^{-4} defects/μm. It may be useful to summarize the defect densities for these radiations of 2 MeV in silicon:

	Protons	Neutrons	Electrons
Range in Si	50 μm	1/e ~ 8.5 cm (or 0.12 interactions/cm)	0.5 cm
Defects/interaction	20	1320	2
Defects/cm-particle/cm^2	4x10^3	150	4

This table is misleading, however, in that the difference in incident particle ranges varies widely over the size of common detector types. Proton damage would affect a thin surface barrier detector of ~ 100 μm but would not be present at all through the active volume of a several cm thick gamma ray detector which could be uniformly irradiated by fast neutrons and much less affected by electrons (if somehow they were to penetrate the detector housing, etc.). Moreover, the defect density per interaction region - the range of the PKA or incident particle is distinctly greatest for neutrons as has been noted. The linear defect density influences the microscopic type of ultimate, stable defect structure that will become electrically active in the device.

Further, we have listed a linear defect density which better describes the effects of each individual interaction and actually inverts the apparent defect density shown in the preceding table. Neutrons which cause an energetic recoil having a very short range produce a dense "cloud" of defects which might be expected to yield rather different electrical effects in a detector.

It is well known that the vacancy - and to a lesser extent, the interstitial ion - of a Frenkel pair are mobile at the temperatures of irradiation and use of most semiconductor detectors. Some vacancy mobility exists[24] in germanium even at 77°K although a higher mobility can be expected at temperatures elevated from this value. It is therefore not improbable that vacancy "clusters" or large area disordered regions have been postulated and observed for fast neutron damage in semiconductors.[25] only modest agglomeration of vacancies is necessary at the defect densities described above for fast neutron effects for the production of disordered regions (and ultimately "voids") having relatively large extent, hundreds of angstroms, for which the physical cross section will lie in the 10^{-12} cm^2 range. Figure 4 shows an electron micrograph of a large disordered region in silicon with a diameter of ~ 150 Å.[26] The electrical activity of disordered regions of diverse size and density will have a continuous band gap level structure. The lower defect densities produced by charged-particle irradiations are less likely to produce clusters or agglomerations of vacancies (although smaller clusters are to be expected for higher energy transfers of high energy heavy particles or for short-ranged lower energy heavy ions) but will yield structures based on isolated single defects. More stable structures that may be mentioned are divacancies and an array of vacancy or interstitial impurity pairs. Specific defect structures will be expected to produce a specific electrical effect, characterized by a particular defect level in the band gap.

The irradiations which produce damage in semiconductor detectors occur at detector temperatures between 77K and 300K which is a temperature range over which profound annealing of initial defects is known to occur. For example, in germanium, Konopleva[27] has reported greatly reduced material conductivity after annealing fast neutron damage from 77 to 120K; presumably further agglomeration of vacancies fully establishes and activates defect clusters. Whan[28,29] notes the appearance of a specific single defect as the annealing temperature is raised above 200K indicating the breakup of clusters first into smaller clusters and finally less stable isolated defects. Defect stabilities are well studied over a wide temperature range in silicon. "Self-annealing" of various effects may therefore be expected from detectors, especially from room temperature usage. The study of defects in semiconductors is a large and detailed field which is difficult to encapsulate. The conference proceedings referred in Ref. 6 are recommended and in particular a review by Stein of damage in silicon.[30]

EFFECT OF DEFECTS ON SEMICONDUCTOR DETECTOR PERFORMANCE

Defect structures in a semiconductor act as charge traps and are characterized by discrete levels in the band gap. The permanence of the trapping is described by a level depth. The most direct effect of charge trapping is the degradation of energy resolution through loss of a certain fraction of the carriers of either sign produced by radiation in the device. Trap species can be such that either electrons or holes are preferentially trapped for periods at least as long as the pulse processing time, which removes them from the observed signal. Trapping centers can also remove majority carriers or compensate their ionized level such that a significant change in material resistivity is observed.[31] Although this effect is often quoted in the semiconductor literature for higher fluences than are generally encountered as backgrounds for semiconductor detectors, the comparative purity of detector materials keeps them at risk for this effect. A reduction of majority carrier mobility has also been suggested[32,33] as contributing to observed resistivity increases; however this effect is studied at somewhat higher fluences than are of interest here.

Trapping centers effectively reduce the minority carrier lifetime - the lifetime of the carriers created by the radiation. Whereas the charge collection decrement can also be described by a drift length[34] (equal to a drift velocity times lifetime) the formulation of damage in terms of lifetime is of interest primarily through the description of leakage current,[35] (with apologies for a factor of 2):

$$J = q\, n_i\, x_d / 2\tau \ ,$$

which describes a current density caused by generation of carriers across the band gap through a mid-band defect level. As will be mentioned, a common effect in silicon particle detectors is an increase in bulk leakage current which is described in device literature as a lifetime reduction.

The degradation of energy resolution in a thick semiconductor detector is most easily presented if one considers the trapping of one carrier type - for example, holes - by a concentration of traps N_T having a cross section σ_T. In a planar device, a variable charge loss ΔQ will occur depending on whether the interaction event was near the contact to which the holes are attracted (little charge loss) or near the contact from which the holes must traverse the entire detector thickness, x_d. A rectangular distribution of collected charge will replace the single line spectrum expected with limits between the full energy and a full charge loss ΔQ. Thus the energy resolution degradation

$$\Delta E/E \sim \Delta Q/Q = N_T\, \sigma_T\, x_d \ .$$

It is easy to distinguish which - or if - single carrier is being trapped by using a collimated beam of radiation to place the interactions near one contact or the other. It is assumed that radiation deposits its entire energy in one definite region, as in a photoelectric event for x or λ rays. If the energy is distributed throughout the detector, suitable averaging of the charge loss must be made to estimate the resolution degradation.

If $\Delta Q/Q$ is of the order of the resolution of the detector or its electronic system resolution, the rectangular effect on energy resolution may be perceived as the resolution "tail" of an imperfect detector. Unfortunately, the degradation effect appears as a product $N_T \cdot \sigma_T$ within which a distinction between trapping types and concentration cannot be made. Specifically, vacancy clusters of large spatial extent having $\sigma_T \sim 10^{-11}$ cm^2 but few in number will have the same effect as a large number of single defect traps with σ_T between 10^{-13} and 10^{-15} cm^2. These extremes represent the differences expected from the several radiations mentioned previously. The distribution between traps of each disparate type may also change drastically through purposeful annealing - simple temperature cycles - or in-situ annealing at the operating temperature, and may depend critically on the temperature at which the irradiation occurred.

The remaining parameter in the above equation, the detector size, or width, x_d, is also important in defining its sensitivity to radiation damage. Sensitive volumes constrained by a width or depletion depths vary widely over the range of available detector types. It is illustrative to compare the 50 μm depletion depths of silicon surface barrier detectors with the several cm thicknesses of Ge gamma ray spectrometers. Their relative sensitivities to charge loss by radiation-induced traps are directly contained in the distance over which charge must be collected. The effect of high energy protons on thick Ge(HP) detectors observed by Pehl[36] illustrates this point.

Other damage effects will be discussed relative to the particular detector types to be reviewed.

FAST NEUTRON DAMAGE IN GERMANIUM GAMMA RAY DETECTORS

Ge(Li) and Ge(HP) gamma ray spectrometers are often used in experimental environments having a substantial background of fast neutrons which ultimately cause sufficient damage thet requires the detector to be replaced. These effects have been studied empirically for many years, dating nearly to the first introduction of germanium detectors.[1-5] This section will summarize a recent review article devoted principally to damage in germanium detectors.[20]

Aspects of the irradiation peculiar to germanium are the facts that irradiation is carried out at 77K where some decreased mobility of vacancies exists and from which temperature cycling is possible but not expected. Germanium gamma ray spectrometers are large, thick ~ 1 cm devices (mostly coaxial structures) which suggests that charge trapping and energy resolution degradation will be a dominant problem. Effects that have been observed are:

1. Resolution degradation occurs for large, ~ 1 cm thick devices (coaxial or planar) at fluences between 10^9 and 10^{10} n/cm^2.

2. Hole trapping predominates.

3. The step-wise temperature cycling of an irradiated detector is shown in Fig. 4, which have the following distinct features:

    a. Following 10^{10} n/cm^2 1.4 MeV fast neutrons, the ^{60}Co gamma ray energy is degraded to 3.0 keV (from 1 to 2).

    b. Two cycles of device temperature to 200K, dry ice, drastically worsen the resolution to 80 keV FWHM with a distinct one carrier trapping spectrum (3,4). This anneal cycle has been observed by Konopleva[27] and may represent the (further) agglomeration of multiple and single defects into clusters with distinctly greater hole trapping cross sections. Temperature cycling of any high purity detector suspected of neutron exposure should be definitely avoided.

c. Room temperature anneals (6,7) restore some measure of carrier collection efficiency with perhaps single carrier trapping being less evident.

d. Extended anneals to only 100K (9,10) largely restore previous device performance. Initial performance is realized after ≤ 140K anneals for periods of several hours.

4. Figure 6 shows the effect at several fluences of 5.5 MeV fast neutrons on the capacity of a planar high purity germanium detector. The effect of carrier removal in the base material raises the resistivity and effectively "unshorts" the undepleted base region capacity. The geometrical capacity, C_o, is the series capacity of C_b and C_d.

5. Figure 7 plots the observed FWHM of the 1.33 MeV ^{60}Co peak versus fast neutron fluence for planar Ge(HP) detectors exposed to 1.4, 5.5 and 16 MeV neutrons. If a $\Delta E \sim \Delta Q$ of 3 keV is suggested as a measure of the onset of severe trapping, we find roughly a factor of 4 between the fluence required to produce the same effect (N_T) between 1.4 and 16 MeV fast neutrons. This factor bears loose agreement with the fourth column of Table II, Defects/neutron-cm.

6. Some variability in the fluence required for similar resolution degradation which had been observed and attributed to a material effect has been largely explained by Hubbard and Haller[37] who assert the requirement for strict intercomparison of only the detector resolution (excluding the system) at identical applied field strengths.

7. No basic differences in fast neutron damage susceptability have been observed between Ge(Li) and Ge(HP) devices. Although Ge(Li) coaxial detectors were observed to suffer energy resolution degradation at fluences in the 10^7 to 10^8 range in an early study,[5] this susceptability may be attributed to the relatively lower fields used in early detectors. Field strengths in coaxial structures are now comparable to planar devices and coaxial detectors do sustain fluences into the 10^9/cm^2 range.

8. Somewhat in contradiction to the preceding statement, charge collection in coaxial geometry does suffer from an inherently low field near the large area outer contact. The field in a p^+-i-n^+ coaxial structure (Ge(Li), e.g.) varies as 1/r, which is least near the outer periphery. In the usual electrode configuration of Ge(Li) and p-type Ge(HP) detectors, the outer peripheral contact is n^+, biased positively. This forces holes that most likely originate near the periphery of the cylinder (where most of the volume occurs) to make a longer traversal of the detector material than electrons and also requires that the holes start, and are accelerated, in a region of lowest electric field. Moreover, the outer field strength in a p-type base material Ge(HP) detector depleting from the inner coaxial electrode is even less than that of a p-i-n structure as depletion moves from the inner contact to the outer and couples the linearly decreasing field of a junction detector with the 1/r field effect of a coaxial geometry. Most of the volume of a n^+-p-p^+ (inner to outer) Ge(HP) detector can have exceedingly low fields in which holes will spend much of their journey to the inner electrode at velocities below saturation velocity and are thus more subject to trapping. Pehl et al.[38,39] realized that this configuration is the least radiation "hard" and suggested turning the electrode configuration around so that holes are collected in the nearby peripheral contact. Further, if n type high purity germanium is used, the inner to outer structure is n^+-n-p^+ and depletion proceeds from the outer to the inner contact with the high linear field at the depleting contact opposing or complementing the 1/r reduction of the coaxial geometry.

Two closed-end coaxial detectors were fabricated from different portions of the same high purity ingot at positions where the material was respectively p-type and n-type. Radiation susceptability could therefore by directly compared between different material types without extraneous (or irrelevent) factors of having different starting materials. Irradiations up to 10^{11} n/cm^2 were performed with a PuBe neutron source having a central energy of 5 MeV and the energy resolution was observed as the irradiation proceeded; the results are shown in Fig. 8.[40] It can be seen that the n-type coaxial detector retained usable detector performance up to a fluence ~ 30 times that at which the p-type detector was retired. This effect was expected and has provided powerful motivation for the commercial preference for n-type high purity coaxial detectors.

9. The two detectors described above proved to be much more interesting than originally expected. Months after irradiation, having been kept continually at 80K, bias was reapplied and a transient phenomenon in energy resolution[41] was observed in each detector as shown in Fig. 9. These transients were interpreted in terms of trap-filling and detrapping according to the following scenario: The p-type coaxial detector when unbiased provides sufficient majority carriers (holes) to fill the hole traps. Thus when biased initially it yields reasonably good energy resolution which degrades with time as hole detrapping in the depleted material occurs and the hole traps reactivate. On the other hand, the unbiased n-type detector provides no holes to neutralize the traps which, as they detrap, remain unfilled and active negatively charged). Thus, when bias is applied the energy resolution is at its worst, as observed following neutron irradiation. The ionization of test sources serves, however, to fill the traps and the resolution improves at a rate that can be influenced by the external source strength. Darken, et al.[41] interpreted the n-type resolution transient in terms of hole trapping by defect clusters but could best describe the p-type transient by the detrapping of isolated, single defects. Both types of defects could, of course, occur in an unannealed system; however it is somewhat unsatisfying not to have a unified description. In a second paper in which capacitive transients were observed and were interpreted by the type and resistivity changes to be expected from active or neutralized hole traps, Darken, et al.[42] estimate a $N_T \sigma_T$ product of 4×10^{-2} cm^{-1} together with $N_T = 1.7 \times 10^9$/cm^2. Thus σ_T must be 2.5×10^{-11} cm^2 which is far too large to represent an isolated defect but is a cross section expected for a defect cluster. The $N_T \sigma_T$ product also accounts for the resolution degradation observed. The detrapping characteristics of the defect, which would be required to explain the p-type resolution transient, are however not described.

RADIATION DAMAGE IN SILICON DETECTORS

Radiation damage in silicon detectors was studied almost concurrently with their introduction in the early 1960's.[43,44] With the single important exception of Si(Li) x-ray spectrometers which are seldom subjected to hazardous backgrounds, silicon detectors are most used for charged particle detection and their degradation may be due to either the primary source or its contaminants. Dearnely[45] listed the following "allowable" fluences of particles of interest for junction detectors:

Particle	Energy	Fluence
α's	5-50 MeV	$10^{10}/cm^2$
protons	5-10 MeV	$10^{11}/cm^2$
electrons	2-5 MeV	10^{13}-$10^{14}/cm^2$
fast neutrons		10^{12}-$10^{13}/cm^2$

Tolerable fluences for Li-drifted detectors were suggested to be one to two orders of magnitude less. Coleman, *et al.*[46,47] observed increased leakage currents as a primary effect in both junction and drifted detectors at fluences about an order of magnitude greater than those above. This discrepancy may be explained by the fact that devices in the latter study were thinner and operated at higher biases. "double peaking" in charged particle spectra was often reported after damage in devices with increased leakage current, which could have been due in part to greatly reduced collecting fields. The effect of carrier trapping on energy resolution is not a prime result of radiation damage (compared to germanium detectors) because of relatively smaller detector dimensions.

Important radiation damage effects are summarized below:

1. Increased leakage currents in both junction and drifted detectors at proton fluences of $\sim 10^{11}$ to $10^{12}/cm^2$.

2. Change of base material resistivity due to majority carrier removal[33,45] at fluences somewhat above this value.

3. "Self annealing" of some defect structures as irradiation is usually carried out at room temperature. Although defect clusters are expected and observed in silicon as in germanium for fast neutron bombardment[48] some modifications may occur with time after irradiation. Smaller, single defect-type structures such as divacancies have been found to be stable to annealing temperatures above 250°C. For the case of fast neutron bombardment in silicon at high fluxes, vast experience of ion implantation is available. Resolution "transients" similar to those described for germanium have been mentioned.[49]

In addition to the ion implantation literature which is relevant, the field of radiation effects in semiconductor devices offers considerable experience to the detector community. The carrier lifetime associated with the "generation-regeneration" leakage current has been found to decrease linearly with fluence $\emptyset$:[50]

$$1/\tau = 1/\tau_o + k_\tau$$

where k is a damage constant to be associated with a particular radiation and effect. The effect of deep level introduction will reduce carrier lifetime and cause an increase in leakage current density ΔJ according to the relationship

$$\Delta J = q\ n_i\ x_d\ k_\tau\ \emptyset/2$$

where q is the charge of the electron, n_i the intrinsic carrier concentration ($1.2 \times 10^{10}/cm^3$ in Si at 300K) and x_d the depletion depth, governing active volume. The damage constant k_τ will be used as defined;[50] it is sometimes cited as an inverse.[51] Van Lint[50] has summarized the damage constant for radiations listed below and several measurements of Srour[52] are included; this summary is represented as Table III.

TABLE III

Radiation	Damage Constant		Reference
	k_τ (cm^2/sec) n-type	Silicon p-type	
Fission neutrons	0.5×10^{-5}	2.5×10^{-6}	Srour[51]
1 MeV neutrons	1×10^{-5}	2.5×10^{-6}	Van Lint[50]
14 MeV neutrons	2×10^{-6}	0.7×10^{-6}	Srour[51]
20 MeV protons	2-10×10^{-5}	1.3×10^{-5}	Van Lint[50]
3 MeV electrons	2-10×10^{-8}	3×10^{-9}	Van Lint[50]
GeV muons	1.4×10^{-7}	-	Heijne[53]
Min. Ionizing protons	3.5×10^{-8}	-	Menzione[54]

These values are taken for the lowest current injection levels and highest material resistivity quoted to provide the best analogy to semiconductor detectors. Consideration of the effects of material impurities and growth types was taken by Van Lint.[50] That the damage constant differs for n and p-type material is a further reminder of the details of the specific deep levels in the band gap that are involved in the "gen-regen" current and that the defects themselves are type dependent.[48] The somewhat lower values of k for 14 MeV neutrons compared with 1 MeV neutrons differs from the calculated number of defects in Ge (Table II) and that expected in Ge; however this difference might be explained by differences in fast neutron interaction cross sections, e.g. a decreased inelastic contribution in Si at 14 MeV.

A line separates the device-derived damage coefficients from two other inclusions from recent reports of damage in silicon by high energy particles. Both Heijne and Menzione have reported leakage current increases in n-type surface barrier silicon strip detectors exposed to GeV muons and protons respectively. Although errors are not quoted, large errors should be assigned to these results when suggesting intercomparisons due to the secondary nature of their derivation. However, from the leakage current increases observed, values of k are derived which are more comparable to the 3 MeV electron values than the more highly ionizing heavy particle values as is to be expected.

A short study with high energy particle exposure has been reported[55] which resulted in two standard transmission-mounted surface barrier detectors being subjected to $\sim 10^{14}$ fast neutrons/cm^2. Greatly increased leakage currents were observed which can be reasonably explained using the above formulation with a representative damage constant. A change in material type from n to p was also observed and could have been expected. Further recent interest[56] in the damage effects from high energy particles has been stimulated by the discovery of cosmic ray-induced errors in semiconductor memories and devices.[57] Examination of this literature and data[58] will add to the understanding and estimation of lifetimes for silicon detectors in high energy physics environments.

ACKNOWLEDGEMENTS

It is a pleasure to thank several collaborators of long standing; R. H. Pehl, G. E. Haller, C. Chasman, and K. W. Jones for their continued interest and contribution. F. S. Goulding provided the opportunity for this survey and V. Radeka has provided continued support for the development of the subject. Their input and efforts are appreciated. T. Ludlam has stimulated recent interest in the effects of high energy radiation on silicon detectors.

References

1. H. W. Kraner, C. Chasman, and K. W. Jones, Nucl. Instr. & Meth. 62 (1968) 173 and "Semiconductor Nuclear Particle Detectors and Circuits", Publication 1593, National Academy of Sciences, Washington, D. C. (1969).

2. F. S. Goulding and R. H. Pehl, IEEE Trans. Nuc. Sci., NS-19, No. 1 (1971) 92.

3. J. Llacer and H. W. Kraner, Nucl. Instr. & Meth. 98 (1972) 467.

4. H. W. Kraner, R. H. Pehl, and E. E. Haller, IEEE Trans. Nuc. Sci. NS-22, No. 1 (1975) 149.

5. P. H. Stelson, A. K. Dickens, S. Raman, and R. C. Trammell, Nucl. Instr. & Meth. 98 (1972) 481.

6. "Radiation Effects in Semiconductors", Paris Royamont, 1964, Academic Press, N.Y. (1965).

   "Radiation Damage in Semiconductors", Paris Royamont, 1964, Academic Press, N. Y. (1965).

   "Lattice Defects in Semiconductors", R. R. Hasiguti, ed., Penn State University Press (1967).

   "Radiation Effects in Semiconductors", F. L. Vook, ed., Plenum Press, N. Y. (1968).

   "Radiation Effects in Semiconductors", J. W. Corbett and G. D. Watkins, eds., Gordon Breach Science Publishers, N. Y. (1971).

   "Radiation Effects in Semiconductors", N. B. Urli and J. W. Corbett, eds., The Institute of Physics, Bristol and London (1977).

   "Defects and Radiation Effects in Semiconductors", The Institute of Physics, Heyden and Son, Inc., Philadelphia, PA (1978).

   "Defects and Radiation Effects in Semiconductors", The Institute of Physics, Heyden and Son, Inc., Philadelphia, PA (1981).

7. IEEE Annual Conferences on Nuclear and Space Radiation Effects, NS-28, No. 6 (1981), NS-27, No. 6 (1980), NS-26, No. 6 (1979), and previous issues.

8. G. J. Dienes and G. H. Vineyard, "Radiation Effects in Solids", Interscience Publishers, N. Y. (1975).

9. D. S. Billington and J. H. Crawford, Radiation Damage in Solids, Princeton University Press, Princeton, N. J. (1961).

10. V. S. Varilov, Effects of Radiation in Semiconductors, Consultants Bureau, N. Y. (1965).

11. V. S. Varilov and N. A. Ukhin, Radiation Effects in Semiconductors and Semiconductor Devices, Consultants Bureau, N. Y. (1977).

12. J. W. Corbett and J. C. Bourgin, Point, Point Defects in Solids, J. H. Crawford and L. M. Slifkin, eds., Plenum Press, NY, Vol. 2 (1975).

13. D. L. Garber et al., Angular Distributions in Neutron-Induced Reactions, Vols. I & II, BNL 400 (1970).

14. D. L. Garber and R. R. Kinsey, Neutron Cross Sections, Vol. II, BNL 325 (1976).

15. G. H. Kinchin and R. S. Pease, Rept. Prog. in Prog. in Phys. 18 (1955) 1.

16. c.f. D. G. Doran, Nucl. Sci. & Eng. 49 (1972) 130.

17. J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, Kgl. Danske Vedenskab Selskab, Mat-Fys. Medd. 33, No. 10 (1963).

18. J. Lindhard, M. Scharff, and H. E. Schiott, Kgl. Danske Vedenskab Selskab, Mat-Fys. Medd. 33, No. 14 (1963).

19. C. Chasman, Symposium on the Penetration of Charged Particles in Matter, National Academy of Sciences, Washington, DC (1970) and BNL 13667.

20. H. W. Kraner, IEEE Trans. Nuc. Sci. NS-27, 218 (1980).

21. H. E. Schiott, Kgl. Danske Vedenskab Selskab, Mat-Fys. Medd. 35, No. 9 (1966).

22. Yu. V. Bulgakov, T. I. Kolomenskaya, N. V. Kuznetsov, V. I. Shulga, and V. A. Zaritskaya, Radiation Effects, 54, 129 (1981).

23. R. D. Evans, The Atomic Nucleus, McGraw Hill, NY (1955).

24. J. W. McKay and E. E. Klontz, "Radiation Effects in Semiconductors" Paris Royamont, 1964, Academic Press, NY (1965).

25. J. H. Crawford and J. W. Cleland, J. Appl. Phys. 30 (1959) 1204.

    B. R. Gossick, J. Appl. Phys. 30 (1959) 1214.

    J. R. Parsons, R. W. Balluffi, and J. S. Koehler, Appl. Phys. Lett. 1 (1962) 57.

    F. L. Vook and R. Balluffi, Phys. Rev. 113 (1959) 62.

    F. L. Vook, Phys. Rev. 125 (1962) 855.

R. F. Konopleva and A. A. Yuferez, Sov. Phys. Semicond. 7 (1974) 1393.

Yu. V. Martynenko, Rad. Effects 29 (1976) 129.

Yu. V. Martynenko, Rad. Effects 41 (1979) 7.

26. M. Bertolotti in "Radiation Effects in Semiconductors", F. L. Vook, ed., Plenum Press, NY (1968).

27. R. F. Konopleva, S. R. Novikov, E. E. Rubinova, and S. M. Ryvkin, "Radiation Damage in Semiconductors", p. 287, Academic Press, NY (1965).

28. R. E. Whan, Phys. Rev. 140 (1965) A690.

29. R. E. Wahn, J. Appl. Phys. 37, (1966) 2435.

30. H. J. Stein, in "Radiation Effects in Semiconductors", J. W. Corbett and G. D. Watkins, eds., Gordon Breach Science Publishers, NY (1971).

31. H. J. Stein and R. Gereth, J. Appl. Phys. 39, 2890 (1968).

32. R. Swanepoil and P. T. Wedgepohl, Radiation Effects 55, 43 (1981).

33. R. Grube, E. Fretwurst and G. Lindstrom, Nucl. Instr. & Meth. 101 (1972) 97.

34. R. B. Day, G. Dearnely, and J. M. Palms, IEEE Trans. Nuc. Sci. NS-14, 487 (1967).

35. S. M. Sze, Physics of Semiconductor Devices, Wiley-Interscience, NY (1969).

36. R. H. Pehl, L. S. Varnell, and A. E. Metzger, IEEE Trans. Nuc. Sci. NS-25, 409 (1978).

37. G. S. Hubbard and E. E. Haller, IEEE Trans. Nuc. Sci. NS-27, 235 (1980).

38. R. H. Pehl, "Germanium Gamma Ray Detectors", Phys. Today 30 (1977) 50.

39. R. H. Pehl, L. S. Varnell, and R. H. Parker, Bull. Am. Phys. Soc. 23 (1978) 71.

40. R. H. Pehl, N. W. Madden, J. H. Elliott, T. W. Raudorf, R. C. Trammell, and L. S. Darken, Jr., IEEE Trans. Nuc. Sci. NS-26, 321 (1979).

41. L. S. Darken, Jr., T. W. Raudorf, R. C. Trammell, R. H. Pehl, and J. H. Elliott, "Mechanism for Fast Neutron Damage of Ge(HP) Detectors", Nucl. Instr. & Meth. 171, 49 (1980).

42. L. S. Darken, Jr., R. C. Trammell, T. W. Raudorf and R. H. Pehl, IEEE Trans. Nuc. Sci. NS-28, 572 (1981).

43. G. Dearnely, IEEE Trans. Nuc. Sci. NS-10, 106 (1963).

44. G. G. George and D. M. Gunnerson, Nucl. Instr. & Meth. 25, 253 (1964).

45. G. Dearnely, Nucleonics 22, 28 (1964).

46. J. A. Coleman, D. P. Love, J. H. Trainor, and D. J. Williams, IEEE Trans. Nuc. Sci. NS-15, 363 (1968).

47. Y. M. Liu and J. A. Coleman, IEEE Trans. Nuc. Sci. NS-19, 346 (1972).

48. O. L. Curtis, "Lattice Defects in Semiconductors", The Pennsylvania State University Press, University Park, PA (1967).

49. P. F. Donovan, in "Semiconductors Nuclear Particle Detectors and Circuits", Publication No. 1593, National Academy of Sciences, Washington, DC (1969).

50. V. A. J. Van Lint, G. Gigas, and J. Berenglotz, IEEE Trans. Nuc. Sci. NS-22, 2663 (1975).

51. J. R. Srour, IEEE Trans. Nuc. Sci. NS-20, 190 (1973).

52. J. R. Srour, S. C. Chen, S. Othmer, and R. A. Hartmann, IEEE Trans. Nuc. Si. NS-26, 4784 (1979).

53. E. Heijne, Meeting on the Miniaturization of High Energy Physics Detectors, Pisa, Italy, 18-20 September (1980); Plenum Press (to be published).

54. A. Menziona, Solid State Detector Workshop, Fermilab, 15-16 October (1981).

55. H. W. Kraner, T. Ludlam, D. Kraus, and J. Renardy, Meeting on the Miniaturization of High Energy Physics Detectors, Pisa, Italy, 18-20 September (1980); Plenum Press, to be published, BNL 28311.

56. J. R. Srour, S. Othmer, A. Bohrsman, and R. A. Hartmann, IEEE Trans. Nuc. Sci. NS-28, 3968 (1981).

J. C. Pickel and J. T. Blandford, IEEE Trans. Nuc. Sci. NS-28, 3962 (1981)

57. J. F. Ziegler and W. A. Lanford, Science 206, 776 (1979).

58. R. N. Hamm, M. L. Rustgi, M. A. Wright, and J. E. Turner, IEEE Trans. Nuc. Sci. NS-28, 4004 (1981).

P. J. McNulty, G. E. Farrell and W. P. Tucker, IEEE Trans. Nuc. Sci. NS-28, 4007 (1981).

Figure Captions

Fig. 1. A comparison of the relative energies of primary recoil atoms for incident 1 MeV electrons, protons and neutrons illustrating the differences in primary interactions. The effects of inelastic scattering and non-isotropic, forward-directed elastic scattering in the case of hard-sphere (neutron) scattering is sketched. Relative cross sections are suggested. The average energy of a primary recoil, $\bar{T}$, is shown. E_d is the average energy required per displacement.

Fig. 2. The fractional energy loss of the recoil ions of interest which is partitioned between ionizing collisions (¯/E) and nuclear, displacement-producing collisions ($\bar{\nu}$/E) derived from Lindhard[17] and reproduced from Chasman.[19] The fractional energy losses are plotted as a function of the dimensionless energy parameter, ϵ, of Lindhard with recoil energies for both Si in Si and Ge in Ge added.

Fig. 3 The linear defect production for 6.3 MeV protons in silicon calculated by Bulgakov[22] as a function of proton range. The starting points for portons of several lesser energies are also shown.

Fig. 4. Electron micrograph of disordered regions in n-type germanium caused by fast neutrons.[26]

Fig. 5. The effect of 1.4 MeV neutron irradiation on a planar Ge(HP) detector and subsequent thermal annealing stages.[4] The 1.33 MeV γ-ray peak from ^{60}Co is used as a representative response; only the shape and width of the 1.33 MeV peak is of importance, the channel position is relative. The features of curves 1-10 are described:

1) preirradiation

2) immediately following 10^{10} n/cm^2

3) 50 keV FWHM following one temperature cycle of ~ 35 hr. at 200K

4) 80 keV FWHM following a second 200K cycle of 15 hr.

6) 40 keV FWHM after 14 hr. at 300K

7) 23 keV FWHM after 78 hr. at 300K

9) 4.2 keV FWHM after 4 hr. at 100C

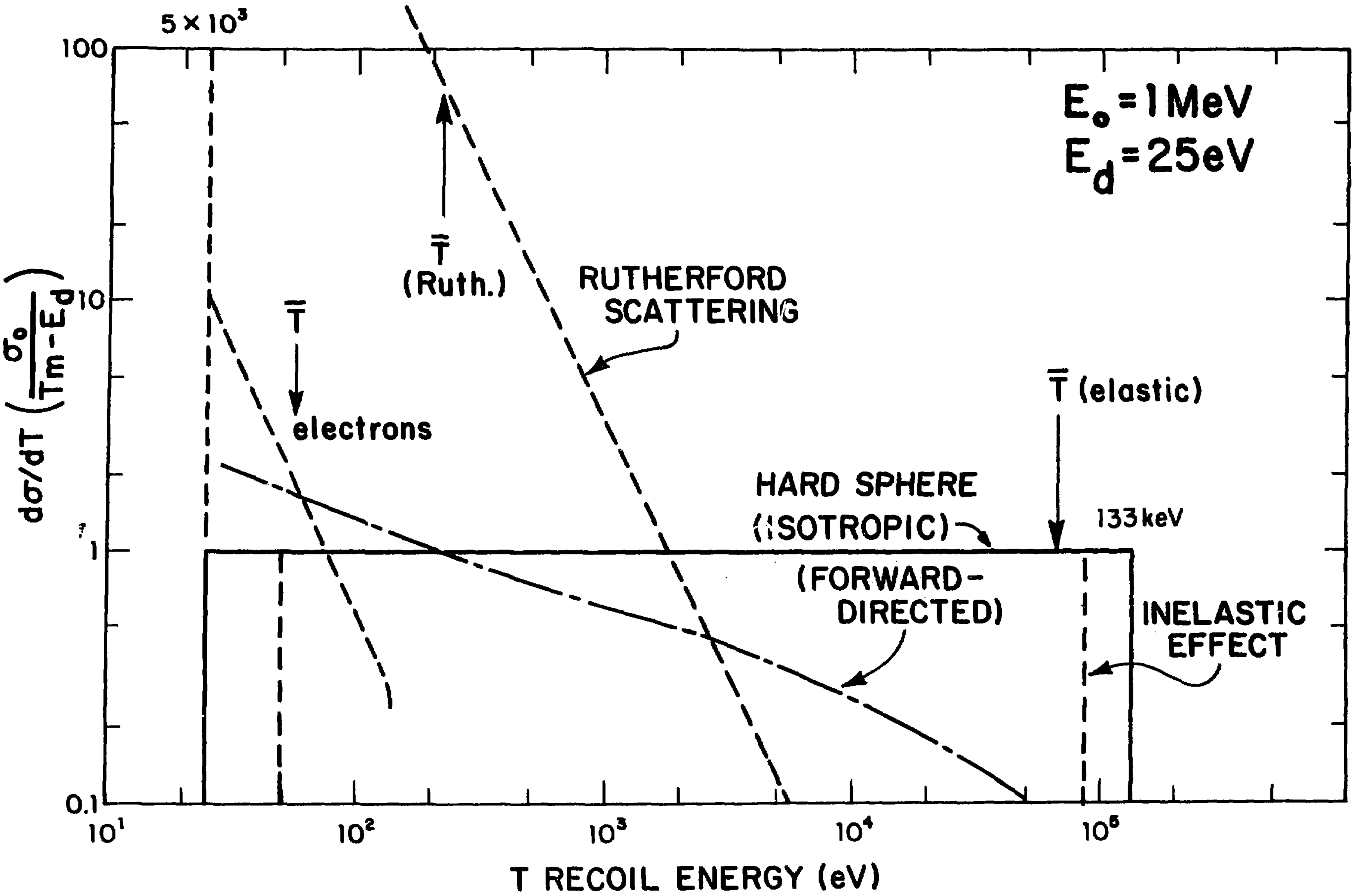
10) 2.1 keV FWHM after 106 hr. at 100C

Fig. 6. The effect of 5.5 MeV neutrons at 1 and 2 x 10^{10} n/cm^2 on the capacitance of a planar Ge(HP) detector.[4]

Fig. 7. The degradation of energy resolution as a function of fast neutron fluence on planar Ge(HP) detectors for neutron energies of 1.4, 5.5 and 16.4 MeV.[4]

Fig. 8. The difference in fast neutron radiation hardness between n and p-type coaxial detectors with different electrode geometries. Detectors reported are from the same ingot which exhibited both n and p-type conductivity in separate regions.[40]

Fig. 9. Energy resolution transients in the n and p-type coaxial detectors that were irradiated with ≤ 10^{10} fast n/cm^2.[41] The energy resolution of the 1.33 MeV ^{60}Co γ-ray is observed as a function of time following application of bias.



5 × 10³
100
10
1
0.1
10¹
10²
10³
10⁴
10⁵
$E_o = 1 MeV$
$E_d = 25 eV$
$d\sigma/dT \left(\frac{\sigma_o}{T_m - E_d}\right)$
T RECOIL ENERGY (eV)
$\bar{T}$ (Ruth.)
RUTHERFORD SCATTERING
$\bar{T}$ electrons
$\bar{T}$ (elastic)
HARD SPHERE (ISOTROPIC)
133 keV
(FORWARD-DIRECTED)
INELASTIC EFFECT

Fig.1.

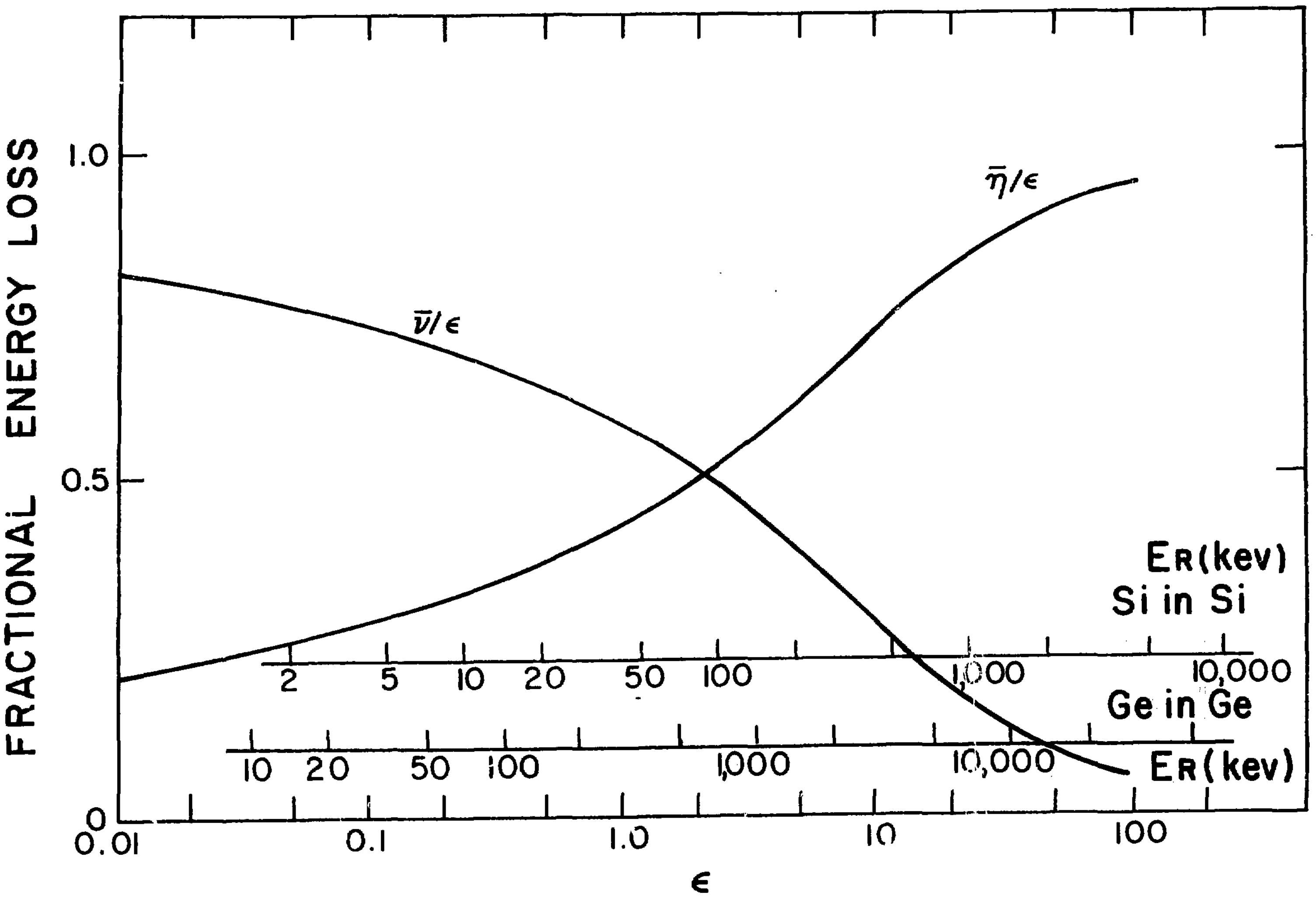

FRACTIONAL ENERGY LOSS
1.0
0.5
0
0.01
0.1
1.0
10
100
ϵ
$\bar{\nu}/\epsilon$
$\bar{\eta}/\epsilon$
ER(kev)
Si in Si
2
5
10
20
50
100
1,000
10,000
Ge in Ge
10
20
50
100
1,000
10,000
ER(kev)

Fig. 2.

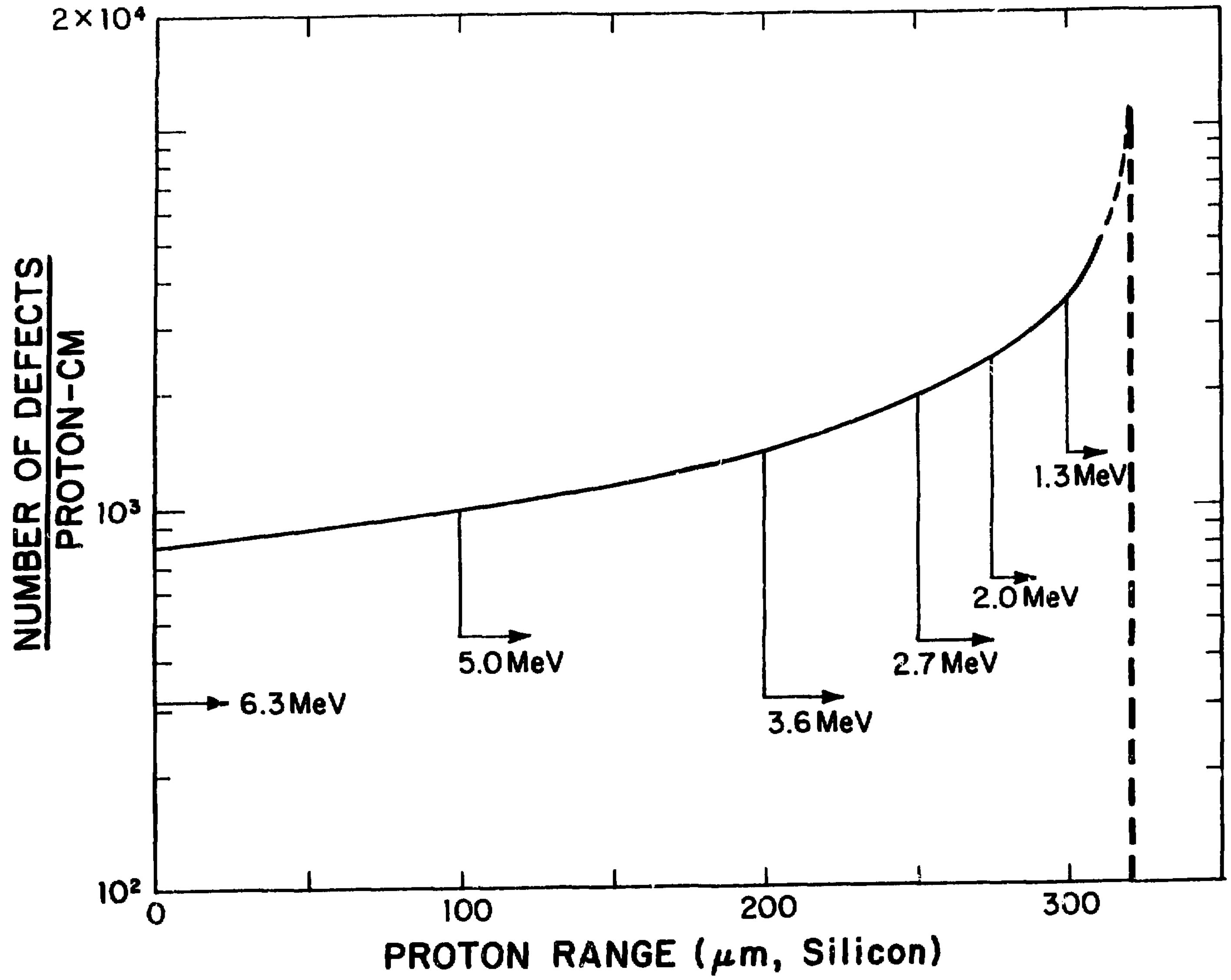

2×10⁴
10³
10²
NUMBER OF DEFECTS / PROTON-CM
0
100
200
300
PROTON RANGE (μm, Silicon)
6.3MeV
5.0MeV
3.6MeV
2.7MeV
2.0MeV
1.3MeV

Fig. 3.

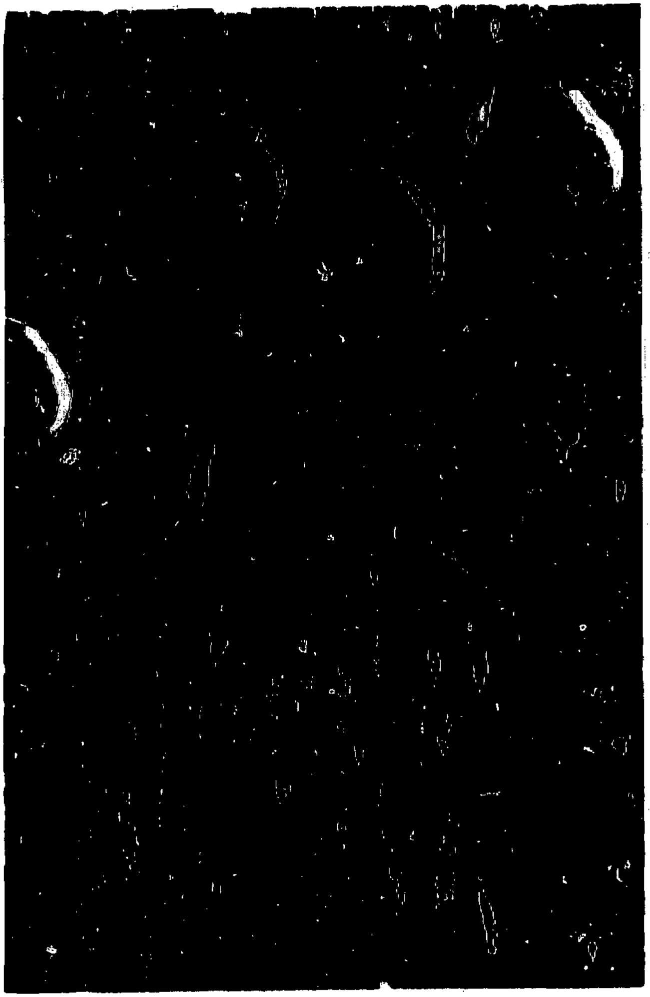


Fig. 1. General aspect of damage regions in neutron-irradiated n-type germanium

Fig. 2. Enlargement of a damage region in n-type germanium

region diameter 150-200 A

M. Bertolotti, Radiation Effects in Semiconductors, F. L. Vook, ed., Plenum Press, New York (1968).

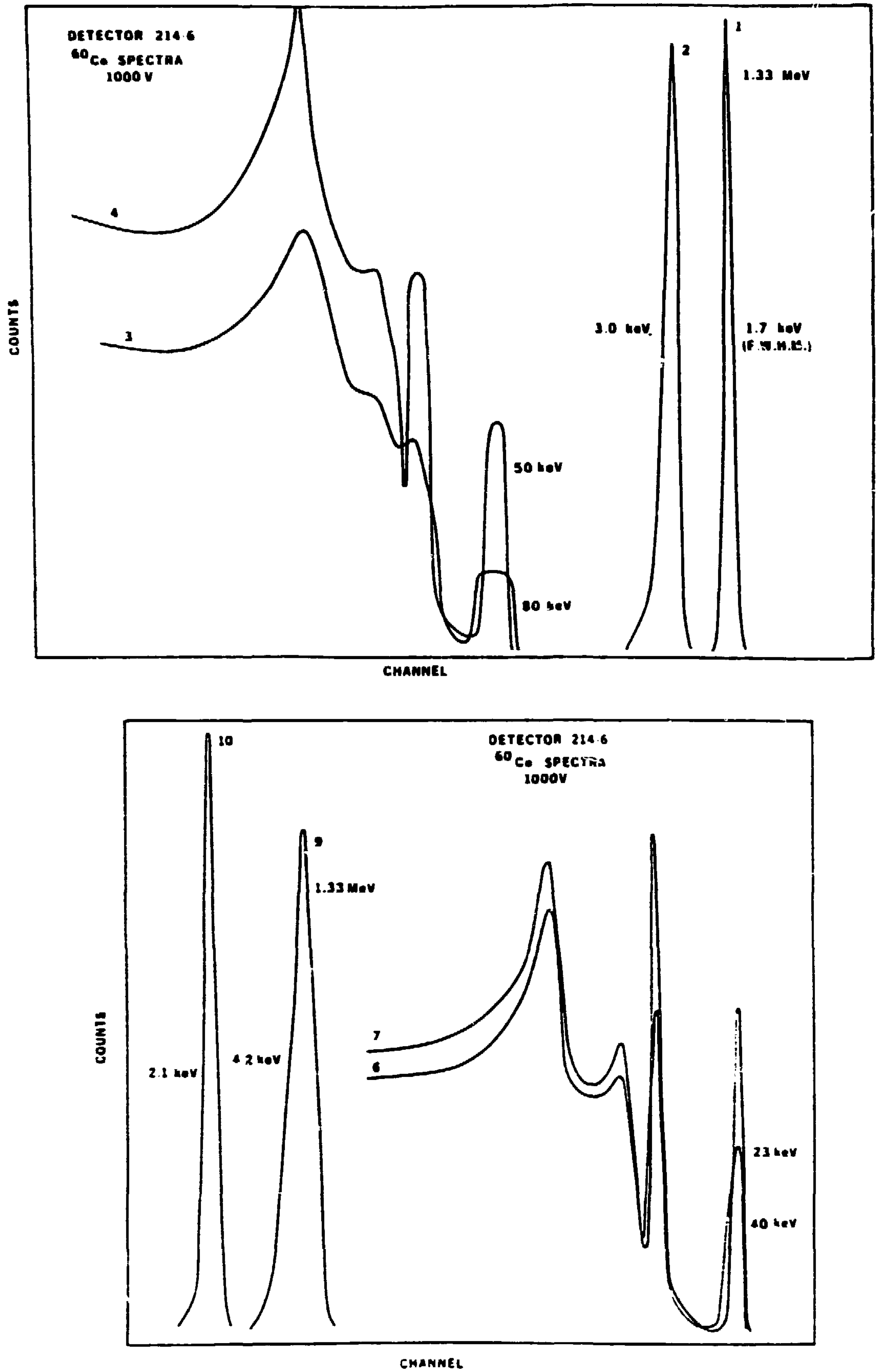

DETECTOR 214-6
^{60}Co SPECTRA
1000 V
4
3
2
1
1.33 MeV
3.0 keV
1.7 keV
(F.W.H.M.)
50 keV
80 keV
COUNTS
CHANNEL
10
9
1.33 MeV
2.1 keV
4.2 keV
DETECTOR 214-6
^{60}Co SPECTRA
1000V
7
6
23 keV
40 keV
COUNTS
CHANNEL

Fig. 5.

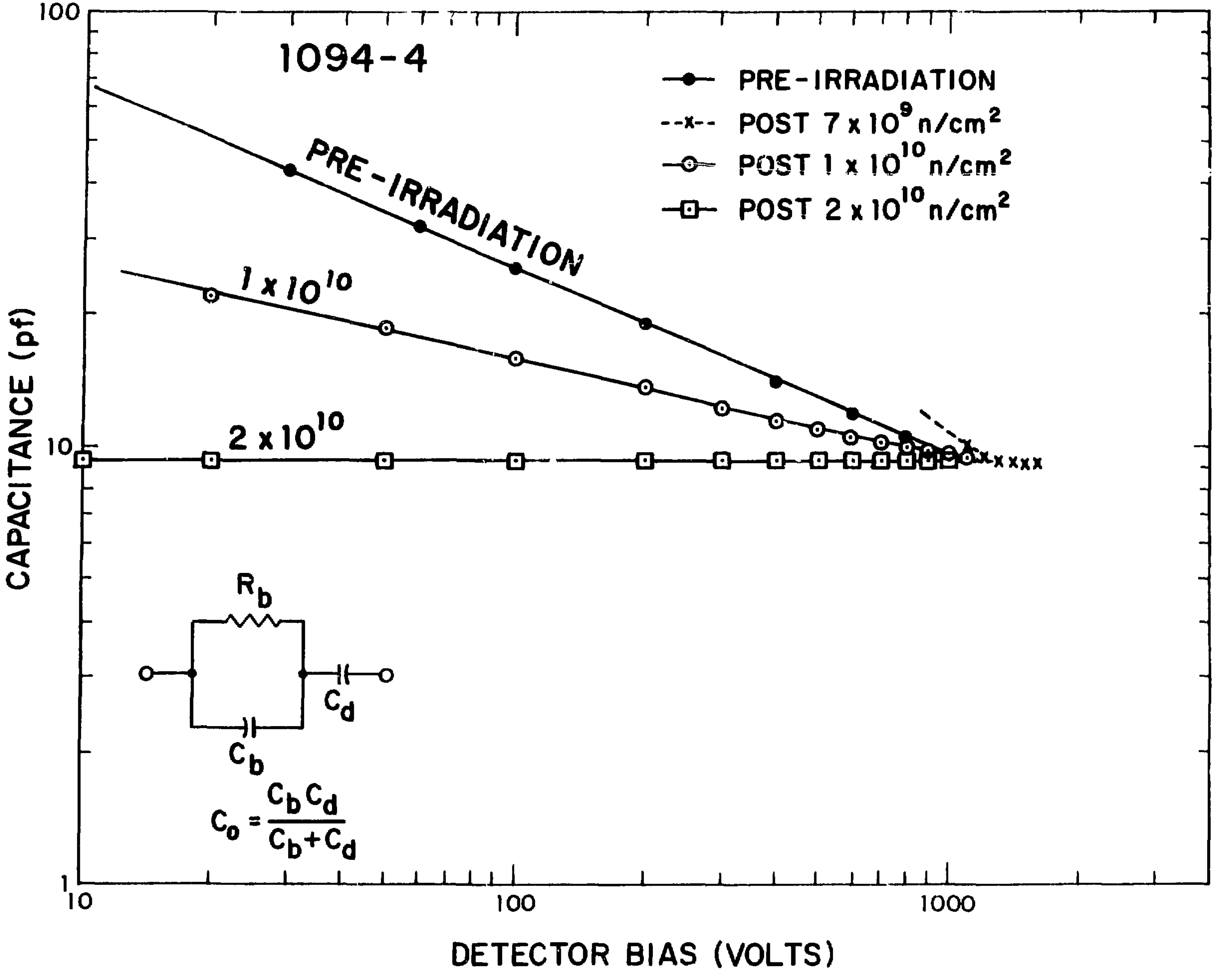

1094-4
PRE-IRRADIATION
POST 7 x 10^9 n/cm^2
POST 1 x 10^10 n/cm^2
POST 2 x 10^10 n/cm^2
PRE-IRRADIATION
1 x 10^10
2 x 10^10
CAPACITANCE (pf)
DETECTOR BIAS (VOLTS)
100
10
1
10
100
1000
R_b
C_d
C_b
C_o = C_b C_d / (C_b + C_d)

Fig. 6

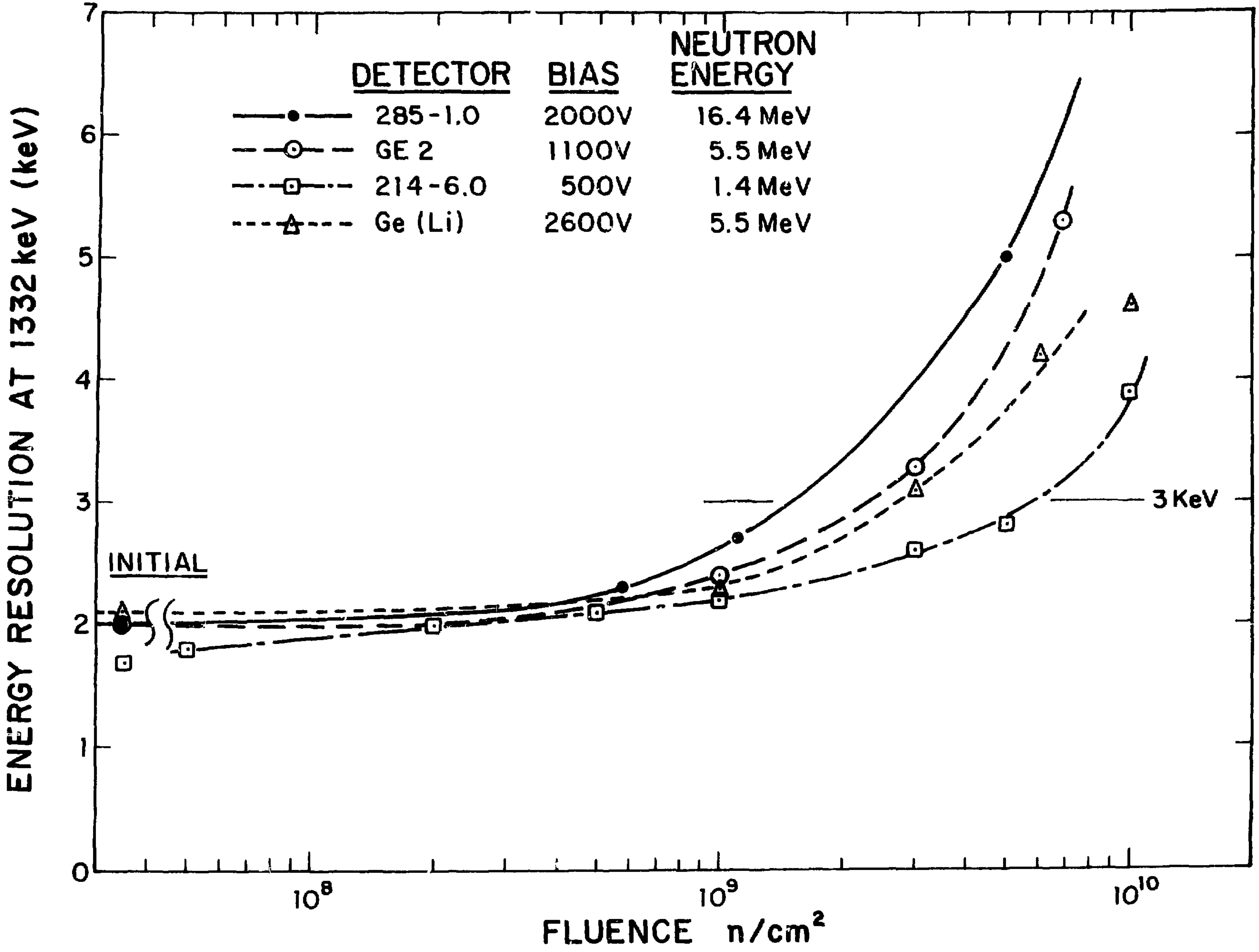
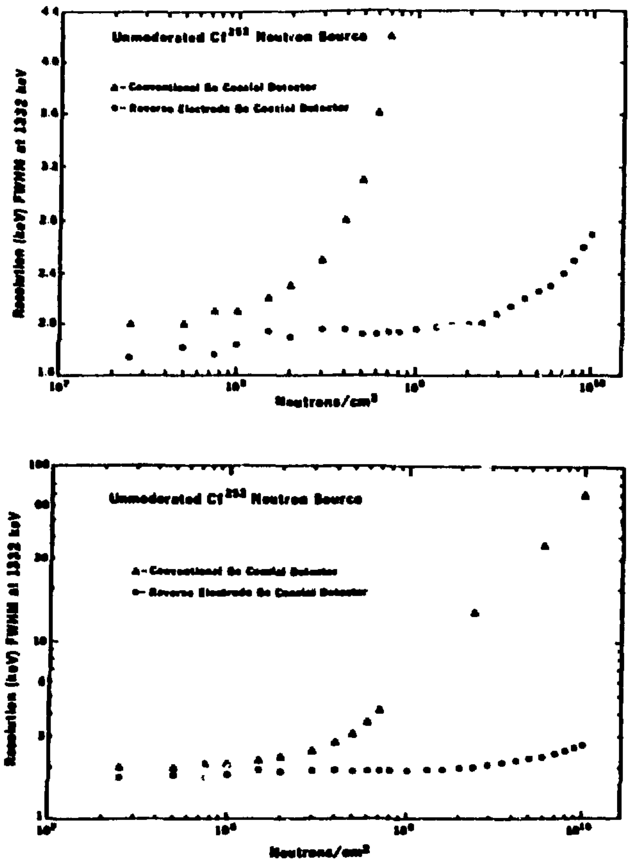
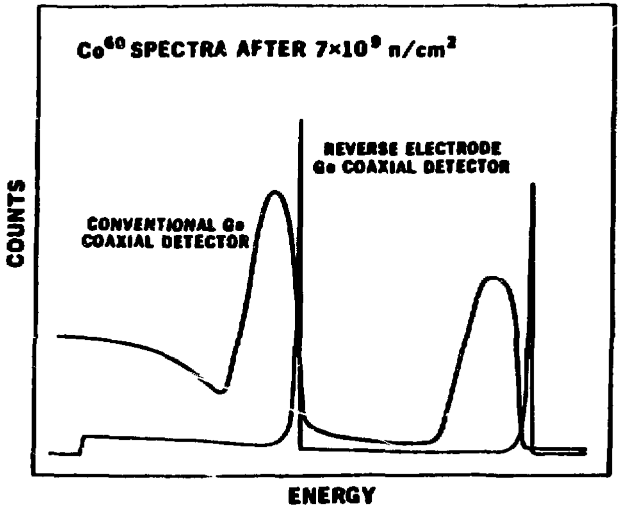

DETECTOR
BIAS
NEUTRON ENERGY
285-1.0
2000V
16.4 MeV
GE 2
1100V
5.5 MeV
214-6.0
500V
1.4 MeV
Ge (Li)
2600V
5.5 MeV
INITIAL
3 KeV
ENERGY RESOLUTION AT 1332 keV (keV)
FLUENCE n/cm²
0
1
2
3
4
5
6
7
10⁸
10⁹
10¹⁰

Fig. 7



Effect of neutron fluence on the energy resolution (FWHM) of the 1332 keV ^{60}Co line for both the conventional and reverse electrode configuration Ge coaxial detectors. Electronic noise has not been subtracted.



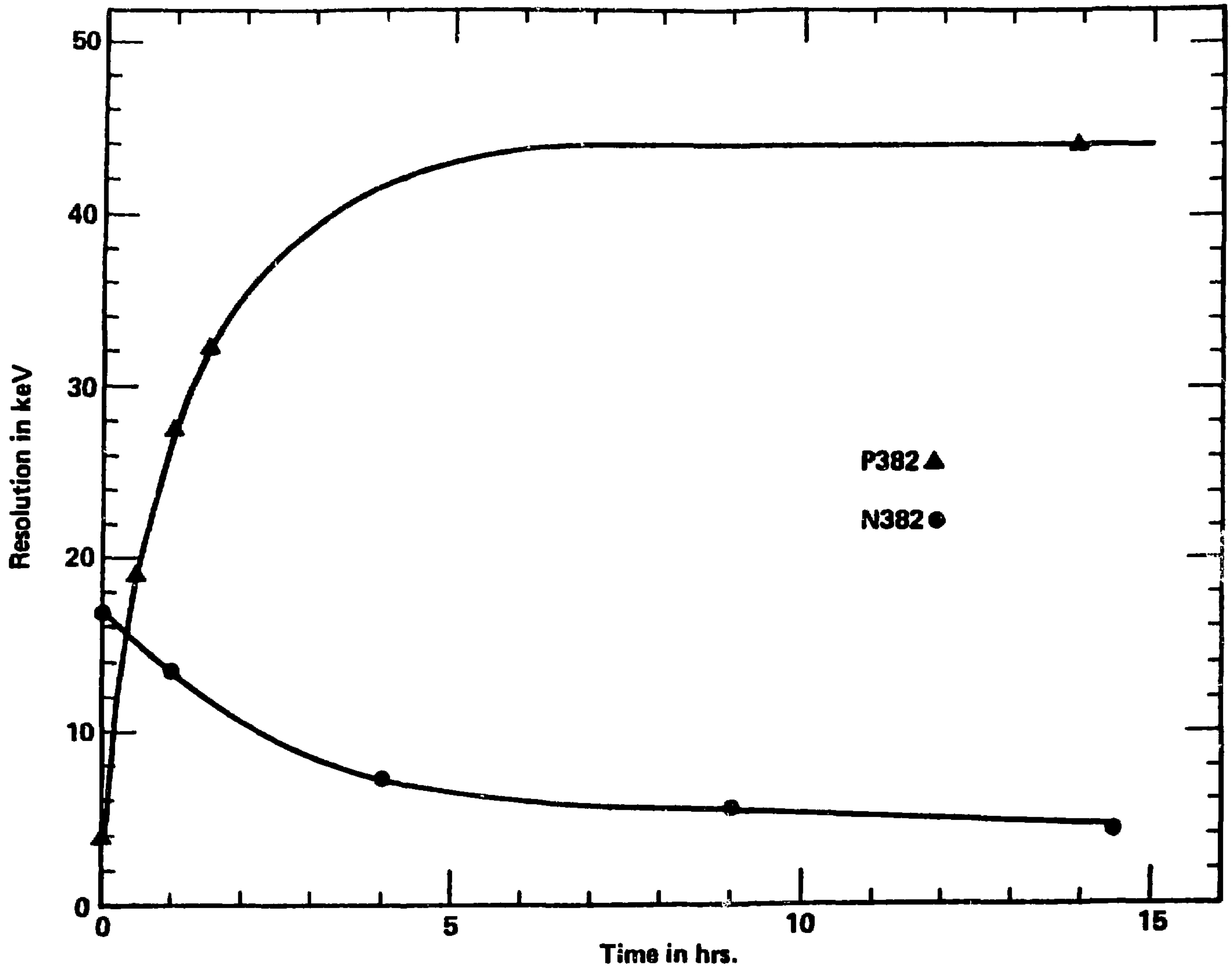
^{60}Co energy spectra obtained from both the conventional and reverse electrode configuration Ge coaxial detectors after a neutron fluence of 7 x 10^9 n/cm^2.

IEEE Transactions on Nuclear Science, Vol. NS-26, No. 1, February 1979

RADIATION DAMAGE RESISTANCE OF REVERSE ELECTRODE GE COAXIAL DETECTORS

Richard H. Pehl*, Norman W. Madden*, Jack H. Elliott**
Thomas W. Raudorf+, Rex C. Trammell+ and Lawrence S. Darken, Jr.+

Fig. 8.



L. S. Darken, T. W. Raudorf, R. C. Trammell, R. H. Pehl
and J. H. Elliott, "Mechanism for Fast Neutron Damage of
Ge(HP) Detectors. Nucl. Inst. & Meth. 171, 49 (1980)

Fig. 9 .