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A Study of Drift Mobility in Neutron Irradiated n-Type Germanium

William H. Closser

A STUDY OF DRIFT MOBILITY IN NEUTRON IRRADIATED n-TYPE GERMANIUM

By

William H. Closser

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E. A. Castetter
Dean

April 25, 1961
Date

Thesis committee

W. W. Grammann
Chairman

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William H. Closser

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CHAPTER I

INTRODUCTION

With the advent of the transistor in the late 1940's have come an entirely new field of engineering and a greatly renewed interest in solid state physics.

From the early experimental and theoretical work on the transistor, which was carried on by a group at Bell Telephone Laboratories, it was apparent that very high purity materials were needed in order to make good quality transistors.

This material was just what was needed by solid state researchers in order for them to study easily many of the fundamental properties of solids.

The most popular semiconductor materials to date have been germanium and silicon. A myriad of workers has turned out almost unlimited work on the optical, electrical, metallurgical and atomic properties of these materials.

This paper will be concerned in general with the electrical properties of these materials, and specifically with the drift mobility of the minority carriers in n-type germanium. The minority carrier in n-type material is the hole. The definition of drift mobility is: the mean carrier velocity per unit electric field.[1]

Drift mobility experiments were first reported by J. R. Haynes and W. Shockley in 1949[2], and more exhaustive measurements with the first details of germanium were given by Shockley, Pearson, and Haynes[3] a short time thereafter.

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[1] Dunlap, C. W., An Introduction to Semiconductors, John Wiley and Sons, New York, 1957.

[2] Haynes, J. R. and Shockley, W., "Investigation of Hole Injection in Transistor Action," Phys. Rev., vol. 75, 1949, p. 691.

[3] Shockley, W., Pearson, G. L., and Haynes, J. R., "Hole Injection in Germanium - Quantitative Studies and Filamentary Transistors," Bell System Tech. J., vol. 28, 1949, p. 344.

Since that time, different workers have investigated the drift mobility of minority carriers in n-type germanium as a function of temperature[4,5,6,7], resistivity[8], chemical impurity density[9], and thrust[10], while others have simply improved the accuracy of the mobility measurement.[11] The accuracy of the measurements was increased to ± 5 per cent and, as the material purity became very high, the value of the hole drift mobility approached a constant value.[12]

At this point, the drift mobility question seemed well under control and in 1953, Prince wrote: "I feel that the increasing value of drift mobility for holes and electrons in germanium as a function of the year of their measurement has finally leveled off."[13] With that, the interest in drift mobility measurements wained.

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[4] Lawerence, R., "The Temperature Dependence of Drift Mobility in Germanium," Phys. Rev., vol. 89, 1953, p. 1295.

[5] Lawerence, R., "Temperature Effects on Drift Mobility in Germanium," Proc. Phys. Soc., London, vol. B67, 1954, p. 636.

[6] Prince, M. B., "Experimental Confirmation of Relation between Pulse Drift Mobility and Charge Carrier Drift Mobility in Germanium," Phys. Rev., vol. 91, 1953, p. 271.

[7] Prince, M. B., "Drift Mobility in Semiconductors. I. Germanium," Phys. Rev., vol. 92, 1953, p. 681.

[8] Prince, M. B., ibid.

[9] Prince, M. B., ibid.

[10] Prince, M. B., op. cit. (ref. 6).

[11] Green, M., "Drift Mobility Measurements," J. Appl. Phys., vol. 28, 1957, p. 1473.

[12] Shockley, W., Electrons and Holes in Semiconductors, D. Van Nostrand Co., New York, 1953.

[13] Prince, M. B., op. cit. (ref. 7).

In the years that followed the invention of the transistor, engineers were busy replacing vacuum tubes with their smaller counterparts and developing new and unconventional methods of using more and more transistors. This development was followed by the testing of transistors under extreme environments such as high temperature, high acceleration, shock, and radiation. In the latter, transistors were found to have several shortcomings.

The apparent susceptibility of transistors to radiation damage led to the beginnings of several radiation effects research programs which could, in general, be classified in two groups. One was aimed at relieving the radiation effects problem through circuit design, and the other was aimed at a study of semiconductor material properties to determine the effects of radiation and what could be done to the material to improve the transistors. The groups interested in the material properties soon found that many optical, mechanical and electrical properties were affected by the irradiation, but that in general, the electrical properties were the ones most susceptible to radiation.

The study of radiation effects on the electrical properties of semiconductors centered on changes in Hall mobility[14,15], lifetime[16,17,18,19], and

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[14] Cleland, J. W., Crawford, J. H. Jr., and Holmes, D. K., "Effects of Gamma Radiation on Germanium," Phys. Rev., vol. 102, 1956, p. 722.

[15] Stein, H. J., "Transitory Properties of n-Type Germanium After a Neutron Pulse," J. Appl. Phys., vol. 31, 1960, p. 1309.

[16] Wertheim, G. K., "Electron Bombardment Damage in Si," Phys. Rev., vol. 110, 1958, p. 1272.

[17] Wertheim, G. K., "Neutron Bombardment Damage in Si," Phys. Rev., vol. 111, 1958, p. 1500.

[18] Loferski, J. J. and Rappaport, P., "Electron Bombardment Induced Recombination Centers in Germanium," J. Appl. Phys., vol. 30, 1959, p. 1181.

[19] Curtis, C. L. Jr., Cleland, J. W., and Crawford, J. H. Jr., "Radiation Induced Recombination Centers in Germanium," J. Appl. Phys., vol. 29, 1958, p. 1722.

conductivity[20,21]. Physical models[22,23] were proposed to represent the damage site and explain the experimental results. But in these initial studies, the importance of drift mobility measurement was overlooked.

Among considerations motivating the study described herein was an examination of the following equation for conductivity,

$$\sigma = e(n\mu_e + p\mu_p)$$

where σ is the conductivity, e the electronic charge, n and p are the number of electrons and holes respectively, and μ_e and μ_p are the mobility of electrons and holes respectively. Also, an analysis of transistor action showed that the current gain,

$$\alpha \doteq \frac{1}{1 + \frac{1}{2}\left(\frac{\omega}{L_p}\right)^2}$$

or cutoff frequency,

$$f_a = \frac{L_p^2}{\pi \omega^2 \tau_p}$$

$$L_p^2 = D_p \tau_p = \frac{KT}{e} \mu_p \tau_p$$

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[20] Cleland, J. W. and Crawford, J. H. Jr., "Low Temperature Irradiation on n-Type Germanium," J. Appl. Phys., vol. 29, 1958, p. 149.

[21] Johnson, W. E. and Lark-Horovitz, K., U. S. Government Research Reports, vol. 30, 1958, p. 566.

[22] James, H. M. and Lark-Horovitz, K., "Localized Electronic States in Bombarded Semiconductors," Z. Physik Chem., vol. 198, 1951, p. 107.

[23] Cleland, J. W., Crawford, J. H. Jr., and Pigg, J. C., "Fast Neutron Bombardment of P-Type Germanium," Phys. Rev., vol. 99, 1955, p. 1170.

and other properties are dependent upon the lifetime (τ_p) and the drift mobility of the minority carriers in the base region (μ_p)[24]. These considerations should suggest that a study of drift mobility as a function of radiation damage would be informative.

With the above thoughts in mind, the drift mobility problem was undertaken. Irradiations were made first with electrons. When it became apparent from the experimental measurements that the drift mobility was decreasing because of the electron irradiation, the measurements were repeated on neutron-irradiated material.

The first experimental evidence on the neutron irradiated samples indicated simply a decrease in the mobility caused by the radiation. This decrease was similar to that observed with electron irradiation. However, further experiments were conducted at lower values of flux (less than 10^{12} nvt for the Van de Graaff neutron irradiations which were studied first) and with smaller increments of flux dosage. These revealed an initial increase in drift mobility occurring just before the mobility began to decrease with higher neutron flux dosages.

The mobility increase was first assumed to be anomalous. But when the measurements were repeated, the effect was assumed to be real. The effect, at the time of its observation, was unexplainable in terms of the then existing models for neutron damage.

This mobility effect and a damage model which tentatively explains it are the subject of this paper.

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[24] Dunlap, C. W., op. cit. (ref. 1).

CHAPTER II

EXPERIMENTAL RESULTS AND PROPOSED MODEL

Recently a model for neutron damage in germanium based on the theory of dipole diffusion of the minority carriers was proposed by Gossick and Crawford[25,26]. In the case of n-type material, the neutrons form small highly p-type regions in the n-type matrix. The disordered regions are p-type because the asymptotic state of irradiated Ge is p-type. The p-region is surrounded by a potential well, which arises because the position of the energy bands relative to the Fermi level within the region differs from their position outside. A simplified physical picture of the damage site is shown in Figure 1, and an energy band diagram for an electron is shown in Figure 2. An important consideration is the extent of the radii r_1 and r_2. According to Crawford[27], a disordered region should contain 10^5 - 10^6 atoms. This, with a spherical region, gives a range of r_1 of from 150 to 200 Å. Then according to Gossick[28], the screening distance beyond r_1 must be at least a Debye-Hückel length. Hence r_2, the outer boundary of the double layer, must exceed L_2, the Debye-Hückel length, in the undisturbed lattice. The Debye-Hückel length may be calculated from

$$L_2 = 1/q \left(KT\epsilon/N_2\right)^{\frac{1}{2}} \qquad (1)$$

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[25] Gossick, B. R., "Disordered Regions in Semiconductors Bombarded by Fast Neutrons," J. Appl. Phys., vol. 30, 1959, p. 1214.

[26] Gossick, B. R., "Dipole Mode of Minority Carrier Diffusion with Reference to Point Contact Rectification," J. Appl. Phys., vol. 31, 1960, p. 29.

[27] Crawford, J. H. Jr. and Cleland, J. W., "Nature of Bombardment Damage and Energy Levels in Semiconductors," J. Appl. Phys., vol. 30, 1959, p. 1204.

[28] Gossick, B. R., op. cit. (ref. 25).

where ϵ denotes the dielectric constant, N_2 the concentration of impurities which contribute current carriers in the undisturbed material, while q, K and T have their usual meanings, i. e., electric charge, Boltzmann's constant, and absolute temperature respectively. For 5 ohm cm. material, L_2 is calculated to be 2540 Å, and r_2 must be greater than 2540 Å. The overall representation of the damage site can be pictured as a large void region created in the matrix, because the region is essentially depleated of conduction electrons and the positive space charge zone tends to block electron current flow.

Theoretical work by Gossick[29], using this model to represent the neutron damage site, and the calculations for dipole diffusion about a sphere show that the hole conductivity is enhanced to σ_p. This is defined as

$$\sigma_p = \sigma_{p_o}\left(\frac{1 + 2f}{1 - f}\right) \tag{2}$$

where σ_{p_o} is the conductivity of holes outside the double layer, and f is the fraction of the total volume enclosed by the voids.

The effective mobility of holes may be deduced by the following argument: The density of holes averaged over the sample is transformed from p_o, the original hole concentration, to $(1 - f)\, p_o$ by the presence of the disordered regions. By (2) we then may write

$$\sigma_p = q(1 - f)\, p_o\, \mu_{p_o}\, \frac{1 + 2f}{(1 - f)^2} \tag{3}$$

where μ_{p_o} is the initial hole mobility, and q is the electronic charge. This equation shows that the effective mobility μ is

$$\mu = \mu_o\, \frac{1 + 2f}{(1 - f)^2} \tag{4}$$

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[29] Gossick, B. R., International Conference on Semiconductor Physics, Prague, Czechoslovakia, August, 1960.

which for an f of 10 per cent predicts an increase in the hole drift mobility of approximately 48 per cent.

This model has had some previous experimental verification[30,31], and since it predicts an increase in the drift mobility of the minority carriers, it was adopted in order to explain the observed experimental results. The original Gossick model predicts that the drift mobility μ will increase continuously with f, as shown in Figure 3, until f approaches .25. At this point the initial assumptions upon which the theoretical calculations are based become invalid.

The experimental results show, however, that μ does not increase continuously, but instead reaches a maximum and then decreases with increasing flux dosages, approaching zero as the sample approaches intrinsic. Thus, there is a definite contradiction between the model and the experimental results on this point. Also, if the model is applied directly to the experimental results, e.g., the Omega West results where the maximum drift mobility increase is approximately 25 per cent, Figure 3 shows that f must be 6 per cent. But if f is calculated in the following manner, assuming that only neutrons above .7 Mev can create a void[32], it is found that for

σ_s = collision cross section in Ge = 4.0 barns, $(4 \times 10^{-24}\ cm^2)$

ϕ = flux for max μ change at Omega West = 1.5×10^{12} nvt > 2.5 Mev,

2.72 = conversion factor for ϕ > 2.5 Mev to ϕ > .7 Mev, and

4.45×10^{22} = no. of Ge atoms/cm^3,

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[30]Stein, H. J., op. cit. (ref. 15).

[31]Crawford, J. H. Jr. and Cleland, J. W., op. cit. (ref. 27).

[32]Cleland, J. W. and Crawford, J. H. Jr., International Conference on Semiconductor Physics, Prague, Czechoslovakia, August, 1960.

the result is

$\bar{\Sigma}v$ = probability/cm that each neutron produces a void, or

$\bar{\Sigma}v = 4 \times 10^{-24} \times 4.45 \times 10^{22} \sim .18.$

Then for $\phi > .7$ Mev, the number of voids/cm^3 = $2.72 \times \phi > 2.5$ Mev $\times$ .18.

Voids/cm^3 = $.735 \times 10^{12}$.

Volume of each void, assuming r av. $\sim$3000 Å:

$V = (4/3)\pi r^3 = 113.4 \times 10^{-15}$ cm^3.

The percentage of the volume contained in the voids = f = volume of void x number of voids x 100, and $f = 113.4 \times 10^{-15} \times .735 \times 10^{12} = 8.35\%$.

Thus, again there is a discrepancy between the value of f calculated directly from the model, i.e., from $\mu = \mu_o \frac{1 + 2f}{(1 - f)2}$, and f calculated from an incident flux consideration. Also, f calculated from the model is the smaller of the two values. The last statement says in effect that the observed mobility change for a given f is not as large as the theoretical calculations would indicate.

The experimental results on neutron irradiated material show that drift mobility does decrease with large flux doses, and that the observed increase in mobility is somewhat less than would be expected for a given flux. Therefore, it is apparent that some mechanism other than the voids is causing a decrease in the drift mobility, and thereby is compensating to some extent for the effect of the voids.

A comparison of the curves of drift mobility vs. electron flux and neutron flux, Figures 5 and 6, shows that the decreases in mobility which occur in both cases seem to be quite similar, except that the decrease for neutron irradiated material may be somewhat more rapid. This would suggest that the same mechanism is causing the decrease in both cases. In the case of

electron irradiation, it is known that the mechanism causing the mobility decrease results from the point defects introduced by the radiation. From other work[33,34,35], it is known that point defects also exist in neutron irradiated material. Therefore, in order to explain the experimental drift mobility, it was assumed that the neutron irradiation introduces into the lattice both void regions and point defects similar to those caused by electron irradiation. It also was assumed that the two have compensating effects on the mobility. It was further assumed that these irradiation-induced defects control the mobility, and that all other damage caused by the neutrons, which give rise to the energy levels in the forbidden band other than those associated with the point defects, have no effect on the mobility.

In order to obtain the number of point defects necessary to cause a given mobility decrease, the following calculations were used:

For Sample V-10 irradiated with 2 Mev electrons, the initial resistivity was 6 ohm cm. and the initial resistance was 800 ohms. The initial carrier concentration for this sample was

$$\sigma = ne\mu = \frac{1}{\rho}.$$

Then

$$n = \frac{1}{\rho e \mu}$$

$$= 3 \times 10^{14} \text{ e/cm}^3 \text{ for } \rho = 6 \text{ ohm cm.}$$

$$e = 1.6 \times 10^{-19} \text{ coul. } \mu = 3600 \text{ cm}^2/\text{Vsec.}$$

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[33] Stein, H. J., op. cit. (ref. 15).

[34] Cleland, J. W. and Crawford, J. H. Jr., op. cit. (ref. 32).

[35] Curtis, O. L. Jr., "Radiation Effects on Recombination in Germanium," J. Appl. Phys., vol. 30, 1959, p. 1174.

When the resistance of the sample is increased by a factor of two, then one half of the initial carriers have been removed. For Sample V-10

$$\frac{\text{No.}}{2} = 1.5 \times 10^{14}.$$

From Figure 4, the electron flux required to remove half of the initial carriers is 3.3×10^{14}.

Then, assuming one carrier is removed per defect formed, it is found that the defect introduction rate for the 2 Mev electrons, which is

$\frac{\text{No. of electrons removed}}{\text{Incident flux}}$, is approximately .45 defects/incident electron.

Assuming the defect introduction rate is a constant over a wide range, this figure for defect introduction rate may be used with Figure 5 to calculate the number of point defects necessary to cause a given mobility decrease.

Now that it is possible through the use of electron irradiation data to obtain the effect of point defects on mobility, and since the effect of voids on mobility may be calculated, it is possible to determine the effect of a given neutron flux on the basis of the proposed model. Figure 6 shows that for a neutron flux of 3.25×10^{12} nvt, the value of drift mobility is equal to the initial drift mobility, i. e., for the proposed model, the effects of the voids and point defects are exactly equal and opposite.

For a flux of 3.25×10^{12} nvt > 2.5 Mev, the total number of neutrons capable of producing voids are those with energies greater than .7 Mev. The number may be obtained by multiplying the flux readings by the conversion factor of 2.72. This is the same result as that used previously to calculate the void fraction f. For this case, f may be found from the ratio

$$f = \frac{3.25 \times 10^{12}}{1.5 \times 10^{12}} \times 8.35 = 18.1\%$$

where 1.5×10^{12} and 8.35 are fluxes greater than 2.5 Mev and the per cent void fraction respectively, which were used previously to calculate f.

From Figure 3, for an f of 18.1 per cent the mobility theoretically should be twice its original value; however, experimentally it is observed to be equal to its original value. Thus, the number of point defects added by the neutrons must be sufficient to cause a decrease in mobility equal to the original value of mobility. From Figure 5, the necessary electron flux to cause this decrease would be approximately 1.8×10^{15} e/cm^2.

The total number of point defects should then be: flux times introduction rate which is

$$1.8 \times 10^{15} \times .45 = .81 \times 10^{15} \text{ defects.}$$

Thus, the neutron flux should produce $.81 \times 10^{15}$ point defects in order to cause the same effect on the mobility.

The number of neutrons capable of producing point defects is the total flux greater than 1 Kev, and is obtained by using the correction factor, 6.3. Thus,

$$\phi > 1 \text{ Kev} = 3.25 \times 10^{12} \times 6.3 = 20.5 \times 10^{12} \text{ nvt.}$$

The number of point defects introduced per incident neutron then would be

$$\frac{\text{Required no. of defects}}{\text{Incident neutron flux}} \quad \frac{8.1 \times 10^{14}}{2.05 \times 10^{13}} = 39.6,$$

or approximately 40 defects/neutron.

That is, in order for the proposed simplified model to be able to explain the observed effect, each neutron would have to introduce 40 point defects into the lattice. This is quite a large number and immediately raises some suspicion about the validity of the model.

For a theoretical model to be of any significance, it must not be suitable only for explaining the observed experimental data from one experiment, but it also must fit in well with the overall physical picture of the system. That is,

the model must not contradict the known results of other experiments related to the same problem. Therefore, even though the proposed modified form of the Gossick model can explain the drift mobility results, it must not be allowed to stand on this condition alone; it must be made compatible with other experimental results.

Perhaps the best measurements with which to compare the drift mobility would be the Hall mobility and Hall coefficient measurements on p-type germanium irradiated with electrons. From these measurements one could obtain the effect of charge center scattering on the Hall mobility, and some information could be obtained regarding which defect-associated energy levels were the most important in determining the mobility. This data was not available, however, so instead, carrier concentration measurements were chosen for the comparison.

Extreme caution must be used in making this comparison, however, because the carrier concentration measurement is not a function of the total number of defects; it is instead a function of the difference between the number of donor and acceptor-type defects introduced into the material by the neutron irradiation. This means that if the introduction rates of donors and acceptors were the same, then even extremely high defect concentrations would not be apparent in the carrier concentration measurements, but they would cause large mobility changes.

The proposed model set forth in this paper requires that each neutron produce 40 point defect scattering centers similar to those produced by electron bombardment. From carrier concentration measurements on neutron irradiated germanium it is found that each neutron produces approximately one to two net acceptors (the best numbers to date are 1.6 to 1.8), which are associated with the point defects[36]. From annealing experiments on the Hall coefficient it is found that each neutron introduces about 1.3 donors at the .2 ev level below the conduction band, which are also associated with the point

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[36] Cleland, J. W., Personal communication.

defect[37]. Thus, the combination of carrier concentration and Hall coefficient measurements indicates that each neutron must introduce approximately four charged scattering centers which are associated with the point defects. These measurements indicate that there is a definite contradiction of other available data by the model which is proposed to explain the drift mobility results. For the numbers stated above, the discrepancy is approximately ten.

The discrepancy of a factor of ten in the results appears rather large, but this could be considered the worst possible case. If each point defect were to remove two electrons from the conduction band, as the Lark-Horovitz model for point defects predicts, the defect introduction rate for electron irradiation would be decreased by a factor of two, thereby decreasing the discrepancy. Also, if the effect of hole-hole scattering, which could cause an approximate decrease of a factor of two in the mobility, were considered, then the results of the proposed model would be off by only a factor of 2.5, which, though not completely satisfactory, is not unreasonable in light of the assumptions necessary to make the simple calculations which were used.

One of the initial assumptions was that the neutron damage which gives rise to energy levels in the forbidden band, other than those directly associated with the point defects, had no effect on the mobility. This assumption was made of necessity to permit calculation. But it is not true, since any imperfection in the lattice can give rise to scattering. Several of these energy levels are associated with defects which have only a fractional electric charge on them, the total charge always being a whole number of electronic charges. These levels cannot accept an electron from the conduction band, and hence do not affect the carrier concentration. The abundance of these sites present in neutron irradiated Ge is unknown at present. But for the case of Si, it is found that some of these levels go in rather fast with irradiation, and hence could add an appreciable amount to the charge center scattering.

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[37] Stein, H. J., Personal communication.

The effect of these levels on drift mobility could be calculated easily on a charge center scattering analysis if their concentration were known. It is not, however, and therefore only an assumption of their effect can be made. Since there is a large number of these known levels, and since the concentration of these levels is sufficient for them to be observed, it is assumed that they could easily cause a 20 to 30 per cent decrease in drift mobility.

Using the above set of refinements, which are quite reasonable, the number of charge center scatterers introduced per incident neutron which are related to the point defects can be reduced from 40, which was the necessary number for the first case, to approximately 6 to 7. This is more reasonable, and is within less than a factor of two of agreeing with the number, 4, which is the number of charged scattering centers predicted by the carrier concentration and Hall coefficient measurements.

The calculations used in this model have been made entirely on the data from the Omega West irradiations. Although the results on samples irradiated with neutrons from the Van de Graaff were similar to those obtained from use of the Omega West (Figure 7), it was necessary to confine the calculations to the Omega West data because nothing was known about the energy spectrum of the neutrons from the Van de Graaff, except their most probable energy.

It should be mentioned here that the effect of trapping on mobility was purposely neglected since very little is known about it at this time. However, it is known to exist and should undoubtedly be considered, because it is impossible to explain completely the electron irradiation data without it unless a charge of ± 6 is given to each scattering center, which is very unlikely.

CHAPTER III

CONCLUSIONS

The results of the drift mobility experiments on neutron irradiated material are not explainable in terms of models which picture the damage sites as simple Frenkel (point) defects or groups of such defects acting as charged scattering centers. A mathematical verification of this is given in Appendix II.

Due to the complexity of the drift mobility measurement itself and the fact that the collector and injector must be brought closer together with increased irradiation, because of the decrease in excess carrier lifetime, some question arises as to whether the observed increase in mobility could result from the measurement technique or could be due to a variation in mobility along the samples. The first question is considered in Appendix III; it is shown experimentally that the mobility increase cannot be caused in this manner. The question of a variable mobility is considered in Appendix IV; for the two cases of most practical concern a mathematical analysis shows that the total experimental result cannot be caused by these mobility variations. However, if it were to be assumed that mobility could increase as a function of distance along the sample, a mechanism similar to the void would have to be postulated to explain the increase or a gradient in the concentration of defects, which for a uniformly irradiated sample is highly unlikely.

Since the Gossick model for neutron damage does predict an increase in the drift mobility of minority carriers in n-type germanium, it was adopted to explain the observed experimental results. But this model, too, is somewhat inadequate in its original form because it cannot explain the decrease in mobility which occurs with increased flux dosages.

The model for neutron damage set forth in this paper is simply a combination of the Gossick model, which says the damage site is a large void region, and other models which say the damage site is a charged scattering center.

Essentially, this model says the damage site is neither a void nor a point defect scattering center, but is a combination of both as far as the electrical behavior of the material is concerned.

As shown in the body of this paper, for the worst possible set of conditions that can be imposed on the damage model, the discrepancy between the proposed model and other available data is approximately ten, and the model is meaningless.

If a somewhat better set of conditions is imposed on the model, as also described in this paper, it is found that the model will explain the experimental results within a factor of two to three quite easily, and still not be inconsistent with other experimental data.

In view of the facts that the fluxes are not known to better than 20 per cent, that the effective size of the void region is still unknown (the maximum size was used here), and that trapping was neglected, the discrepancy of a factor of two to three is considered rather good.

Though this model is quite crude and qualitative, it is believed to have some merit, and it can be used on an interim basis to explain partially neutron damage in semiconductor materials.

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APPENDIX I

SAMPLE PREPARATION, IRRADIATION, AND MEASUREMENT

A. SAMPLE PREPARATION

The samples which were used throughout these experiments were 5 ± 15% ohm cm. antimony doped n-type germanium. They were originally cut from single crystal ingots. The samples were cut into rectangular bars which were, on the average, 2 cm. in length with a cross section of .2 cm. x .1 cm. All cutting was done with a diamond cut-off wheel.

The ends of the samples were sanded with 240-grit abrasive paper and tinned with 50-50 tin-lead solder using ruby fluid solder flux. Small copper wires were tinned in the same manner and then attached to the ends of the sample. This procedure was necessary in order to eliminate any possibility of injecting end contacts, since injecting contacts would definitely interfere with the experimental measurements. E-I curves were run on the samples to make sure that the contacts were ohmic. If they were not, the soldering procedure was repeated. When it was established that the end contacts were ohmic, they were coated with beeswax to prevent them from being dissolved when the sample was etched.

The samples were etched in CP-4 etchant which is a composition of hydrofluoric, concentrated nitric, and glacial acetic acids and a few drops of bromine. The etch was continued for a period of from 1.5 to 3 minutes, or until the surface of the sample attained nearly an optical finish. This was done to prevent surface injection which would lead to a false mobility reading. The etching action then was quenched by washing the samples in

distilled water. The beeswax was removed from the end contacts by heating. The samples were then washed in distilled water again and wiped dry to assure that no oil or mineral films remained on the surface. The sample preparation was then complete.

B. SAMPLE IRRADIATION

The electron irradiation work was done with 2 Mev electrons obtained from Sandia's Van de Graaff Accelerator. The particles were nearly monoenergetic, and since the samples were mounted very close to the aluminum window at the end of the accelerator, the particles were incident on the samples with an energy of approximately 2 Mev.

The shape and area of the electron beam at the position of the samples was determined by measuring the change in optical absorption of blue cellophane. It was found that approximately 90 per cent of the total beam was contained in a circular spot 1 cm. in diameter, and that the intensity of the beam was constant throughout this area. That is, the intensity was constant to within the accuracy that could be obtained with the absorption measurements.

However, since the samples were 2 cm. in length and it was necessary to have uniform radiation over the entire sample, it was necessary to use magnetic deflection coils in order to scan the electron beam perpendicular to the horizontal axis along which it was traveling.

The shape and area of the electron beam at the sample when the deflection coils were used was again measured by absorption changes in blue cellophane. It was found that the area was rectangular in shape and that again approximately 90 per cent of the flux was contained in an area of constant intensity.

The electron flux was measured by collecting the total beam in a Faraday cup, and measuring the current with a microammeter as the electrons passed from the Faraday cup to ground. Since the Faraday cup was not evacuated, there was undoubtedly some ionization of the air in the cup by the electrons, and hence, the flux measurements were not extremely accurate.

Since the total number of electrons which were emitted per second, the time for which they were emitted, and the area through which they passed were known, it was possible to calculate the units of flux density (electrons/cm^2) used in this work.

The samples were oriented so that the .1 cm. dimension was parallel to the beam in order to make the damage introduced into the sample nearly uniform throughout. This was necessary since the range of 2 Mev electrons in Ge is about .2 cm., and at the end of the range the damage which would be produced would be nonuniform and would anneal at room temperature. This effect is due to the dE/dx of the electrons. (See Figure 9.)

All irradiations were made at room temperature. The samples were cooled by forced air, or by dry nitrogen which was cooled by passing it over dry ice.

Neutrons were obtained from three sources:

1. Sandia's Van de Graaff Accelerator (Figure 8) using a deuterium on beryllium reaction yielding neutrons with a most probable energy of 4 to 5 Mev in the forward direction.[38]

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[38] Shpetnyi, A. I., "Energy and Angular Distribution of Neutrons Emitted in the $Be^9(d,n)Be^{10}$ Reaction," Soviet Phys. JETP, vol. 5, 1957, p. 357.

2. The Omega West reactor facility at Los Alamos, which gave a normal fission spectrum that was slightly hardened by one foot of water, i.e., the thermal neutrons were removed. The most probable neutron energy was 1.34 Mev.[39]

3. The Godiva pulsed reactor facility, also at Los Alamos, which gave a degraded fission spectrum with a most probable neutron energy of .7 to .8 Mev.

The flux measurements were made with sulphur dosimeters $S^{32}(n, p)P^{32}$ and corrected for each case to give the total flux above 1 Kev. The accuracy of the measurements is not better than 15 to 20 per cent.

All irradiations were made at room temperature. The samples were not cooled for the Omega West and Godiva irradiations, but were cooled for the neutron irradiations from the Van de Graaff. The methods of cooling were the same as those used in electron work.

C. MOBILITY MEASUREMENT

Measurements of drift mobility were made using a standard Haynes mobility measuring circuit with a pulsed electric field to prevent the samples from over-heating. The electrical circuit is shown in Figure 10.

The phosphor-bronze points of the micromanipulator are used for injection and collection of holes, with the point which is connected to the pulse generator doing the injecting.

The timing of the electrical pulses is such that the electric field pulse is applied first and has reached its maximum value before the injection pulse is applied. The injection pulse is kept short, approximately 1 μsec, so that it will not influence the drift of the injected carriers. The injected holes thus drift in a constant applied field.

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[39] Bouchard, G., Work performed in May, 1960, at Sandia Corporation at author's request. Work is unpublished.

When the hole injection pulse is applied to the sample, electrons must also flow into the sample from ground to maintain charge neutrality. These electrons modulate the conductivity of the sample between the collecting point and ground, thus changing the voltage applied to the oscilloscope. As the injected holes, which are drifting toward the collecting point because of the electric field, reach the collector, they again modulate the conductivity changing the input oscilloscope voltage. The picture which is displayed on the screen is shown in Figure 11.

Time is measured along the horizontal scale of the oscilloscope from the center of the injection pulse to the maximum of the collected hole pulse.

The applied field pulse between the emitter and the collector is measured with the oscilloscope by measuring the voltage from each point to ground and taking the difference. The distance between the emitter and collector is measured with a traveling microscope which has an accuracy of .01 mm.

From these measurements the drift mobility can be calculated using the formula,

$$\mu = \ell^2/vt$$

where μ is the drift mobility, ℓ is the separation between the probes, v is the applied voltage between the probes, and t is the time measured as shown in Figure 11.

The voltage measurement is the least accurate of the three measured quantities with an accuracy of no better than 10 per cent. Therefore, the mobility values obtained in these experiments cannot be quoted to an accuracy of better than $\pm$ 10 per cent.

Each point on the mobility-versus-flux graphs is the statistical average of several mobility readings taken after that accumulated irradiation. Also, the curves presented here have been reproduced. In the case of the neutron bombardment curves, the observed mobility increase is large enough to put it out of the statistical range of error in these experiments.

APPENDIX II

EFFECT OF CHARGE CENTER SCATTERING ON MOBILITY

The mobility of the current carriers in germanium is predominately determined by lattice scattering for the intrinsic case, and by both lattice scattering and impurity or charge center scattering for the extrinsic case.[40]

Though the graphs presented in this paper all show the mobility plotted as a function of flux, it must be remembered that these high energy particles actually produce defects in the samples. Thus the mobility as represented by these graphs is actually proportional to the number of defects produced by the irradiation.

It is known that electrons produce Frenkel-type point defects which act as charged scattering centers in the lattice. If we assume that the neutron damage site may be represented simply as clusters of this same type of defect, then the total effect of neutron irradiation on the mobility should also be a charge center scattering effect. Thus for the following calculation, the effect on the mobility of lattice scattering and charge center scattering only will be considered.

The lattice scattering and charge center scattering effects will be separated since the two are independent. Lattice scattering will be treated first.

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[40] Kittel, C., Introduction to Solid State Physics, John Wiley and Sons, New York, 1956.

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[40] Kittel, C., Introduction to Solid State Physics, John Wiley and Sons, New York, 1956.

The mobility associated with lattice scattering in a nonpolar crystal such as germanium has been calculated by Seitz to be:[41]

$$\mu_L = \frac{2^{1/2} 6^{1/3}}{4\pi^{5/6}} \cdot \frac{N^{1/3} e \hbar^2 k^2 \Theta^2 M}{m^{*5/2} C^2 (kT)^{3/2}}$$

where μ_L is the lattice scattering mobility, Θ is the Debye temperature, N is the density of unit cells, m* is the effective mass of the charged carrier which is taken as equal to the mass of the electron, M is the atomic mass of the host lattice, e, $\hbar$, k, and T have their usual meanings (i. e., electronic charge, Planck's constant/2π, Boltzmamm's constant, and temperature respectively). C is defined using the Block function $\mu(r)\, e^{ik \cdot r}$ by

$$C = \frac{\hbar^2}{2m} \int |\text{grad}\, \mu|^2 \, d\tau$$

and is treated as an unknown parameter of a value of 1 to 10 electron volts.

The drift mobility measurements were all made at a constant temperature; hence, the only variable in the equation should be m*, the effective mass. The effective mass is believed to change very little, if at all. Even if its change were appreciable, it would change only for the atoms directly affected by the damage site, which, for the low values of flux of interest here, would give mass changes for only 1 atom in 10^6 or less. Therefore, the lattice scattering contribution to mobility is considered to be a constant, i. e., unaffected by the radiation.

The effect of charge center scattering on mobility has been worked out by Conwell and Weisskopf using the Rutherford scattering formula.[42]

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[41] Seitz, F., "On the Mobility of Electrons in Pure Non Polar Insulators," Phys. Rev., vol. 73, 1948, p. 549.

[42] Conwell, E. and Weisskopf, V. F., "Theory of Impurity Scattering in Semiconductors," Phys. Rev., vol. 77, 1950, p. 388.

The mobility dependence on charge center scattering was found by this method to be:

$$\mu_I = \left[2^{7/2} \epsilon^2 (kT)^{3/2} \ln (1 + x^2)\right] / N_I \pi^{3/2} e^3 m^{*1/2}$$

where μ_I is the ionized impurity mobility, ϵ is the dielectric constant, N_I is the density of ionized impurities, m^* is the effective mass of the charged carrier, and k, T and e have their usual meanings of Boltzmann's constant, temperature, and electric charge respectively. And $x = 6\epsilon dkT/e^2$, where d is one half the average distance between ionized donor neighbors.

The charge center scattering will be divided into two components: (a) that due to the chemical impurity centers, i. e., the donors, and (b) that due to the irradiation-induced defects.

For the low values of flux under consideration, the Fermi level is not changed appreciably, so it will be assumed that the charged donor concentration remains the same. Therefore, the component of mobility due to the chemical impurities, which will be specified as μ_c, remains constant for measurements at constant temperature.

The mobility component due to the irradiation-induced defects, which will be specified as μ_D, does not remain constant, however, but changes because of increased flux since the number of induced defects is proportional to the flux. Thus, the mobility charge is due only to the irradiation-induced defects.

The mobility vs. flux curves used in this work could be replotted as mobility vs. ionized defect density. Thus, for these curves to have a maximum, as is observed for the neutron case, the following condition would necessarily exist:

$$\frac{\partial \mu}{\partial N_I} = 0.$$

Due to the fact that the relaxation times, K_l and K_i, depend differently on the velocity, the mobilities, μ_L and μ_I, cannot be added directly, but must be added by the following formula as shown by Debye and Conwell:[43]

$$\mu = \mu_L \left[1 + M^2 \left\{ Ci\ M \cos M + Si\ M \sin M - \frac{\pi}{2} \sin M \right\} \right]$$

where μ is the total mobility, μ_L is the lattice scattering component of the mobility, Ci and Si are the integral cosine and integral sine functions respectively, and

$$M^2 = 6\,\mu_L/\mu_I .$$

Thus,

$$\frac{\partial \mu}{\partial N_I} = \frac{\partial \mu}{\partial M} \cdot \frac{\partial M}{\partial \mu_I} \cdot \frac{\partial \mu_I}{\partial N_I} .$$

Since the integral sine and cosine functions are difficult to differentiate explicitly, the function, μ, and its derivative, $\partial\mu/\partial M$, were plotted by an IBM 704 computer.

The derivative, $\partial\mu/\partial M$, has no zero point (Figure 12), and hence, $\partial\mu/\partial N_I$ has no zero either since

$$\frac{\partial \mu}{\partial N_I} = \frac{\partial \mu}{\partial M} \cdot \left(\frac{\partial M}{\partial \mu_I} \cdot \frac{\partial \mu_I}{\partial N_I} \right)$$

and it can be shown that

$$\frac{\partial M}{\partial \mu_I} \cdot \frac{\partial \mu_I}{\partial N_I} = \left(\frac{6\,\mu_L K}{N_I} \right)^{\frac{1}{2}}$$

where K is a constant.

Therefore, since $\partial\mu/\partial N_I$ has no zero point, the curve of mobility vs. flux can have no maximum, and the model which depicts the neutron damage site as simply a charged scattering center is incapable of explaining this experimental data.

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[43] Debye, P. P. and Conwell, E. M., "Electrical Properties of n-Type Germanium," Phys. Rev., vol. 93, 1954, p. 693.

APPENDIX III

EFFECT OF MEASURING TECHNIQUE ON DRIFT MOBILITY

Now that it has been shown that charge center scattering from the radiation induced defects cannot cause an increase in mobility, but on the contrary, decreases the mobility, it is necessary to determine whether the measuring technique has any effect on mobility.

The most important question is whether the measurement could cause an increase in mobility for neutron irradiated material.

In making the measurements, it is necessary to bring the emitter and collector points closer together as the radiation dose is increased, because of the decrease in lifetime of the injected carriers. This decrease separation can conceivably cause slight changes in the drift path of the carriers, or could increase the effect of the localized field set up by the injected carriers. For both electron and neutron irradiated material it was necessary to decrease the emitter-collector separation; in fact for electron irradiation, the separation was decreased even more than it was for the neutron case.

A careful examination of the drift mobility of minority carriers as a function of electron flux was carried out to see if electron irradiation would also yield this mobility increase. The results of these experiments were all negative. Therefore, since the measurement technique and the sample geometry were the same for both electron and neutron irradiation, and since the technique did not yield an increase in drift mobility of the minority carriers due to electron irradiation, it can be concluded that the observed increase for the case of neutron irradiation was not due to the measuring technique, but was in fact due to the damage site itself.

The next question of importance is, can the measuring technique used in these experiments cause a decrease in the mobility which would add to the decrease caused by charged center scattering, thereby yielding false values for the mobility?

An experimental answer to this question was obtained for the case of no irradiation by measuring the drift mobility for various probe separations. It was found that the measured drift mobility for probe separations varying between .4 mm and 1.2 mm, which was the general range of separation used throughout the experiments, was constant to within the experimental accuracy. Thus, any decrease beyond that resulting from regular ionized impurity scattering was also due to the damage sites, and was not attributable to the measuring technique.

It should be stated at this point that a comparison of drift mobility vs. electron flux (Figure 5), or radiation induced defects, with the work of Prince [44] (Figure 13), which shows drift mobility as a function of ionized chemical impurities, demonstrates that every radiation induced defect would have to have a charge of ± 6 to account for the decrease mobility if charge center scattering were the only mechanism affecting drift mobility. However, even though charge center scattering by point defects may not account for the total decrease in mobility which is observed experimentally, the experimental measurements are nevertheless true drift mobility readings.

A comparison of the experimental results for electron and neutron irradiated germanium is given in Figure 14.

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[44] Prince, M. B., op. cit. (ref. 7).

APPENDIX IV

EFFECT OF VARIOUS MISCELLANEOUS FACTORS ON THE DRIFT MOBILITY

In addition to the effect of charge center scattering and the measuring technique on mobility, there are several other mechanisms which could affect the mobility, and hence should be given some consideration. Among these are (a) neutral impurity scattering, (b) scattering due to the chemical impurities which are caused by transmutations due to thermal neutrons, and (c) the effect if the mobility were a function of probe separation. There are some other effects also, such as electron-electron scattering and scattering due to dislocations.

The scattering of dislocations has been treated by Dexter and Seitz[45], and as shown, it should be negligible for the case under consideration here. The effect of electron-electron scattering, or for this case, hole-hole scattering, is very difficult to calculate, and usually only an upper limit for the size of the effect can be obtained. Herring has pointed out that it is possible to compute this upper limit for the size of the effect utilizing the usual simplifying assumptions about band structure. If the hole-hole collisions were completely effective in randomizing the drift velocities, the hole distribution in an electric field would be a Maxwellian distribution centered about the drift velocity. It can be calculated that the maximum effect of these collisions will be to multiply the ionized impurity mobility by a factor of .3, and the lattice mobility by a factor of .88[46].

In order to add the lattice scattering and ionized impurity scattering mobility by the method set forth by Debye and Conwell, and used in Appendix II, the

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[45] Dexter, D. L. and Seitz, F., "Effects of Dislocations on Mobility in Semiconductors," Phys. Rev., vol. 86, 1952, p. 469.

[46] Sodha, M. S., "Scattering and Drift Mobility of Carriers in Germanium," Progress in Semiconductors 3, John Wiley and Sons, New York, 1958.

effect of hole-hole scattering must be neglected. However, since the theoretical and experimental data did not completely agree, it was necessary to take the hole-hole scattering effect into account in this experiment. This can be done relatively simply if the only effect of the hole-hole scattering is to reduce the lattice and impurity scattering mobilities by the amount shown above. For the maximum effect on the ionized impurity mobility, which can be expected here because of the high density of holes, the hole-hole scattering can reduce the mobility by a factor of approximately two.

For the case of neutral impurity scattering it will be assumed that in addition to the other damage introduced by the neutrons, they will also produce some neutral scattering centers. Suppose it is assumed that the effect of neutral scattering on the mobility may be added in a direct fashion, such as

$$\frac{1}{\mu} = \frac{1}{\mu_{LI}} + \frac{1}{\mu_N}$$

or as

$$\mu = \mu_o + \mu_v - \mu_I - \mu_N$$

which is the form used in this analysis, where μ is the measured mobility, μ_{LI} is lattice scattering and ionized impurity scattering mobility, μ_o is the initial mobility, μ_v is the void contribution to mobility, μ_I is the irradiation induced charge center scattering mobility, and μ_N is the neutral impurity scattering mobility. Then it is found that for the flux where the mobility is equal to the initial mobility, the neutral scattering component of μ should be approximately 2000 $cm^2/Vsec$. Then from the following formula

$$\mu_N = \frac{1}{20} \frac{m_n e^3}{N_N k h^3}$$

where μ_N is the neutral scattering mobility, k is the dielectric constant, h is Planck's constant, m_n is the effective mass of the hole, and e is the electronic charge, N_N, the neutral scattering center concentration, can be

calculated. From the above calculation it is found that N_N should be approximately 10^{20} neutral scattering centers per cubic centimeter in order to cause the desired mobility change. It is impossible to imagine such a concentration of neutral scatterers, or for that matter, even one 10^{-3} times that concentration; therefore, it is assumed that neutral scattering is not important in the case at hand.

When neutron sources such as Omega West or the Godiva are used, there is always some thermal or slow neutron flux which will cause transmutations, thereby giving rise to more chemical impurities in the sample which will cause scattering. For germanium the transmutations go to Gallium and Arsenic, which are also the chemical doping agents; hence, their effect on the mobility should add directly to that of the chemical impurities already present in the germanium. The total number of chemical impurity scattering centers can be calculated from the formula,

$$N_s = \sigma_T \lambda \phi N_A$$

where N_s is the total number of chemical impurity centers caused by the thermal neutron flux, σ_T is the total atomic cross section for germanium (which is given by Cleland and Crawford[47] to be 2.3×10^{-24} cm^2), λ is the ratio of thermal to fast neutron flux (7:1 for Omega West), ϕ is the measured fast neutron flux, and N_A is the number of germanium atoms per cm^3.

For the fast neutron flux, at which the drift mobility is equal to the initial mobility, N_s is found to be approximately 10^{13} chemical impurities/cm^3. Since the initial concentration was 3×10^{14} /cm^3, this is only a 3 per cent change in impurity concentration and would not cause any appreciable change in the mobility.

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[47] Crawford, J. H. Jr. and Cleland, J. W., Conference on Radio Isotopes in Research and Industry, Copenhagen, Denmark, September, 1960.

The final problem to be considered in this section is that of a variable mobility, i.e., a mobility which varies with length through the samples. In all analyses, mobility is assumed to be a constant independent of the position on the sample. But in the case of neutron bombardment it is conceivable that there could be some situations in which mobility could vary with length. Therefore, the following analysis was made:

Starting with the continuity equation for the case of no external exciting agencies, it is seen that

$$\frac{dP}{dt} = \frac{P}{\tau_p} - \frac{1}{q} \nabla \cdot I_p$$

where dP/dt is the change in excess hole concentration with time, P is the excess hole concentration, τ_p is the hole lifetime, q is the electronic charge, and I_p is defined as

$$I_p = q\mu_p PE - q D_p \nabla P$$

where μ_p is hole mobility, E is the electric field, D_p is the hole diffusion coefficient, and ∇P is the hole gradient. Then the continuity equation becomes

$$\frac{dP}{dt} = \frac{P}{\tau_p} - \frac{1}{q} \nabla \cdot \left(q\mu_p PE - q D_p \nabla P \right).$$

For the one dimensional case and a variable mobility this reduces to

$$\frac{dP}{dt} = - \frac{P}{\tau_p} - \mu_p E \frac{dP}{dx} - PE \frac{d\mu_p}{dx} + D_p \frac{d^2 P}{dx^2}.$$

Assuming that P is a product function of x and t, a general solution for this equation was tried, but found to be impossible. Therefore, some specific solutions were obtained with the aid of an analog computer.

The variations in μ_p which seemed most probable were, (a) a linear variation with x in the form of

$$\mu_p = \mu_o (1 \pm \epsilon x)$$

where μ_p is the measured mobility and μ_o is the mobility at x_o (and is taken as the standard mobility value), and (b) a variation in the form of a delta function.

The linear variation solution obtained by the computer for a variation in mobility of 20 per cent is shown in Figure 15. The solution says that a linear variation in mobility could not cause the observed experimental results, but could cause either an increase or a decrease depending upon the sign of the ϵx term. If the sign of the ϵx term is positive and there is an increase in mobility with x, then for a sample which has been uniformly irradiated, i. e., no defect concentration gradients, a mechanism similar to the Gossick model again must be assumed to explain this increase. This must be done unless the defects are mobile and can concentrate at dislocation lines, thereby setting up conditions which can lead to a delta function change in the mobility. A mobility variation in the form of a delta function becomes very difficult to analyze mathematically; an analysis of the assumed physical picture is much more comprehensible.

The regions where the mobility would experience this large increase are quite small, on the order of 1000 Å or less. Since the point contacts used in the experiments are many times larger than this, only an average effect of these regions could be observed. Thus, if these regions could exist, their presence would cause the mobility to show an average increase as a function of probe separation. Thus on a large scale, the delta function variation in mobility reduces to the same solution for the continuity equation as the linear mobility variation did. For both a delta function variation and a linear variation, the results show an increase or decrease in mobility as a function of probe separation, but neither case can give first an increase and then a decrease in mobility for nearly constant probe separation, as the experimental results indicate. Therefore, a variation in mobility as a function of probe separation was considered unimportant; that is, the observed experimental results would not be indicated in the mathematical solution of the problem assuming a variable mobility.

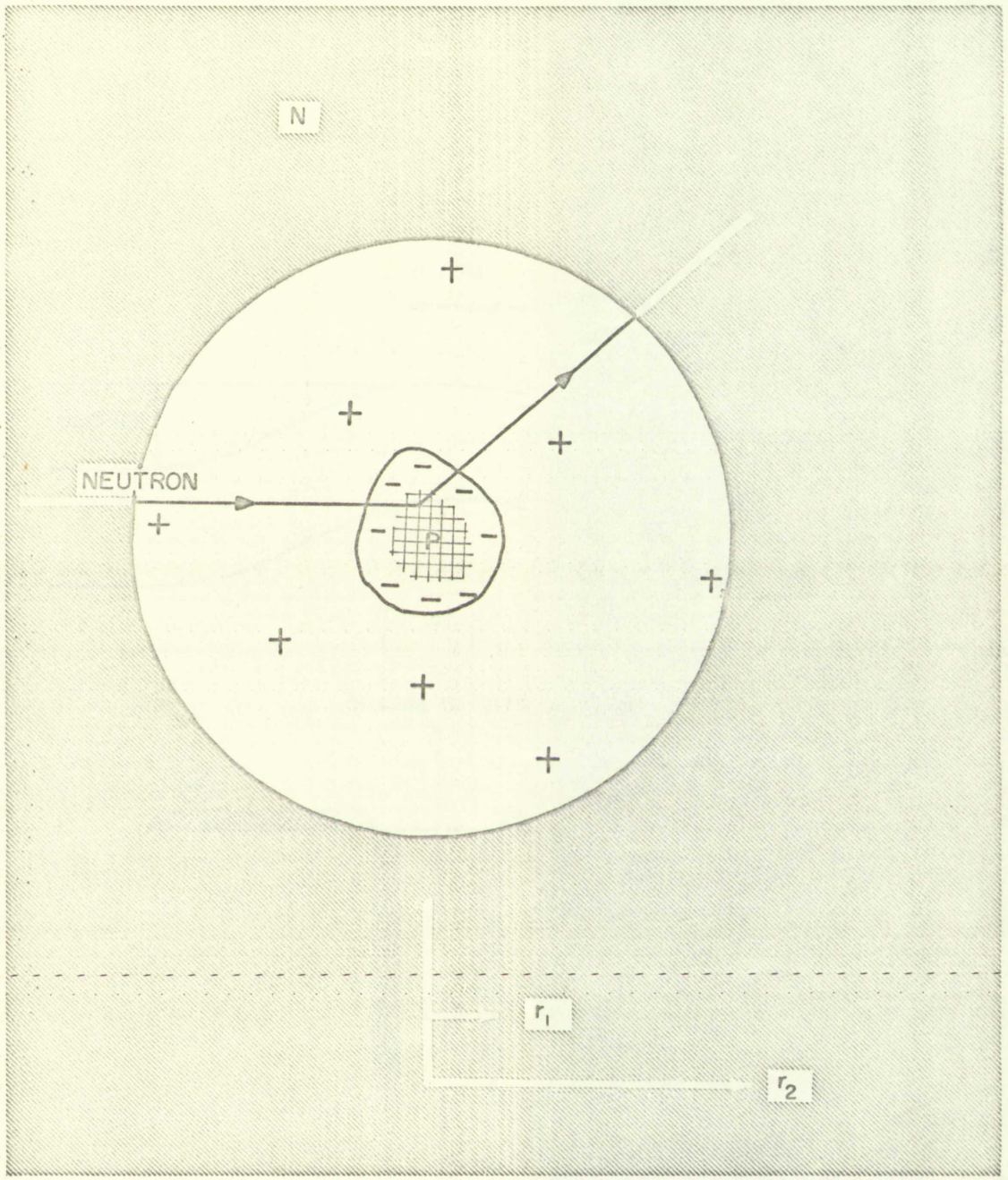

Figure 1

Schematic illustration of a disordered region in n-type germanium (after Gossick)

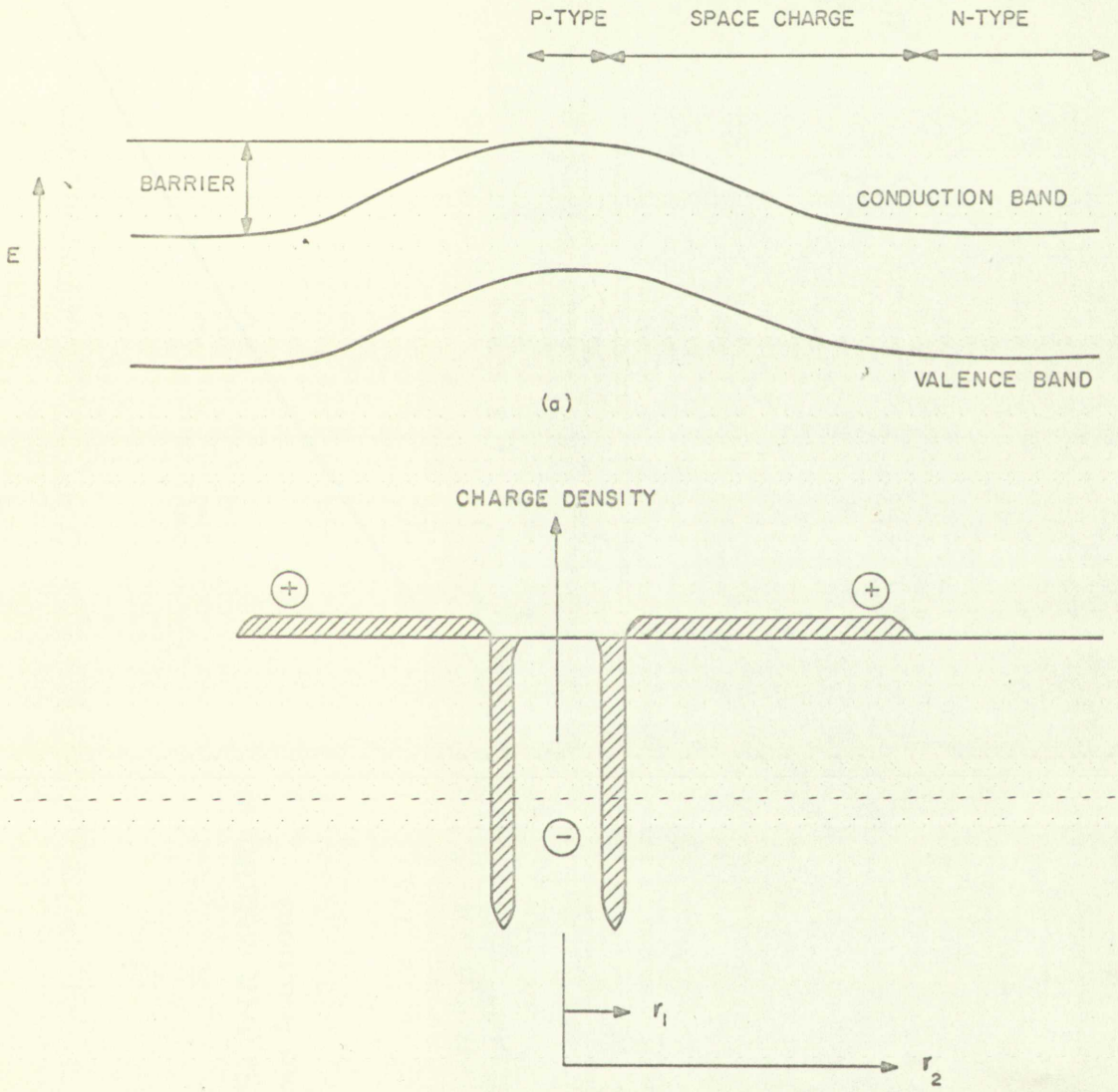

Figure 2

(a) Conduction and valence electron energy band edges

(b) Charge density vs. distance from center of the disordered region (after Gossick)

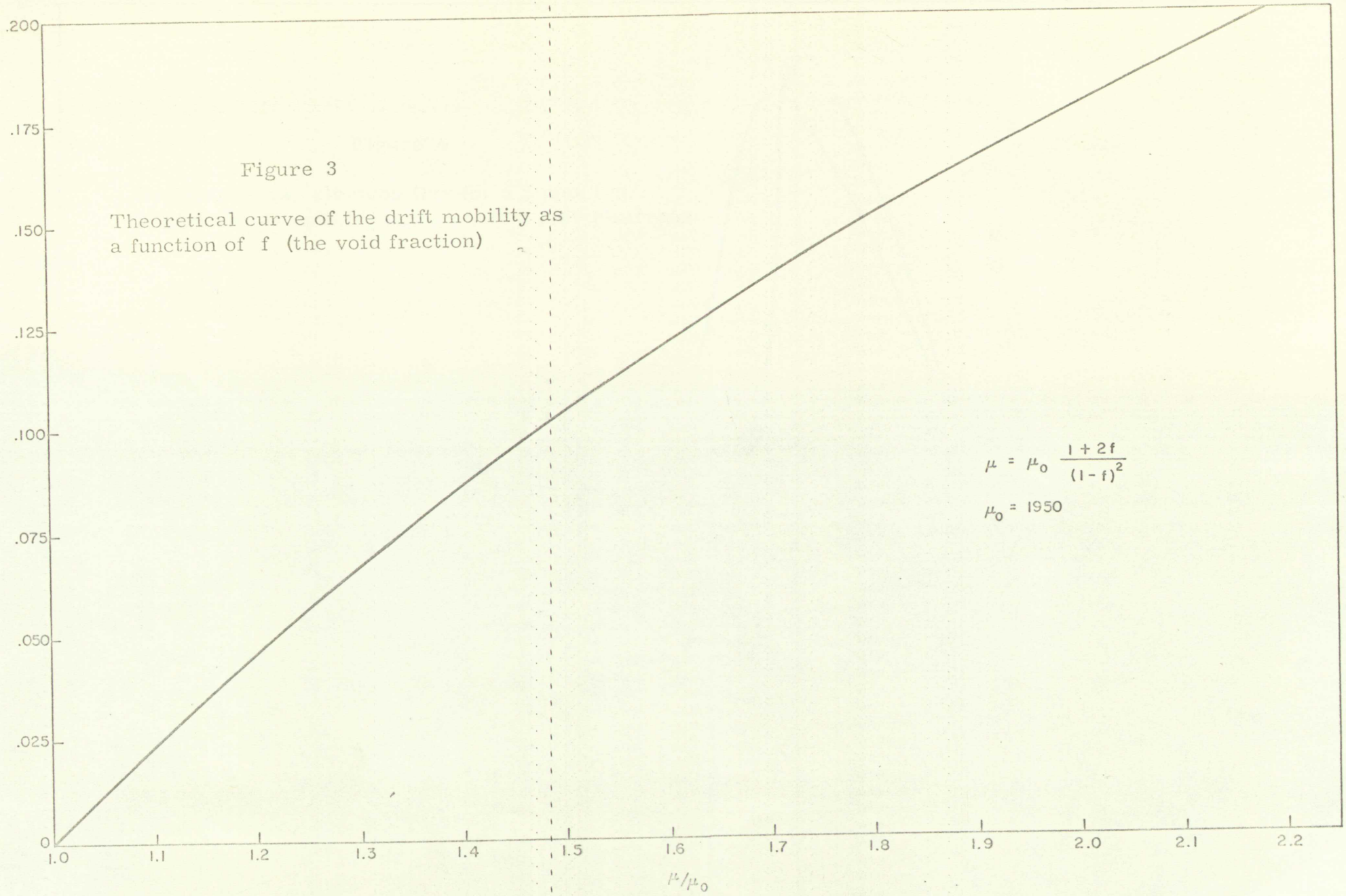

Figure 3

Theoretical curve of the drift mobility as a function of f (the void fraction)

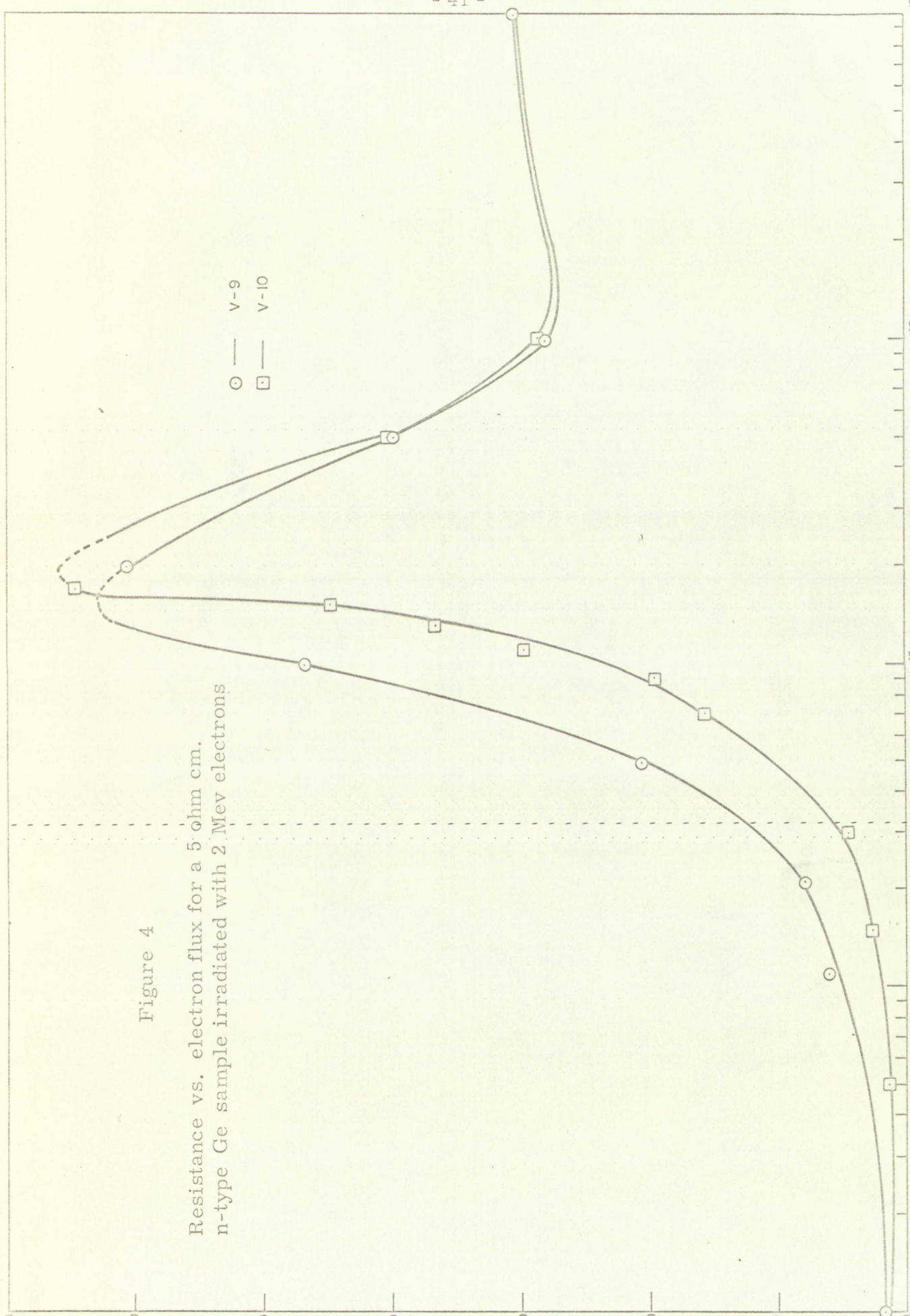

Figure 4

Resistance vs. electron flux for a 5 ohm cm.
n-type Ge sample irradiated with 2 Mev electrons

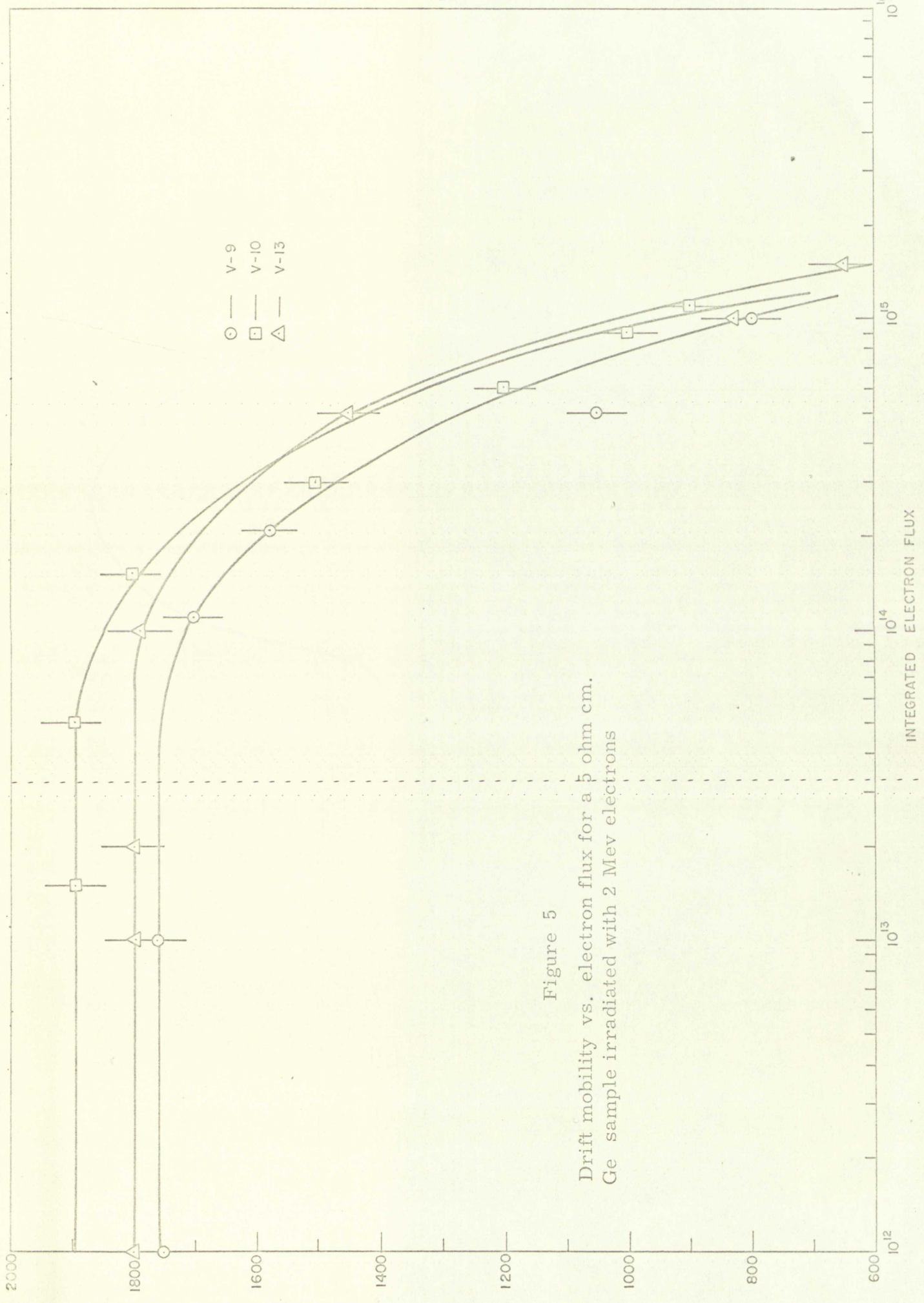

Figure 5

Drift mobility vs. electron flux for a $\frac{1}{2}$ ohm cm. Ge sample irradiated with 2 Mev electrons

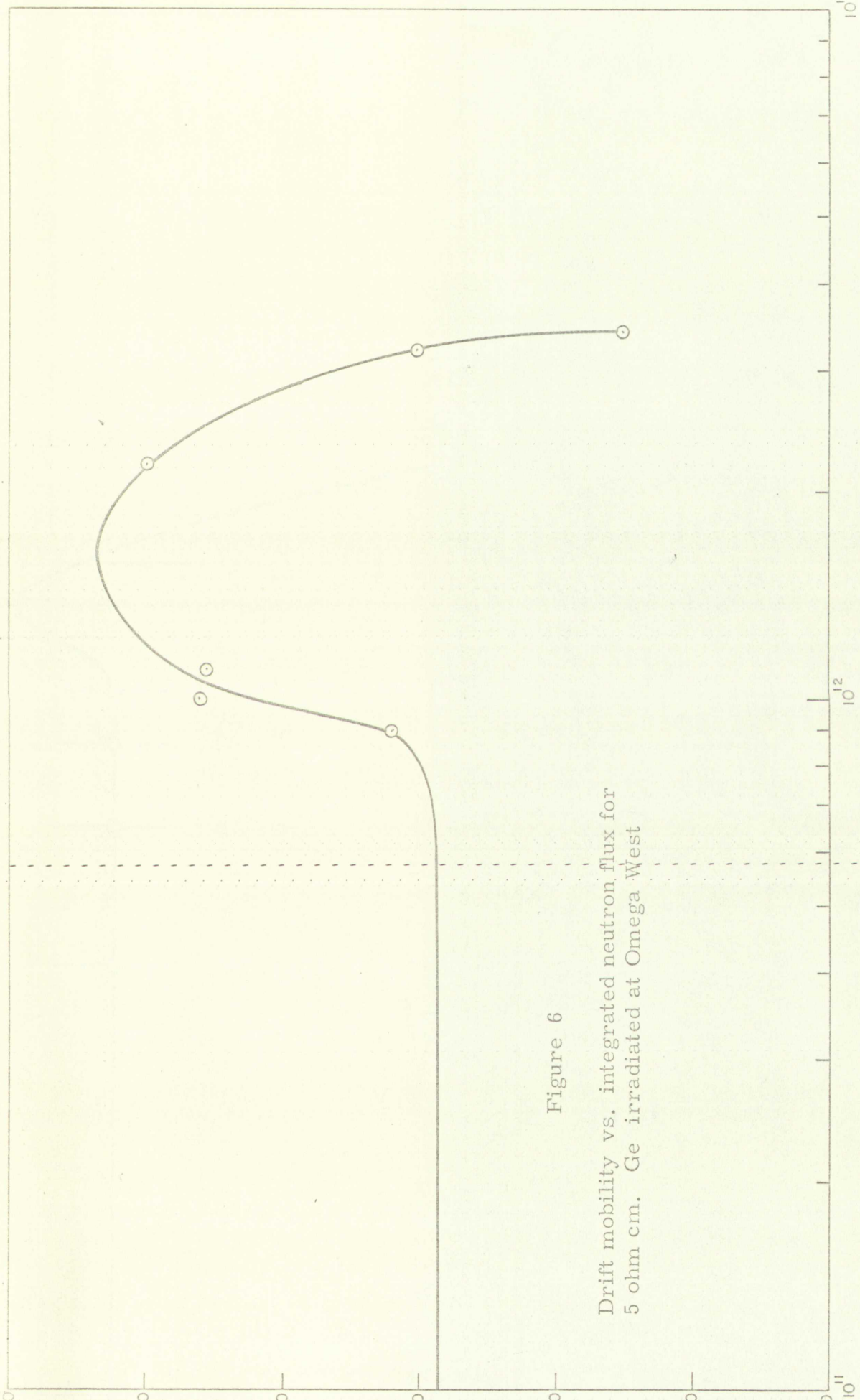

Figure 6

Drift mobility vs. integrated neutron flux for 5 ohm cm. Ge irradiated at Omega West

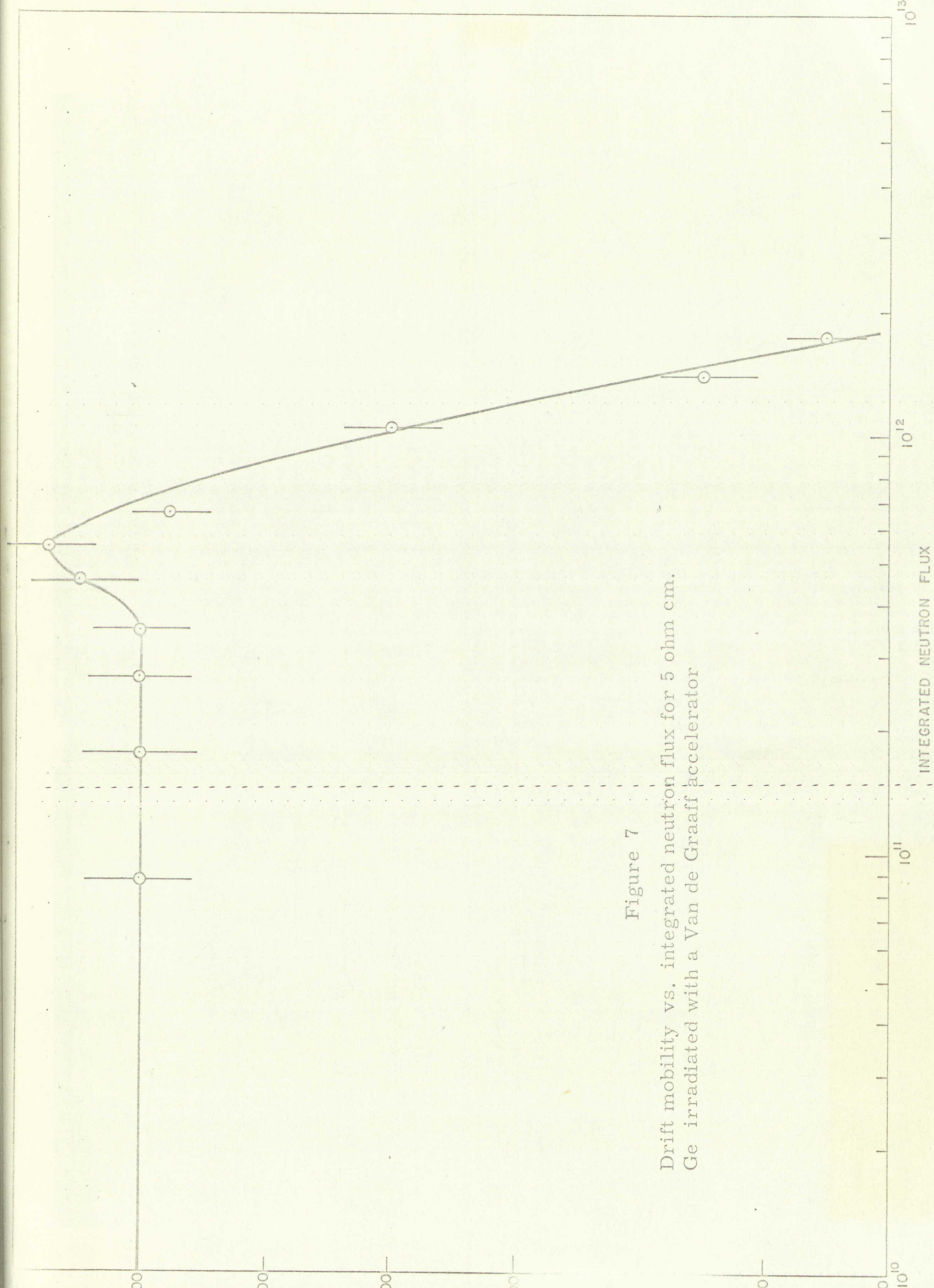

Figure 7

Drift mobility vs. integrated neutron flux for 5 ohm cm. Ge irradiated with a Van de Graaff accelerator

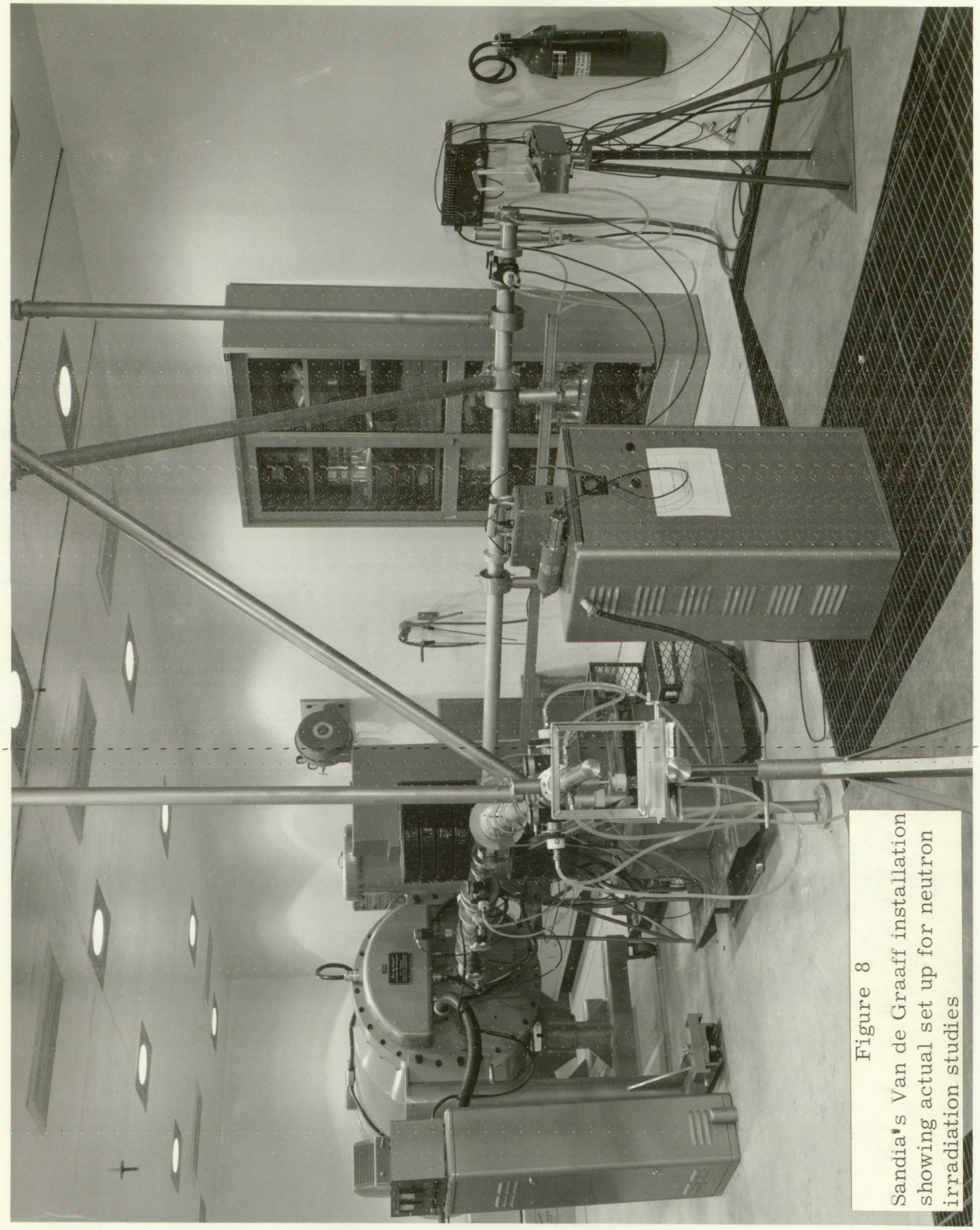

Figure 8

Sandia's Van de Graaff installation showing actual set up for neutron irradiation studies

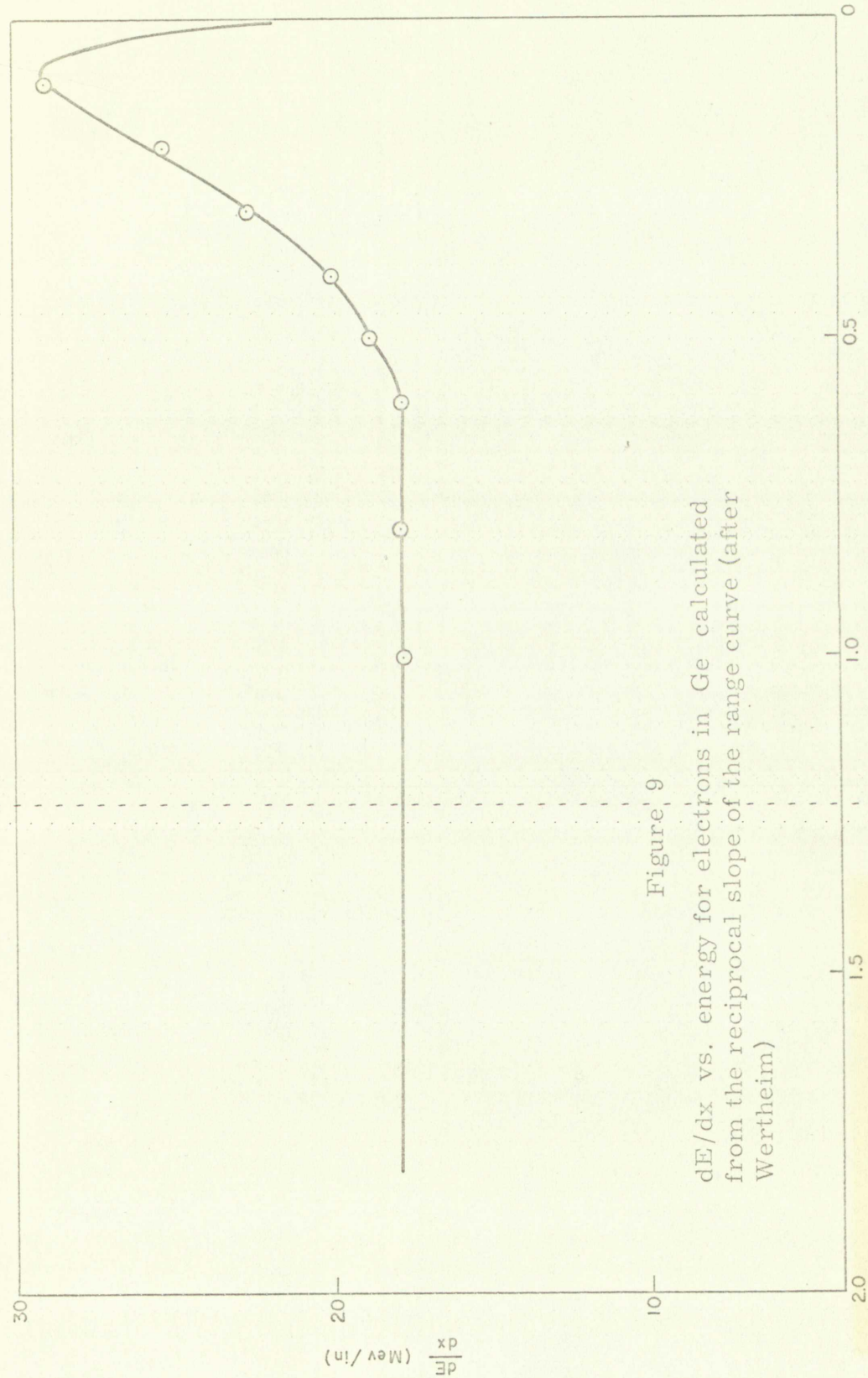

Figure 9

dE/dx vs. energy for electrons in Ge calculated from the reciprocal slope of the range curve (after Wertheim)

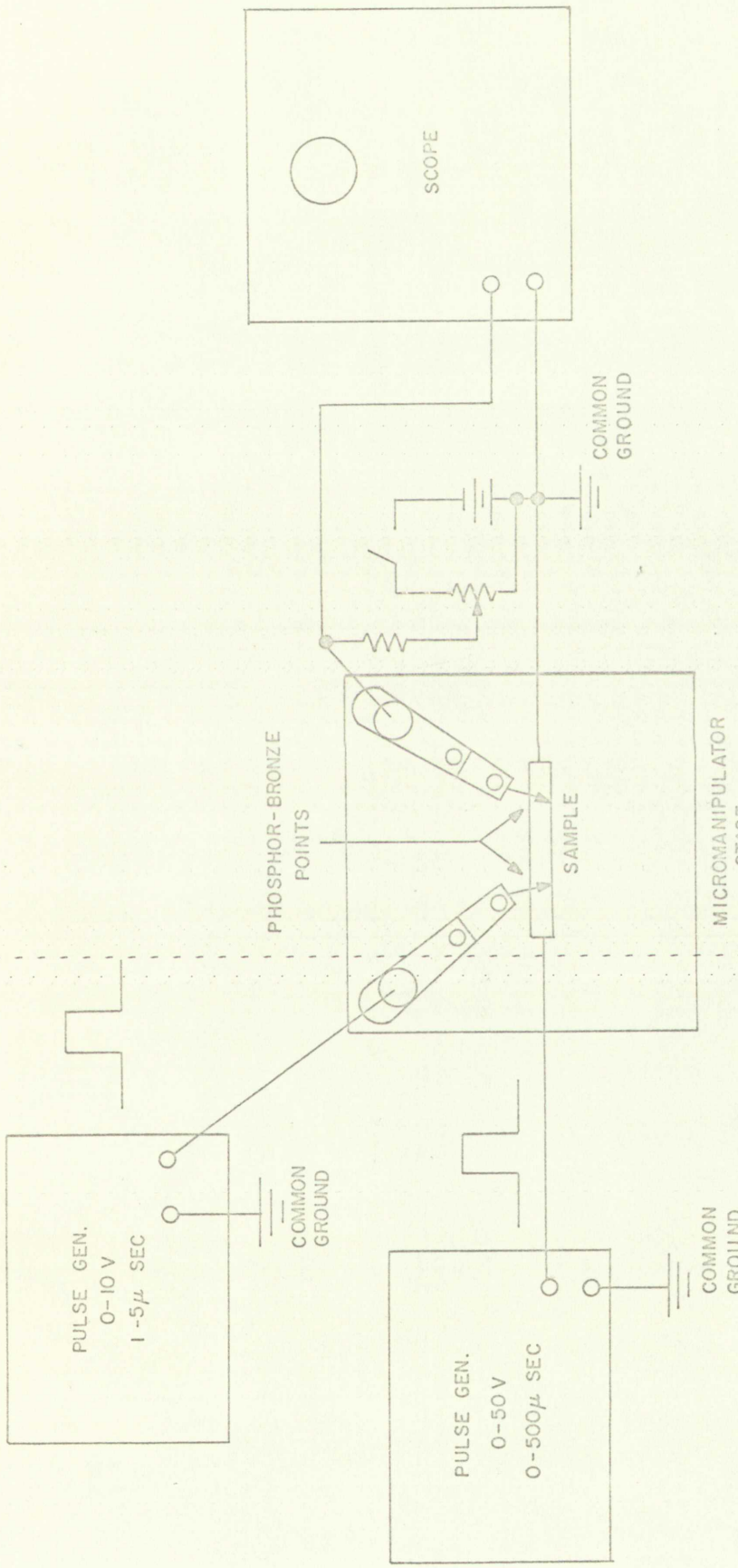

Figure 10

Standard Haynes drift mobility measuring circuit with pulsed electric field

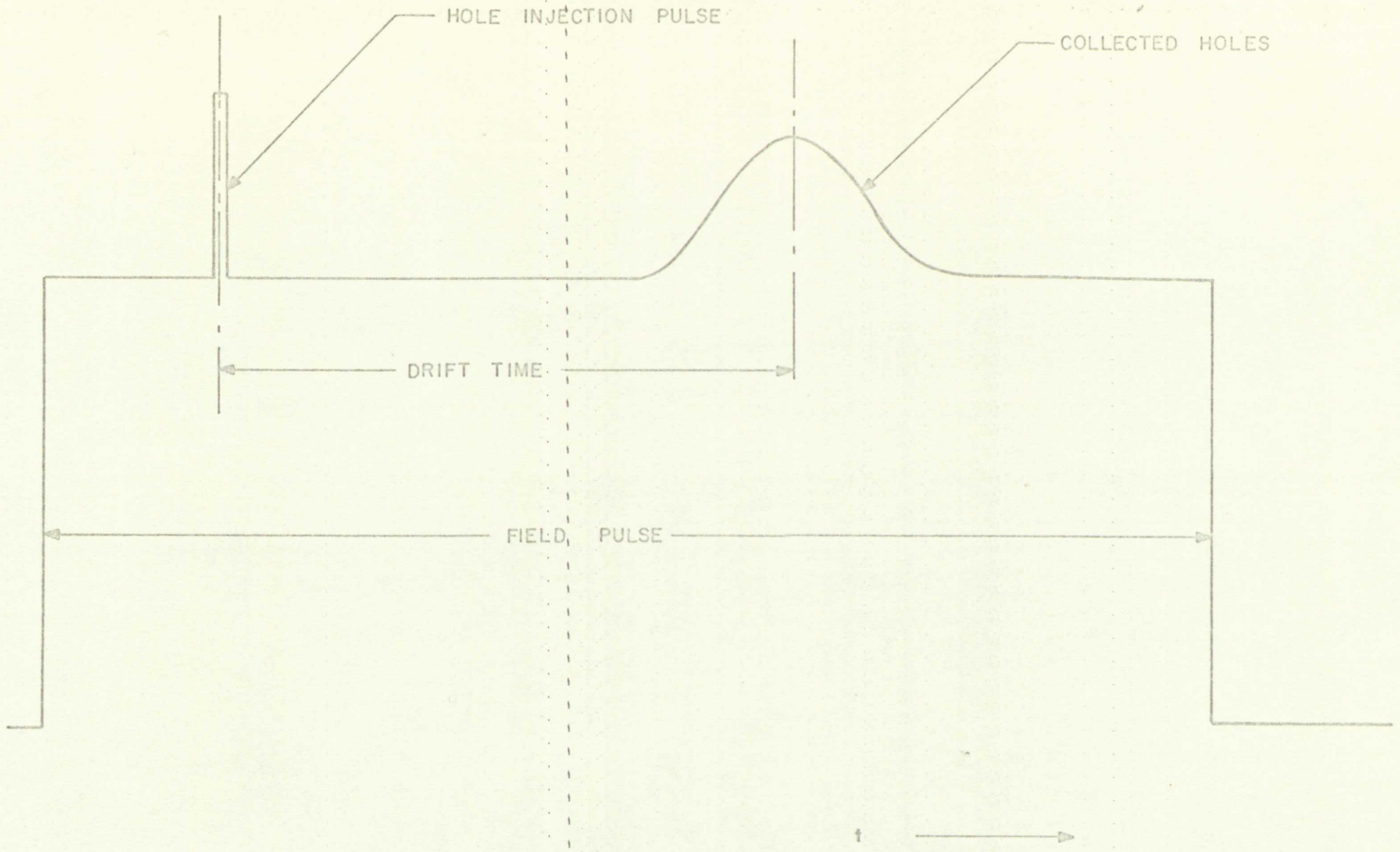

Figure 11

Representation of the oscilloscope picture from which drift mobility is measured

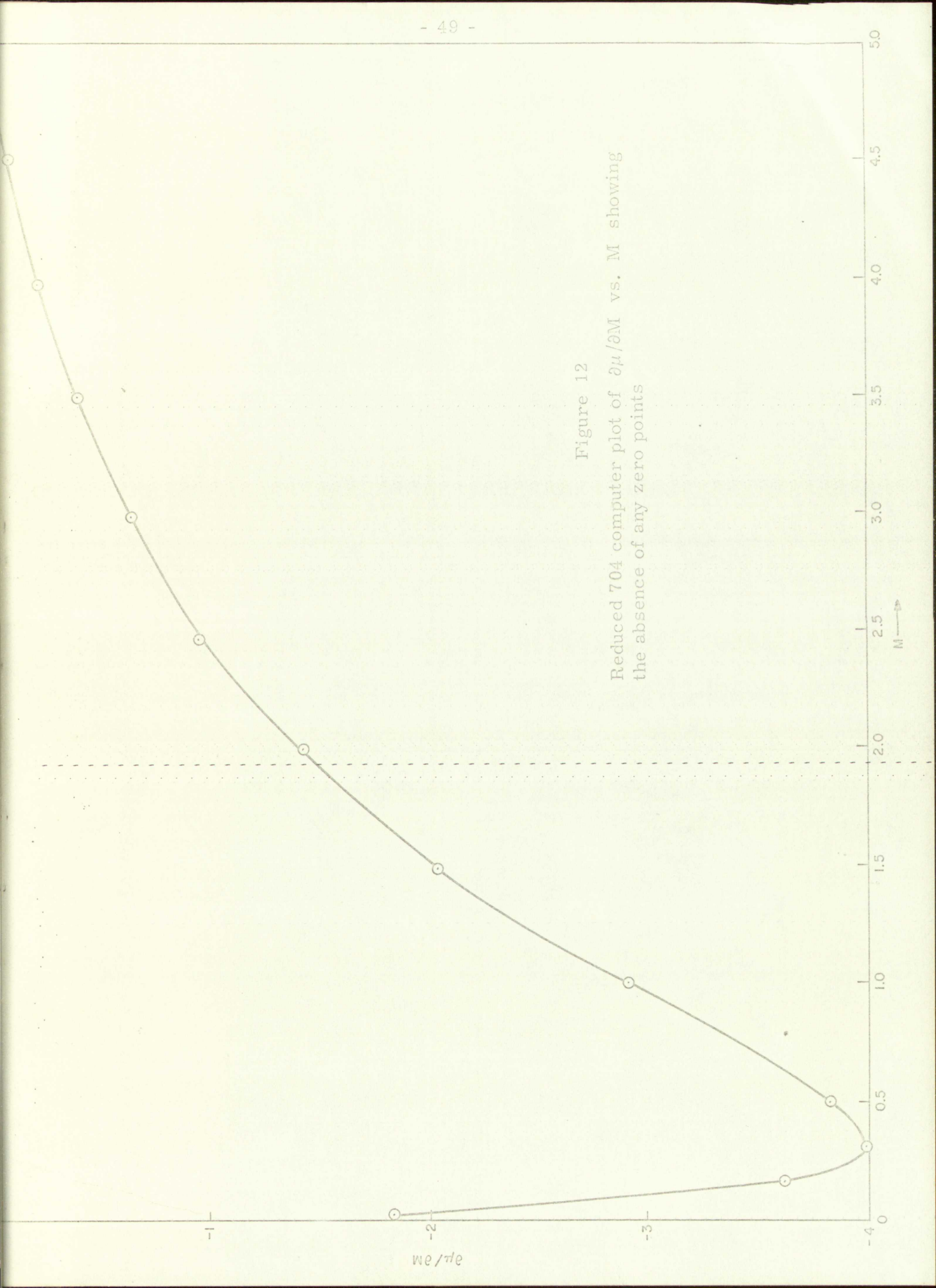

Figure 12

Reduced 704 computer plot of $\partial\mu/\partial M$ vs. M showing the absence of any zero points

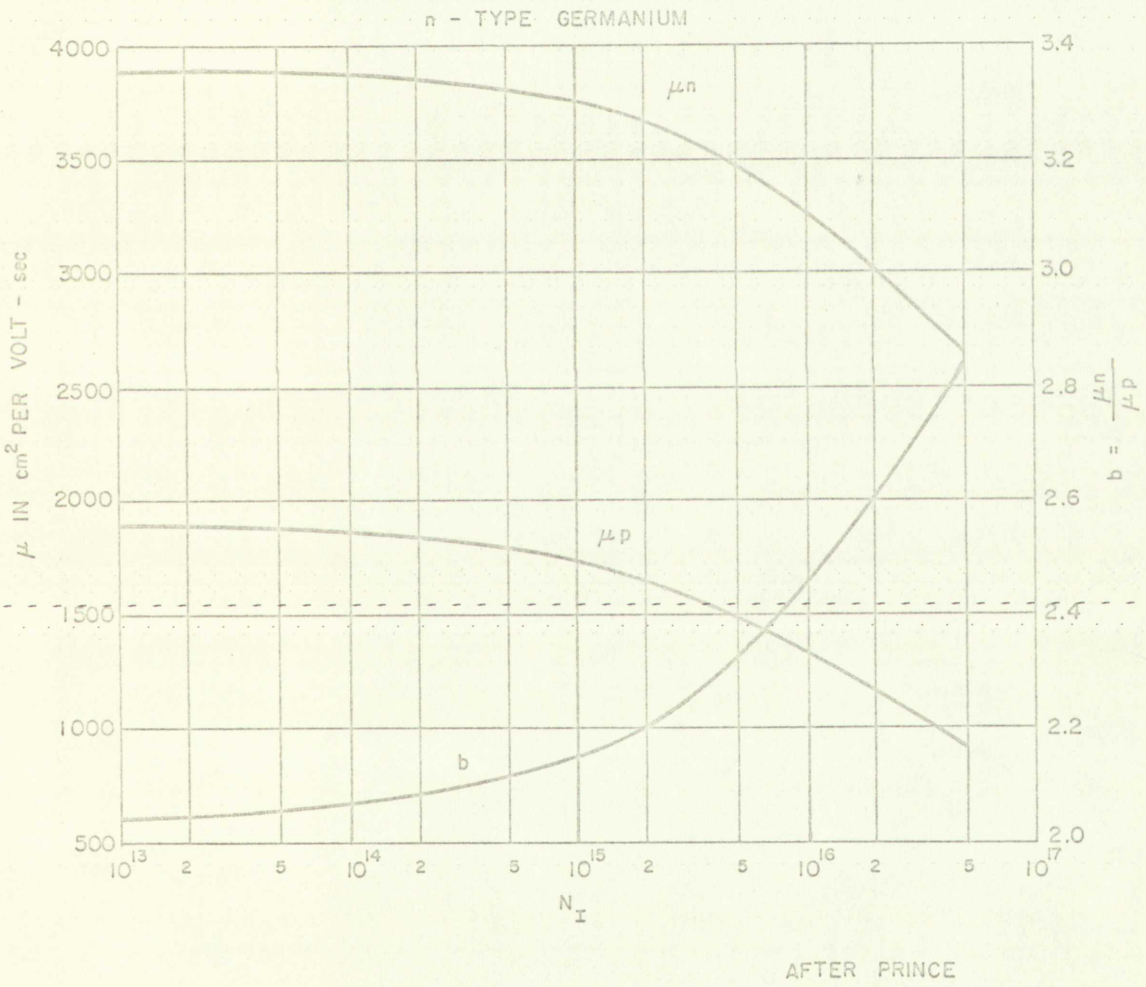

Figure 13

Mobility as a function of ionized impurity density (after Prince)

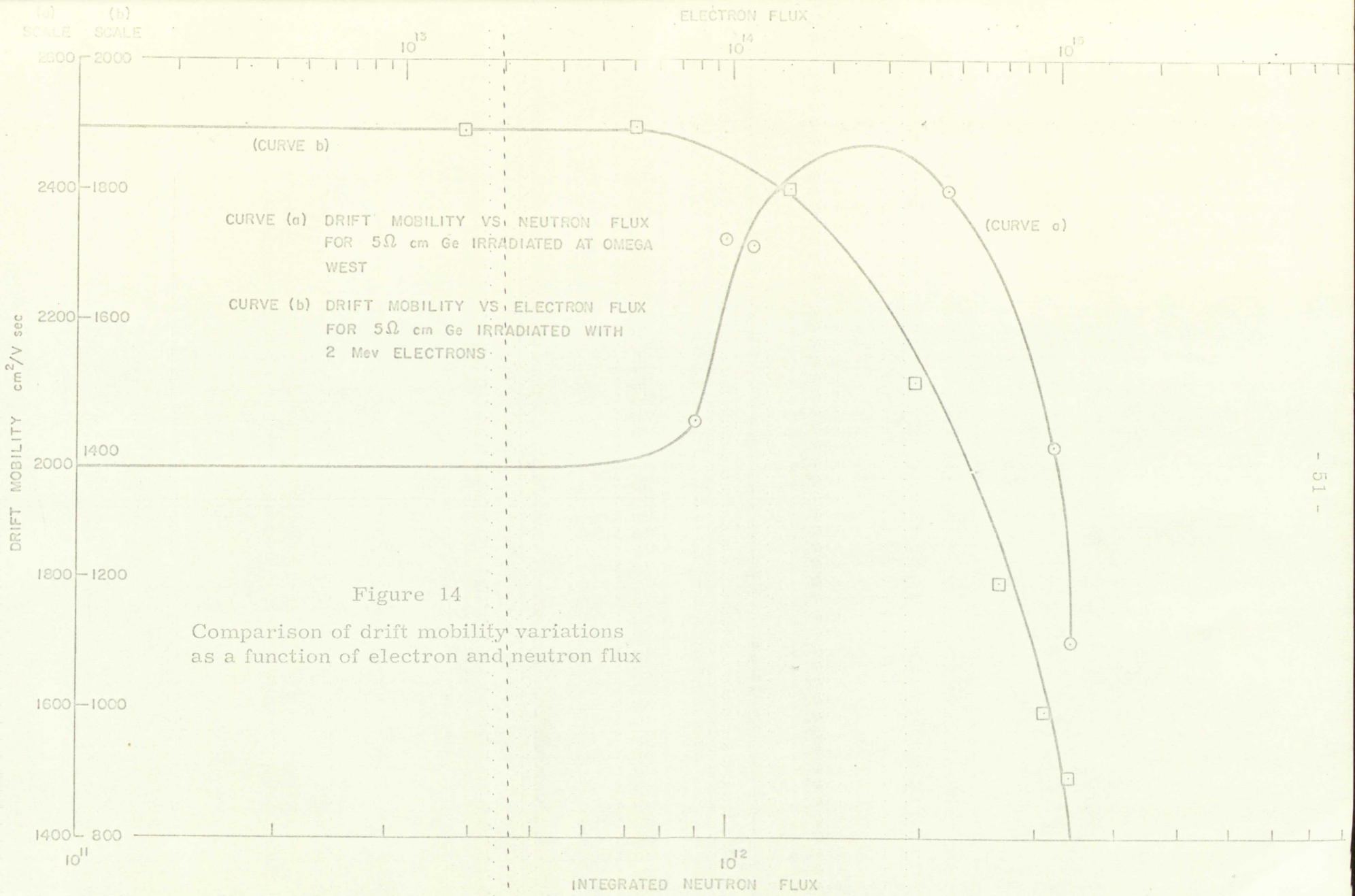

Figure 14

Comparison of drift mobility variations as a function of electron and neutron flux

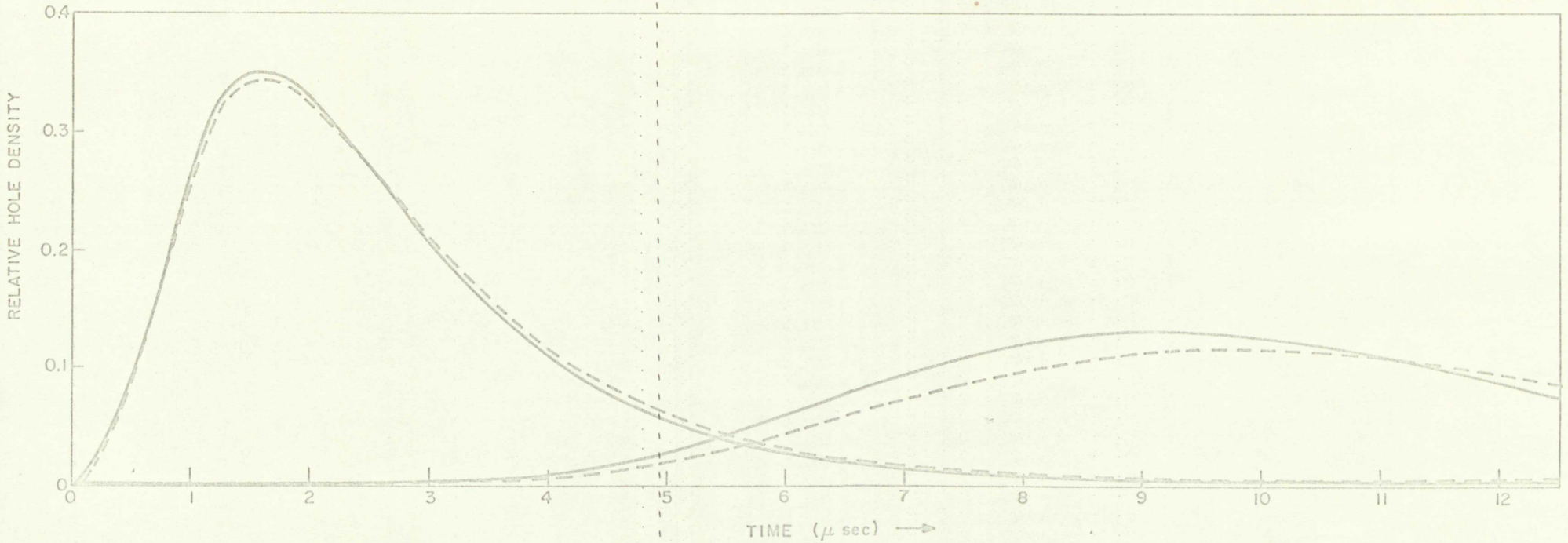

Figure 15

Analog computer plot of hole concentration as a function of space and time assuming a linear variation of mobility of 2 and 20 per cent

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