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EFFECTS OF ELECTRON IRRADIATION ON P-TYPE GERMANIUM
AT LIQUID HELIUM TEMPERATURES USING AC HOPPING CONDUCTIVITY

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October 1973

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Raymond Mervin Roop, Ph.D.
Department of Physics
University of Illinois at Urbana-Champaign, 1973

P-type germanium single crystals (8×10^{14} Ga/cm³ and 6×10^{15} Ga/cm³) were irradiated with 1.1 MeV electrons at pumped liquid helium temperatures and defect production and annealing studied using ac hopping conductivity. Production rates obtained from measurements at 1.5 K and 10^4 Hz were .6 cm⁻¹ for samples doped 6×10^{15} Ga/cm³ and .11 cm⁻¹ for samples doped 8×10^{14} Ga/cm³. Above 10^{14} e/cm² fluence the production rates for the higher doped samples decreased to approximately .06 cm⁻¹ at 10^{15} e/cm² fluence except for one sample which was anomalous. No such long irradiation of the low doped samples was made. The apparent inconsistency between these results and production rates of less than 3×10^{-4} cm⁻¹ observed by previous workers has been resolved by introducing a donor level for the defect produced by irradiation near the chemical acceptor level, so that the defect would be neutral at temperatures near 30 K and charged +1 at 1.5 K. Some surface effects were seen which did not affect production rate measurements at 1.5 K more than +10% but did influence annealing behavior at 100 K. The fact that the production rate observed increases with the impurity concentration leads one to propose that some defects must be mobile at the irradiation temperatures, which were usually 1.8 K. The fact that the production rate was 0.11 cm⁻¹ +27% in the low doped p-type samples instead of 1.4 cm⁻¹ or $0.95 \pm .05$ cm⁻¹ as observed by other workers in n-type samples of similar dopant concentration also supports this conclusion. This led to the suggestion that germanium and silicon are similar as far as lattice vacancy and interstitial

behavior. The similarity of the migration energies of the doubly negative vacancy in silicon to the activation energy of 65 K stage in n-type germanium thus indicates that this stage could be due to vacancy migration. The migration energy of the neutral vacancy in silicon is similar to the activation energy of the 200 K stage in p-type germanium observed by other workers.

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I. INTRODUCTION

The purpose of this experiment is to study the defect production and recovery found in p-type germanium at low temperatures after bombardment with 1.1 MeV electrons.

When n-type germanium is irradiated at liquid helium temperatures doubly negative defects are produced.^{1/} However, in lightly doped p-type material irradiated with 1 MeV electrons no charged defects have been observed immediately after irradiation by previous authors.^{2/} Illumination with less than band gap light causes charged defects to appear in irradiated p-type samples.^{2/}

Recent experiments have suggested that defects are mobile in silicon^{3,4/} and gold^{5/} at temperatures below 5 K.

Ac hopping conductivity has been used by McKeighen^{4/} to study electron irradiation damage in silicon. However, no annealing peaks were observed. It seems useful to use the ac hopping method in a material which has a well-studied annealing stage to verify that the method gives results consistent with other methods for monitoring radiation damage in semiconductors. Since n-type germanium is suitable for this purpose, this material was irradiated and the production and annealing compared with other experiments.

To the author's knowledge, no experiments have been carried out in which electrical measurements were made below 30 K on irradiated moderately doped p-type germanium. In the present study, measurements have been made down to 1.4 K. The technique used to monitor defect production and annealing was ac hopping conductivity.

II. DISCUSSION OF AC HOPPING CONDUCTIVITY

Many electrical measurements used to monitor defect concentrations in semiconductors, such as Hall effect and the capacitance-voltage relationship of a metal-semiconductor surface-barrier diode depend on a sizable number of charge carriers being present in the conduction or valence band. Such methods can therefore not be used much below 10 K in moderately doped germanium. Ac hopping conductivity, on the other hand, can be used down to below 1 K.

Consider a crystal doped with a large number N_D of donors and a smaller number N_A of acceptors. Near $T = 0$, the following conditions apply.

1. Essentially no electrons will be in the conduction band and no holes in the valence band.

2. All of the acceptors will be negatively charged.

3. $N_D - N_A$ donors will be positively charged and the rest will be neutral. Figure 1 illustrates this situation. A number of neutral donors are shown in the vicinity of a charged acceptor. One of the donors is ionized and the rest are neutral. A suitable electric field applied to the sample causes the positive charge on the one donor to jump to a donor farther from the charged acceptor. An alternating field will cause the positive charge to hop back and forth between two donor atoms. This hopping process is assisted by the phonons of the crystal. The changing dipole moment between the two charges due to the hopping gives rise to a polarization current. The part of the polarization that is in phase with the applied field is measured as a conductance. The part of the polarization 90° out of phase with the applied field is measured as a capacitance.

Figure 1: Three-dimensional representation of a random distribution of majority atoms in the coulombic potential of the negatively charged acceptor. See Reference 6 for details.

The theory of hopping conductivity has been developed by Pollak and Geballe,^{6/} Pollak,^{7/} Golin,^{8/} Miller and Abrahams,^{9/} and Scher and Lax,^{10/} among others.

Pollak^{7/} has estimated the maximum doping at which the hopping can be thought of as occurring between a pair of majority dopant sites. Above this concentration hopping occurring in groups of three or more sites makes a significant contribution to the conductivity. This maximum doping is given by

$$N_{MAJ} \approx .007 r_T^3 / r_\omega^6 \quad (1)$$

where

N_{MAJ} = the maximum majority doping

r_T = $e^2 / 4\pi K k T$

e = electronic charge

K = dielectric constant (MKS units)

k = Boltzmann constant

T = temperature in °K

r_ω = $a [16.3 + 0.53 \ln(\frac{T}{\omega})]$

a = effective Bohr radius associated with the majority dopant

ω = angular frequency

For p-type germanium measured at 10^4 Hz, 1.5 K, and $a = 74.5 \times 10^{-10}$ meters,^{8/} it is found from the above equation that $N_{MAJ} = 1 \times 10^{16}/\text{cm}^3$. Since the samples used in this experiment were all doped less than $1 \times 10^{16}/\text{cm}^3$ multiple hops, that is, hops taking place in groups of three or more sites, should not make a significant contribution to the conductivity at 1.5 K.

Golin^{8/} relates the ac conductivity σ to the doping by

$$\sigma = C N_{\text{MIN}} (N_{\text{MAJ}} - N_{\text{MIN}}) \quad , \quad (2)$$

where

C = a constant which is independent of doping, but depends on ω , T , and a .

N_{MIN} = minority dopant concentration

N_{MAJ} = majority concentration .

This equation is not perfectly obeyed and the constant C does vary with doping as will be seen from discussions in following chapters. The ac conductivity is frequency dependent. When the dc conductivity is small compared to the ac, σ is proportional to ω^s where $s \sim 0.6-0.8$, depending on temperature and concentration. When the dc conductivity is on the order of the ac conductivity, a transition to dc is observed as the frequency is decreased and then s is no longer constant.^{10/} Here dc conductivity refers to the hopping of charge from one site to another all the way through the crystal, not to conduction by charge carriers in the conduction or valence bands.

According to Golin's theory,^{8/} σ is proportional to a^5 . Then for the same dopant concentration in n- and p-type,

$$\frac{\sigma_n}{\sigma_p} = \left(\frac{a_n}{a_p} \right)^5 \quad , \quad (3)$$

where σ_n is the conductivity of the n-type material, σ_p is the conductivity of the p-type material, a_n is the donor state orbit radius of the dopant in the n-type material, and a_p is the effective Bohr radius in p-type. Golin^{8/} found $a = 74.5\text{\AA}$ by fitting his theory to his σ versus temperature curves for gallium doped material. For n-type crystals, Miller and Abrahams^{9/}

quote both thermal and optical results for a. For the case of antimony and gallium, $\frac{\sigma_n}{\sigma_p} = .70$.

To study radiation damage using ac hopping conductivity, we start with a crystal initially doped with an acceptor, for example. According to the equation of Golin,^{8/} $\sigma = C N_D (N_A - N_D)$ which is approximately $\sigma = C N_D N_A$ for small N_D . Charged defects introduced by the irradiation will change N_A if they are negative and N_D if they are positive. Since, however, we started with a relatively large N_A we would have to produce many acceptor-like defects in order to change N_A enough to affect σ appreciably. On the other hand, N_D is small before irradiation so that donor-like defects will change σ significantly. Therefore hopping measurements reflect mainly changes in minority-like defect concentration.

III. EXPERIMENTAL DESCRIPTION

A. Sample Preparation

Samples used in this experiment were cut from single crystal ingots obtained from Eagle-Picher Industries and Nucleonic Products Company. The ingots were horizontally grown. Dislocation densities were less than $2500/\text{cm}^2$ in all samples.

A typical preparation sequence was as follows: slices approximately one-half millimeter thick (500 microns) were cut from ingots using a diamond wafering saw. The slices were made with the (111) crystallographic direction perpendicular to the face of the cut. Wafers were then cut to dimensions of $\frac{1}{2}'' \times \frac{9}{16}''$, lapped lightly on both sides with 600 grit silicon carbide, and resistivity measured using a four-probe technique. The wafers were then cleaned by scrubbing with acetone, and boiling them in first acetone, then trichloroethylene. They were rinsed with ethyl alcohol and then dried with freon after each boiling. Samples were etched four minutes in cp-4. The etch was quenched with water of 10^{-8} ohm/cm conductivity distilled from deionized water in a quartz still. Samples were then placed in methanol one minute, then removed and dried with freon. The wafers were etched a second time in cp-4 for one minute, and a similar procedure followed. After the second etch the samples were approximately 200 microns thick. (Thickness was not measured until after the samples were used to avoid scratching the surface of the sample with the micrometer.) Tweezers used to handle the samples were carefully cleaned in trichloroethylene before use.

Silver electrodes, one $\frac{1}{8}''$ and one $\frac{1}{4}''$ in diameter were evaporated on opposite sides of the wafers in an Ultek TNB-X system. An electropolished stainless steel sample holder and evaporation mask was used. Four samples

could be prepared at once. Rectangular recessed areas were machined in the sample holder to position the wafers so that when they were turned to evaporate the second electrode, the centers of the two electrodes would line up.

Five nines grade silver shot supplied by Cominco American was used as the silver source and evaporated from a .005" tungsten boat about 10 cm from the samples. A current of 144 amps was sufficient to evaporate the silver at a rate of $1000\text{\AA}/\text{minute} \frac{11}{10}$ so that after two minutes the electrodes were about $2000\text{\AA}$ thick. A shutter masked the silver source from the samples, and therefore the boat could be brought up to temperature and degassed before the actual deposition was started. Background pressure during evaporation was usually less than 2×10^{-8} torr.

The completed four samples were then mounted on a pyrex plate $1\frac{31}{32}" \times 1\frac{7}{16}" \times \frac{1}{16}"$ (in the last run a sapphire plate was used) by attaching one edge of each sample to the plate with G.E. 7031 clear varnish. The pyrex plate had four $\frac{1}{4}"$ diameter holes cut in it to allow passage of the electron beam. Electrical leads were attached to the samples using #44 heavy form-var insulated copper wire (.0032" diameter) and silver micropaint. Two carbon resistors (Allen-Bradley 200 ohm, $\frac{1}{8}$ watt) were also varnished onto the sample plate. See Figure 2. These resistors were used for temperature measurement and control. The pyrex plate was then mounted on a gold-plated copper plate $\frac{1}{8}"$ thick. The copper plate had four $\frac{1}{8}"$ holes through which the electron beam irradiated only the area of the sample covered by the $\frac{1}{8}"$ silver electrode. The plate was attached with screws to copper posts in the sample chamber of the dewar.

In the last run, the samples were mounted on a sapphire plate $\frac{1}{16}" \times 1\frac{7}{16}" \times 2\frac{1}{2}"$. A heater winding consisting of enough #36 advance alloy wire

Figure 2: Samples and pyrex mounting plate: A) germanium sample;
B) pyrex plate; C) carbon resistors.

to make 80 ohms was also varnished to the plate near the top edge. The carbon resistors were mounted between the samples and the heater winding near the samples. The sapphire was thermally isolated from the underlying copper plate by use of nylon screws for mounting and by use of .020" teflon washers between the copper and the sapphire. This configuration was intended to allow faster rise times for annealing.

A summary of the crystals used in this experiment is given in Table 1, and a complete listing of sample parameters is given in Table 2.

B. Cryostat and Sample Chamber

Two different five liter helium cryostats were used in this experiment. One has been described by McKeighen^{4/} previously. The other cryostat is similar to the McKeighen design except that no rigid tail assembly was used. Both dewars with which the two cryostats were constructed were purchased from Superior Air Products Company, Newark, New Jersey. A schematic of the second cryostat is shown in Figure 3 and the following discussion applies to the second cryostat.

A chamber at 77 K around the sample mounting chamber had entrance and exit windows for the electron beam covered with .0007" thick aluminized mylar varnished to the chamber. The entrance window consisted of four holes of irregular shape but larger than a $\frac{7}{16}$ " diameter circle. The exit window was a square $1\frac{1}{2}$ " $\times$ $1\frac{1}{2}$ ". The bottom section of the nitrogen shield was demountable for easy access to the sample chamber. The can immediately surrounding the samples had entrance and exit windows covered with .002" thick duraluminum. The entrance window consisted of four $\frac{3}{8}$ " diameter holes and the exit window was a square $1\frac{1}{4}$ " on a side. The duraluminum was attached to the gold-plated copper sample can with a flexible epoxy made from equal

TABLE 1

Crystals used in this experiment.

Designation	Dopant and approximate concentration (cm^{-3})		Dislocation density specified by manufacturer (cm^{-2})	Supplier*	Used in runs
[†] V566C	Sb	5×10^{15}	1500	NPC	9
GeT00173	Sb	9×10^{14}	500	NPC	9
LC 898	Ga	7×10^{15}	<2500	EP	10-14
LC 901	Ga	8×10^{14}	<2500	EP	10,14

* EP - Eagle-Picher Industries
NPC - Nucleonic Products Company

[†]This crystal was pulled. The rest were horizontally grown.

TABLE 2

Sample parameters.

Run	Sample	Dopant	Dopant Concentration $\pm 8\%$ (cm^{-3})	Thickness ± 5 microns	Electrode area (cm^2)	Fringing correction factor $Z \pm 1\%$ (at 1.5 K)
9	1	Sb	8.9×10^{14}	393	$.0871 \pm .2\%$	.798
	2	Sb	5.3×10^{15}	355	$.0866 \pm .4\%$	.821
	3	Sb	8.9×10^{14}	400	$.0862 \pm .2\%$	.794
	4	Sb	5.3×10^{15}	342	$.0867 \pm .2\%$	.827
10	2	Ga	7.3×10^{15}	245	$.0886 \pm .2\%$	.866
	3	Ga	7.8×10^{14}	211	$.0884 \pm .2\%$	.873
	5	Ga	7.7×10^{14}	168	$.0852 \pm .2\%$	.898
11	4	Ga	7.3×10^{15}	254	$.0794 \pm 1\%$	.855
	7	Ga	7.0×10^{15}	252	$.0797 \pm 2\%$	.856
	8	Ga	7.0×10^{15}	91	$.0801 \pm 2\%$	.939
	9	Ga	6.9×10^{15}	71	$.0805 \pm .4\%$	.952
12	11	Ga	5.2×10^{15}	272	$.0794 \pm .4\%$	.848
	4	Ga	7.3×10^{15}	254	$.0794 \pm 1\%$	.855
	13	Ga	5.0×10^{15}	203	$.0788 \pm .3\%$	.880
	14	Ga	5.7×10^{15}	180	$.0790 \pm .7\%$	.889
13	12	Ga	5.7×10^{15}	246	$.0789 \pm .2\%$	.859
	15	Ga	6.0×10^{15}	286	$.0790 \pm 1.2\%$	.840
	16	Ga	7.6×10^{15}	294	$.0782 \pm .2\%$	.837
	18	Ga	8.8×10^{15}	244	$.0792 \pm .7\%$	.858
14	10	Ga	5.6×10^{15}	257	$.0792 \pm .6\%$	.855
	23	Ga	8.0×10^{14}	185	$.0792 \pm .2\%$	.882
	17	Ga	8.3×10^{15}	335	$.0800 \pm .4\%$	.821
	18	Ga	8.4×10^{14}	191	$.0767 \pm .4\%$	.877

Figure 3: Helium cryostat schematic: A) dewar mounting flange; B) 12 liter capacity liquid nitrogen reservoir; C) 5 liter liquid helium reservoir; D) vacuum-tight enclosure for introduction of exchange gas to the sample chamber, and for wire feed-throughs; E) sample chamber; F) gate valve for opening to Van de Graaff beam tube.

parts of Shell Epon Resin 828 and General Mills Versamid 125 polyamide resin. The epoxy was cured three hours at 60°C. This can was attached to a top flange making use of an indium o-ring.

Details of the sample chamber are shown in Figure 4. Exchange gas was admitted to the sample chamber through the $\frac{5}{16}$ " inconel tube shown. Electrical leads were run down this tube and consisted of two RG-178/U teflon jacketed coaxial cables, eighteen #36 (.005") advance alloy varnish insulated wire, and two #36 varnish insulated copper wires. The wires run from the top of the dewar to the pin block in the sample chamber. The two copper wires attach to a heater wound around the small helium reservoir. The heater consists of enough advance wire to give 400 ohms. An optical shield was used at the junction of the $\frac{5}{16}$ " inconel tube and the top flange of the chamber to prevent room temperature photons from entering the sample chamber and causing photoconductivity in the samples. The two coaxial cables attach to two samples each through #44 (.0032") copper wires which were silver painted to the sample electrodes and soldered to appropriate terminals of the terminal strip. The advance alloy wires connect to the remaining sample electrodes, the beam monitors (to be described below), and the carbon resistors. The front and back wires for a particular sample are shielded from each other by the shield of the coax. The sample wires are connected to BNC connectors at the top of the dewar while the other wires are terminated at octal plugs. The sample chamber was all gold-plated except for the terminal strips, wiring, glass mounting plate, and beam monitor isolators.

Four beam monitors were attached to the side facing the beam of the copper plate to which the pyrex sample mounting plate was attached. See

Figure 4: View of the sample mounting chamber: A) $5/16'' \times 0.006''$ w inconel tube carrying exchange gas and lead wires to sample chamber; B) $1/8'' \times 0.004''$ w inconel tube carrying liquid helium to the reservoir in sample chamber, with a needle valve flow control positioned above this tube; C) $3/16'' \times 0.006''$ w inconel tube for venting helium gas; D) demountable indium o-ring seal for removing outer cylinder to mount samples; E) strip of teflon with copper pins to which wires are attached leading to the top of the dewar and to which wire leads on samples can be readily attached; F) $1/8''$ diameter hole in $1/8''$ thick copper plate through which electron beam passed to irradiate samples when mounted; G) copper posts to which copper plate is mounted and which are hollowed out so that the reservoir can be filled with liquid helium and vented. Note that these hollow posts are also filled with liquid helium during irradiation; H) 2" diamter hollow copper cylinder holding ~ 90 cc of liquid helium; a heater wire is wrapped around this cylinder; I) copper cylinder holding helium exchange gas around samples and having entrance and exit windows for the electron beam of 0.002" duraluminum.

Figure 5. The beam could be monitored on these annular shaped pickups, but the presence of exchange gas necessary for cooling the samples sometimes causes spurious effects in beam measurements. The spurious effects are due to ionization of the gas by incident electron irradiation. Therefore in later runs the beam was also measured by using the entire dewar as a Faraday cup. Knowing the ratio of the current collected by the dewar to the current picked up by a dummy sample with no exchange gas, one can get the flux by measuring the total dewar current.

The dewar vacuum was maintained by either a Varian 50 l/s ion pump or a pumping station with a Veeco EP-2A 90 l/sec two-inch diffusion pump with a liquid nitrogen cold trap, or both.

To obtain temperatures below 4.2 K, a Welch 1398 rotary pump was used when the apparatus was in the accelerator room. When the samples were not being irradiated, the apparatus, which is mounted on a movable frame, was located in a nearby lab and two 1397 pumps in parallel were used to pump on the liquid helium. A one-inch Veeco valve in parallel with a needle valve throttled the pumps so that the temperature could be controlled by varying the effective pumping speed.

C. Temperature Measurement

1. Above 4.2 K

The temperature of the samples was measured by a carbon resistor varnished to the pyrex (or sapphire) mounting plate. The same resistor was used throughout the experiment. A small portion of the resistor along its length was filed flat to facilitate mounting. Resistances were measured by passing a 10 microamp current through the resistor and measuring the voltage across it with a Leeds and Northrup K-3 potentiometer. Separate

Figure 5: (a) Back view of metal plate to which the pyrex sample mounting plate attaches.

(b) Front view of plate showing attached beam monitor assembly with four monitors electrically isolated from the plate.

(c) Side view of plate and attached assembly.

(a)

(b)

(c)

current and voltage leads were used. Therefore the current could be turned off and the voltage leads checked for thermal emfs. Thermal emfs were generally small enough to be neglected except during annealing under certain conditions. Essentially, there were no significant thermal emfs as long as an exchange gas was present in the sample chamber. The resistor used was an Allen-Bradley 200 ohm, $\frac{1}{8}$ watt resistor. The resistance at 4.2 K was about 3000 ohms. The thermometer was calibrated using the resistances at liquid nitrogen and liquid helium temperatures to determine the constants A and C in the equation

$$\left[\frac{\ln R}{T} \right]^{\frac{1}{2}} = c + A \ln R, \quad (4)$$

where R is the resistance and T the temperature in degrees Kelvin. Franck and Martin^{12/} reported that this equation gives the temperature correctly to within 0.4% in the temperature range 4.2 K - 25 K. More recently, however, Weinstock and Parpia^{13/} have published data on Allen-Bradley and Ohmite resistors manufactured after 1967 when a change in production technique by Allen-Bradley took place. An attempt to use the above equation for a 12 ohm resistor studied by Weinstock and Parpia^{13/} yielded a maximum error of 8.1%. The same calibration points as used by Franck and Martin^{12/} (4.2 K and 20 K) were used, and the nominal resistance of Franck and Martin's^{12/} resistor was 10 ohms. Therefore, either the fit of Franck and Martin^{12/} was fortuitous or the "new" Allen-Bradley resistors do not fit the equation as well. A comparison was also made between the measurements of Schulte^{14/} on "old" 270 ohm Allen-Bradley resistors and a "new" 330 ohm Ohmite resistor studied by Weinstock and Parpia.^{13/} Calibration points of 4.2 K and 20 K were again used to find the constants C and A in Equation (1). The calculated temperature was compared with the actual temperature at 6 K, 8 K,

and 10 K. The maximum error was .5% for the case of Schulte^{14/} and 2.0% for the 330 ohm resistor of Weinstock and Parpia.^{13/} Therefore it does appear that Equation (4) is not as good for the "new" resistors.

The resistor used in this experiment was purchased in 1970 and therefore should be a "new" resistor. To check the validity of Equation (4) as used in this experiment, constants A and C were found for Weinstock and Parpia's^{13/} 180 ohm resistor using their measured resistances at 77 K and 4.2 K. The temperatures obtained from Equation (4) were compared with the actual temperatures for given resistances. The errors obtained are shown below.

TABLE 3

Accuracy of Equation (4) when checked against Weinstock and Parpia's^{13/} data for a 180 ohm Ohmite resistor. Calibration points at 4.2 K and 77 K.

T(K)	% error
6	- 5.0
8	- 7.5
10	-10
20	-11
30	- 8.4
40	- 6.3
60	- 3.3
77	0.00
100	+ 1

McKeighen^{15/} has estimated the difference in temperature across a sample due to electron beam heating. He obtained

$$\Delta T = \frac{I \Delta E a^2}{2 K b} \quad (5)$$

where ΔT is the temperature rise, ΔE is the energy loss of the beam in the sample, a is the width of the sample (which is thermally sunked at one edge),

b is the thickness, K is the thermal conductivity, and I is the electron beam current density. In the present experiment, typical values are

$$\begin{aligned} I &= 1.8 \times 10^{-9} \text{ amps/cm}^2 \\ \Delta E &= .2 \times 10^6 \text{ eV/electron} \\ a &= 1 \text{ cm} \\ b &= .2 \text{ cm} \\ K &= 0.13 \text{ W/cm}^\circ\text{K at } 1.7 \text{ K}^{16/} \\ \Delta T &= .004 \text{ K} \end{aligned}$$

This is actually an overestimate of ΔT because the electron beam only passes through a $\frac{1}{8}$ " diameter dot in this experiment whereas McKeighen's treatment is for the case of the beam striking the entire area of the sample. Also, cooling by the exchange gas is not taken into account. During irradiation at 4.2 K and above, one atmosphere of helium at 300 K was used as an exchange gas. This gave ~ 70 mm at 4.2 K.

2. Below 4.2 K

Below 4.2 K, the pressure above the liquid helium bath was measured in addition to the measurements made on the carbon resistor. The temperatures deduced from the vapor pressure and the carbon resistor agreed within 0.15 K between 1.5 K and 2.0 K. The Wallace-Tiernan gauge model FA-160 used to measure vapor pressure had a range of 0 to 50mm of mercury in 0.2mm increments. The scale can be read to $\pm .02$ mm with care. A Consolidated Vacuum Corporation GM-100 McLeod gauge was used to calibrate the FA-160 from 1 to 10mm to $\pm 1.1\%$ or .05mm, whichever was larger. Above 10mm Hg, the FA-160 was assumed to be accurate to the manufacturers tolerance of $\pm .1$ mm.

An error in measurement of the pressure over the liquid helium bath arises from the impedance which the tubing in the neck of the dewar offers to the flow of gas molecules. We have

$$\Delta P = \frac{T}{C}, \quad (6)$$

where ΔP is the pressure difference between the vapor pressure over the liquid and the pressure at the measurement point, T is the throughput (pressure $\times$ volume/time), and C is the conductance of the tubing. The conductance of an annular region is given by^{17/}

$$C = \frac{\pi P}{8\eta L} \left[b^4 - a^4 - \frac{(b^2 - a^2)^2}{2n(b/a)} \right] \quad (7)$$

where

a = inner radius

b = outer radius

P = average pressure

η = viscosity of gas

L = length

The configuration in the experiment is not quite annular because a $\frac{5}{16}$ " diameter inconel tube which passes through the 1" diameter tubing leading to the helium bath is nearer to the edge of the one-inch tube than the center. Using

$$P = .25 \text{ cm}$$

$$L \approx 45.7 \text{ cm}$$

$$a = .397 \text{ cm}$$

$$b = 1.27 \text{ cm}$$

$$\eta = 1.943 \times 10^{-4} \text{ poise}$$

we find $C = 6780 \text{ } \ell/\text{m}$ for helium gas at 15°C . at 2.5 mm . About $3 \text{ } \ell/\text{day}$ of liquid helium boils off from the dewar. Since one liter of liquid gives 750 liters at 300 K, this boil-off corresponds to $1.56 \text{ } \ell/\text{m}$ of gas. The throughput is

$$T = 760 \times 1.56 = \frac{1180 \text{ } \ell \cdot \text{mm}}{\text{min}}, \quad (8)$$

and so

$$\Delta P = .17 \text{ mm at } P = 2.5 \text{ mm} \quad (9)$$

This pressure gradient will depend on the temperature of the tubing leading to the liquid helium reservoir. Immediately after pump-down, the neck of the dewar is quite cold due to rapid boil-off during pump-down, and a resistance of 63,385 ohms for the carbon resistor usually corresponds to a reading on the Wallace-Tiernan gauge of 2.60 mm . After nine hours, a reading of $\sim 2.40 \text{ mm}$ is obtained. Possibly the level of the helium in the cryostat may be a significant factor in determining the temperature of the pumped gas and tubing in the dewar, since it does not seem reasonable that it would take nine hours for the tubing to reach a steady state temperature distribution.

The conductivity of the samples measured in this experiment was strongly temperature dependent as can be seen from Figure 6. Therefore, it was necessary to control the temperature to $\sim .0003 \text{ K}$ in order to maintain an error of $\sim .001$ micromhos in the high doped samples at 1.5 K . The temperature was controlled by throttling the pump with a valve to vary the effective pumping speed on the liquid helium bath so that the resistance of the carbon

Figure 6: Conductance versus temperature and thermometer resistance for antimony doped samples after a fluence of $3 \times 10^{14} \text{ e/cm}^2$ and an anneal to 80 K for 7 minutes.

resistor previously described stayed constant. The resistance is 63,385 at ~ 1.5 K, and a change of .0003 K corresponds to ~ 63 ohms. 63,385 ohms corresponds to .63385 volts as measured by the K-3 potentiometer. Since the K-3 and associated Leeds and Northrup 9834 null detector can resolve .00002 v in this measurement, ample sensitivity is available to sense a temperature change .0003 K near 1.5 K. Stability of the carbon resistor must be considered, however. Anderson^{18/} has shown that as one measures the resistance of a carbon resistor at fixed temperature near 2 K after reducing the temperature from 4 K there will be a slow decay in the resistance value which corresponds to an apparent $\frac{\Delta T}{T}$ of $\sim .003$. This change is such that if one controls the cryostat so that the resistance remains fixed, the actual temperature of the bath rises. When p-type samples doped $\sim 6 \times 10^{15} \text{ cm}^{-3}$ were held near 1.5 K for 15 hours, an average increase of .006 micromhos was observed. The .006 micromhos change corresponds approximately to $\Delta T = .002$ K. We would expect $\Delta T = .003 \times 1.5 = .0045$, so that the change in conductance seen is smaller than changes which could be expected from drift of the carbon resistor. The resistor was mounted out of the electron beam and behind a $\frac{1}{8}$ " thick copper plate. Carbon resistors are quite insensitive to irradiation. Ohmite resistors exposed to 10^6 rads of gamma radiation and 2×10^{10} neutrons showed no change at 1 K.^{19/} The helium exchange gas of ~ 70 mm at 4.2 K condensed to form a superfluid film below the λ point. This helped to maintain the samples at a uniform temperature during measurement.

The superfluid film also provided additional cooling during irradiation. Before low temperature irradiations were carried out, $\frac{1}{2}$ atmosphere of helium was admitted to the sample can at 4.2 K. Measurements were made to determine the temperature difference between the samples and the carbon resistance

thermometer during irradiation. A second 200 ohm carbon resistor was varnished to a sample and a known current passed through the resistor at a given voltage while the temperature seen by the thermometer was kept constant. This was done by varying the pumping speed on the helium bath. The new σ_{ac} of the sample was noted. The current through the second resistor was then turned off and the temperature of the bath adjusted so that the same sample conductance as with the resistor current on was again obtained and the bath temperature noted. By subtracting the temperature of the bath with current through the second resistor, from the bath temperature with no current but the same sample conductance, one gets the temperature rise of the sample due to the known power input. It was found that 1.8 mW of power caused a temperature rise of $.005 \text{ K} \pm .001 \text{ K}$. The beam deposits $\sim .03 \text{ mW}$ in an area about the same size as the area of contact between the heating resistor and the sample to which it was mounted. Therefore the temperature difference between the sample and a thermometer mounted nearby should be less than $.005 \text{ K}$ during irradiation when a superfluid film is present in the sample chamber. Another measurement of the temperature rise was performed as follows. A carbon resistor was mounted on a sample directly in the path of the electron beam. During irradiation near 1.7 K , the difference between this resistor and the usual thermometer was $.02 \text{ K}$. This is a larger difference than was expected and could be due to excitation effects of the electron beam in the irradiated resistor. Even so, $.02 \text{ K}$ is also a small temperature rise for the purposes of this experiment.

D. Data Acquisition and Analysis

The conductance and capacitance of the samples was measured with a General Radio Model 1615-A capacitance bridge with a Princeton Applied

Research Model HR-8 lock-in amplifier used both as a signal generator and null detector for the bridge. Most measurements were made at 10^4 Hz although some measurements were made at 10^2 , 10^3 and 10^5 Hz as well. The voltage applied to the samples was .01 volts peak-to-peak. Higher voltages resulted in the samples becoming non-ohmic. (The conductance increased with voltage.) This is in reasonable agreement with the observations of Golin^{8/} who states that samples showed a departure from Ohm's law at fields greater than 1 v/cm, or ~.02 volts for the present samples.

The 1615-A bridge is a three terminal capacitance bridge and therefore capacitances and conductances between the sample and ground such as those due to coaxial cables do not alter the bridge balance conditions and thus do not affect the measurements. This feature is necessary for the measurement of small capacitances and conductances. When using the bridge in the conductance mode, it is necessary to correct for non-linearity of the bridge as stated in the instruction manual. This was done by using the formula

$$G = \frac{10^{-6} MN}{1+0.2N} \quad (10)$$

where G = conductance in mhos

N = number read from bridge balance setting

M = multiplier read from bridge balance controls

The conductance G and capacitance C obtained in these measurements were the equivalent parallel capacitance and conductance of the sample measured. There is a small zero offset of the bridge at 10^4 and 10^5 Hz when checked in the calibrate position. This offset varies from scale to scale at a given frequency and output voltage of the HR-8. It is usually about twice the experimental uncertainty in conductance at 10^4 Hz, but is sometimes ten

times the uncertainty at this frequency. This zero offset has been subtracted from the data. All conductance values reported have been corrected for bridge non-linearity.

The conductivity σ is commonly obtained from

$$\sigma = \frac{\ell G}{A} \quad (11)$$

where ℓ is the thickness of the sample, A is the area of the smaller electrode of the sample, and G is the conductance. However, this formula neglects the effect of fringing fields and these should be considered for the samples of this experiment. Consider the sample shown in Figure 7. The current flowing out of the electrode is given by

$$i = \int_{S'} \vec{j} \cdot d\vec{S} = \int_{S'} \sigma \vec{E} \cdot d\vec{S} \quad (12)$$

where $\vec{j}$ is the current density and $\vec{E}$ is the electric field. Since most of the electric field is within the region of the sample, the surface S' can be extended to S to form a nearly closed surface around the sample, excluding the wire attached to the electrode. We wish to find a charge which when placed on the electrode would produce the field $\vec{E}$. Following Harnwell²⁰ we note that in finding this charge the integral

$$\int_S \vec{E} \cdot d\vec{S} \quad (13)$$

is very close to the integral over a closed surface and that the small area of the wire excluded may be neglected and Gauss's theorem used. Then

$$i \approx \sigma \int_S \vec{E} \cdot d\vec{S} \approx \frac{\sigma q}{K_0} \quad (14)$$

(K_0 is the permittivity of free space.) Now $q = C_0 V$, where $C_0 = \frac{C}{K}$, and C

Figure 7: Germanium sample showing surface used in deriving

$$i = \frac{\sigma q}{K_o} \cdot$$

is the capacitance of the sample and K the dielectric constant. Using $V = \frac{i}{G}$, we have $C_o = \frac{qG}{i}$. Using this in

$$i = \frac{\sigma q}{K_o} , \quad (15)$$

we get

$$\sigma = \frac{GK_o}{C_o} : \quad (16)$$

Scott and Curtis^{21/} give a modification of Kirchoff's formula for the case of one large and one small electrode:

$$C_o = \frac{1.13D^2}{16b} + \frac{1.13D}{4\pi} \left[\ln\left(\frac{\pi}{b}\right) - 3 \right] \quad (\text{pf}) , \quad (17)$$

where D = diameter of the small electrode in cm

b = distance between electrodes in cm

Scott and Curtis^{20/} also developed an empirical formula for the calculation of capacitance with $K > 1$ which agreed with experiment to within 1%. The empirical formula is

$$C = KC_n + \left(\frac{1}{30} \ln\left(\frac{3.8}{b}\right) + .0405 K \right) P \quad (\text{pf}) , \quad (18)$$

where P = perimeter of the electrode (cm)

$$C_n = \frac{1.13D^2}{16b} \quad (\text{pf}) . \quad (19)$$

C_n is the capacitance neglecting fringing effects. Then $C_o = \frac{C}{K}$, or

$$C_o = C_n + \frac{P}{K} \left(\frac{1}{30} \ln\left(\frac{3.8}{b}\right) + .0405 K \right) . \quad (20)$$

C_o above can be used in Equation 15 to calculate σ . For convenience, we define a quantity Z to account for fringing effects such that

$$\sigma = \frac{Z \ell G}{A} \quad (21)$$

If there were no fringing effects, we would have $C_o = C_n$, and so

$$\sigma = \frac{GK_o}{C_n} \quad (22)$$

With fringing $\sigma = \frac{GK_o}{C_o}$. Since $C_o = \frac{C}{K}$, $\sigma = \frac{GK_o K}{C}$ with fringing. Then

$$Z = \frac{GK_o K/C}{GK_o/C_n} \quad (23)$$

or

$$Z = \frac{KC_n}{C} \quad (24)$$

where K is the dielectric constant and C is the measured capacitance. The empirical formula can be solved for K and the result is

$$K = \frac{C - (P/30) \ln(3.8/b)}{C_n + .0405 P} \quad (25)$$

Using the expressions for C_n and K in Equation (24), we have:

$$Z = \frac{1.13D^2}{16bC} \cdot \frac{C - (P/30) \ln(3.8/b)}{(1.13D^2/16b) + .0405P} \quad (26)$$

In a typical sample doped 6×10^{15} Ga/cm³ at 1.5 K a calculation of σ making use of the Kirchoff formula differs by 3% from the σ obtained using the above result derived from the Scott and Curtis formula. Calculations of σ neglecting fringing give results ~12% higher than the Scott and Curtis formula.

E. Irradiation and Annealing Procedure

Irradiations were performed using 1.1 MeV electrons supplied by the Materials Research Laboratory Van de Graaff accelerator. The method of measuring the current in the case of the dewar designed for this experiment

has been described in Section B. For those runs in which McKeighen's dewar was used the beam was collected on a $\frac{1}{8}$ " brass plate. Four holes in the plate allowed the beam to pass through the plate to irradiate the samples mounted $\frac{1}{16}$ " behind it. The current passing through each hole was collected on dummy samples in a trial run and the ratio of plate current to sample current was obtained for each sample. The electron current was measured and integrated on an Elcor Current Integrator Model (A309B) to give the total electron fluence.

Isochronal anneals were done by closing the needle valve to isolate the sample chamber from the helium bath, pumping out the exchange gas to a pressure of several millimeters, and heating the sample chamber to the desired temperature by passing a current of up to 200 ma through the heater. The time at the annealing temperatures below 295 K was ~15 minutes except for run 9 when seven minutes was used. At the end of the anneal, the needle valve was opened allowing liquid helium to cool the sample chamber. At temperatures above 60 K, it was often necessary to refill the dewar with liquid helium due to rapid boil-off of helium during the anneal. The thermal mass of the sample chamber limits the speed at which a given temperature can be attained. All anneals were started from a temperature of 10 K. Typical up and down times are two minutes to reach 30 K and five minutes to return to 4.2 K; five minutes to reach 56 K and five minutes to return; six minutes to reach 80 K and ten to twenty minutes to reach 4.2 K; and 15 minutes to reach 100 K, and roughly 7 minutes to come down to 80 K. In the last run, an arrangement was tried to overcome this long up and down time. The samples were mounted on a sample plate thermally isolated from the sample chamber when the exchange gas was pumped out to at least 20 microns. The needle

valve was not closed. To quench the anneal exchange gas was readmitted to the sample chamber. A temperature of 100 K could be reached in less than four minutes. Only one minute was required to return to 4.2 K. There were problems with this arrangement which will be discussed in the next chapter.

When exchange gas pressure is several millimeters thermal emfs in the thermometer leads are below 1.0 μv at 56 K. At 100 K thermal emfs are -18.0 μv at first, but after 15 minutes are -6.0 μv . -18 μv corresponds to a correction to be made of -2 K at 100 K. At 56 K, 1 μv implies a correction of -.05 K.

Anneals to 295 K were done by allowing the liquid helium to boil away and then emptying the dewar liquid nitrogen jacket. Room temperature air was circulated through the nitrogen volume until the emerging air no longer felt cool (about five hours). This was usually done overnight. After warming the nitrogen reservoir, the pumping station was valved off and helium gas admitted to the dewar vacuum jacket. Only an hour or so was then required to reach room temperature. Typically the dewar was evacuated after one hour and allowed to remain at room temperature for at least two hours more before recooling to helium temperature.

IV. EXPERIMENTAL RESULTS

A. N-type Germanium

Samples doped 8.9×10^{14} Sb/cm³ and 5.3×10^{15} Sb/cm³ were irradiated with 1.1 MeV electrons to a fluence of 3×10^{14} e/cm². These samples had previously been irradiated to a fluence of less than 2×10^{12} e/cm² and annealed to 295 K. Figures 8-11 and Tables 4-7 show production data for these samples. In the tables, T_{IRR} is the irradiation temperature, T_{MEAS} the measurement temperature, f the measurement frequency, and ϕ the total fluence. Measurements were carried out at $1.42 \text{ K} \begin{smallmatrix} +.03 \text{ K} \\ -.01 \text{ K} \end{smallmatrix}$. Irradiations were done at temperatures between 3 K and 4 K in the dewar designed and built by McKeighen. Current densities were about 9×10^{-9} amps/cm².

Production data obtained from these samples were analyzed to obtain the constant C_N in the expression

$$\sigma = C_N N_A (N_D - N_A) \quad (27)$$

The production rates were calculated using the linear part of the production curves. For the lower doped samples σ reaches a maximum. There is some bending over in the curves for the higher doped samples, but no maximum was seen. The expression above has maximum at $N_A = \frac{N_D}{2}$. Now

$$P = \frac{\Delta N_A}{\Delta \phi} \quad (28)$$

where P = production rate

ΔN_A = change in acceptor concentration in cm⁻³

$\Delta \phi$ = fluence in electrons/cm²

Since the production rate is calculated from the linear part of the conductivity versus fluence curves we assume that $N_A \ll N_D$ in this region so that

Figure 8: Conductance versus fluence, Run 9, Sample 1, 10^4 Hz.

Figure 9: Conductance versus fluence, Run 9, Sample 2, 10^4 Hz.

Figure 10: Conductance versus fluence, Run 9, Sample 3, 10^4 Hz.

CONDUCTANCE VS. FLUENCE

RUN 9, SAMPLE 3

 $9 \times 10^{14} \text{ Sb/cm}^3$ $T_{\text{IRR}} \approx 3.8 \text{ K}$ $T_{\text{MEAS}} = 1.4 \text{ K}$ $f = 10^4 \text{ Hz}$

Figure 11: Conductance versus fluence, Run 9, Sample 4, 10^4 Hz.

CONDUCTANCE VS. FLUENCE

RUN 9, SAMPLE 4

 $5 \times 10^{15} \text{ Sb/cm}^3$ $T_{\text{IRR}} \approx 3.8 \text{ K}$ $T_{\text{MEAS}} = 1.4 \text{ K}$ $f = 10^4 \text{ Hz}$

TABLE 4

Run 9. Production data, Sample 1, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Total fluence $\pm 15\%$ (10^{12} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	.0387 $\pm$.001	4.97 $\pm$.1
3.7	.0328 $\pm$.001	4.75 $\pm$.01
18	.0390 $\pm$.0001	4.96 $\pm$.01
36	.0390 $\pm$.0002	4.96 $\pm$.01
71	.0407 $\pm$.001	5.04 $\pm$.01
142	.0495 $\pm$.001	5.1 $\pm$.1
*142	.059 $\pm$.01	5.3 $\pm$.1
304	.0458 $\pm$.0003	5.36 $\pm$.01

* Samples brought up to 4.2 K for four days before this measurement.

TABLE 5

Run 9. Production data, Sample 2, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Total fluence $\pm 15\%$ (10^{12} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	.404 $\pm$.01	8.2 $\pm$.1
3.5	.407 $\pm$.001	8.14 $\pm$.01
17	.414 $\pm$.001	8.20 $\pm$.01
34	.422 $\pm$.002	8.27 $\pm$.02
68	.440 $\pm$.002	8.44 $\pm$.01
134	.483 $\pm$.01	8.9 $\pm$.1
*134	.486 $\pm$.008	8.81 $\pm$.02
287	.535 $\pm$.002	9.34 $\pm$.01

* Samples brought up to 4.2 K for four days before this measurement.

TABLE 6

Run 9. Production data, Sample 3, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Total fluence $\pm 15\%$ (10^{12} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	.0298 $\pm$.001	4.6 $\pm$.1
3.3	.0256 $\pm$.001	4.50 $\pm$.01
16	.0287 $\pm$.0002	4.62 $\pm$.01
31.4	.0298 $\pm$.0002	4.63 $\pm$.01
64.2	.0338 $\pm$.0015	4.89 $\pm$.01
*126	.0495 $\pm$.007	5.0 $\pm$.1
269	.0353 $\pm$.0008	5.16 $\pm$.01

* Samples brought up to 4.2 K for four days before this measurement.

TABLE 7

Run 9. Production data, Sample 4, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Total fluence $\pm 15\%$ (10^{12} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	.405 $\pm$.002	8.1 $\pm$.2
3.2	.404 $\pm$.002	8.14 $\pm$.02
15	.410 $\pm$.001	8.21 $\pm$.01
31	.408 $\pm$.002	8.17 $\pm$.1
63	.439 $\pm$.002	8.53 $\pm$.01
122	.470 $\pm$.001	8.9 $\pm$.1
*122	.493 $\pm$.015	8.8 $\pm$.1
262	.530 $\pm$.002	9.26 $\pm$.01

* Samples brought up to 4.2 K for four days before this measurement.

$$\sigma \approx C_N N_A N_D \quad (29)$$

Then

$$C_N = \frac{\sigma}{N_A N_D} \quad (30)$$

or

$$C_N = \frac{\Delta\sigma}{N_D P \Delta\phi} \quad (31)$$

where $\Delta\sigma$ is the change in conductivity corresponding to an increment of fluence $\Delta\phi$. The conductivity σ is obtained from the measured conductance using the formula

$$\sigma = Z \frac{\ell}{A} G \quad (32)$$

where ℓ is the thickness, A is the electrode area, G is the conductance, and Z is a correction factor to account for fringing fields as previously discussed. In these samples, Z is approximately 0.8. In the higher doped samples σ_{dc} is over 50% of the measured σ_{ac} at 10^4 Hz. The σ_{dc} value was estimated by extrapolating to zero frequency. Although Golin^{8/} subtracted σ_{dc} from his data before analyzing it, this has not been done here. It is not clear that such a separation is meaningful. At zero frequency charge carriers hop from the region of one minority site to another all the way through the crystal. As the frequency is increased from zero the hopping of the charge becomes more and more localized. Thus one has the picture of the non-localized dc hopping becoming transformed into localized ac hopping, as opposed to the creation of an entirely new and independent mechanism of conduction at finite frequency. Also, the ratio $\frac{\sigma_{dc}}{\sigma_{ac}}$ is the same before and after irradiation to within 3% so that σ_{dc} depends on N_A in the same way as σ_{ac} . We do expect that the fact that the higher doped samples exhibit a

significant σ_{dc} may cause a deviation from the theory of Golin, specifically, that majority concentration dependence and the exact position of the maximum in the σ versus ϕ curve may not be as predicted. We do expect that σ will be proportional to the minority concentration for small concentrations N_{MIN} . (See also the theory of Scher and Lax.)^{10/}

The production rate P is known from the work of Callcott and MacKay^{1/} and MacKay, Klontz, and Gobeli.^{22/} It is 3 cm^{-1} at 1.1 MeV for material doped $10^{14}/\text{cm}^3$ and 2 cm^{-1} for material doped $7 \times 10^{17}/\text{cm}^3$. Therefore P is nearly independent of N_D in the range $.9 \times 10^{15}$ and $6 \times 10^{15} \text{ Sb}/\text{cm}^3$. P decreases with energy and this means that a sample 400 microns thick will have a production rate less than a sample 200 microns thick (by a factor of .83, in fact) due to energy loss of the beam and hence a lower effective production rate as the beam traverses the thicker sample. The effective production rate versus thickness for a 1.1 MeV incident beam is shown in Figure 12, assuming the production rate is one-half the production given by Callcott and MacKay.^{1/} See Appendix A for the details of this calculation. One-half the production rate is used because defects in n-type material are known to be doubly charged when defects have been annealed to 10 K.^{1/} When samples are irradiated at 4.2 K, however, the defects are only singly charged.^{1/} Since measurements were taken before annealing to 10 K, it is appropriate to assume that only one electron is on a defect and therefore we must divide the production rates of MacKay and Klontz by two since they give number of electrons removed per incident electron after samples have been heated to 10 K. In addition, it is uncertain whether doubling the charge on a defect should or does double the hopping conductivity contribution from that defect. This will be discussed later.

Figure 12: Variation of production rate in n-type germanium with thickness as calculated using the production rate energy dependence data of Callcott and MacKay.^{1/}

Results for the calculation C_N from the data are shown below.

TABLE 8

C_N as obtained from the data of Run 9.

Sample	Doping $\pm 8\%$ (cm^{-3})	C_N at 1.42 K $\begin{smallmatrix} +.03 \text{ K} \\ -.01 \text{ K} \end{smallmatrix}$ ($\text{ohm}^{-1} \text{ cm}^5$)
1	8.9×10^{14}	4.1×10^{-38}
2	5.3×10^{15}	2.8×10^{-38}
3	8.9×10^{14}	5.1×10^{-38}
4	5.3×10^{15}	2.4×10^{-38}

C_P was calculated from Golin's data^{8/} and is shown below.

TABLE 9

C_P from Golin's data.

Golin's Sample	Doping (cm^{-3})	C_P at 1.4 K ($\text{ohm}^{-1} \text{ cm}^5$)	C_P at 1.45 K ($\text{ohm}^{-1} \text{ cm}^5$)	C_P at 1.5 K ($\text{ohm}^{-1} \text{ cm}^5$)
C	7.8×10^{14}	$5.55 \times 10^{-38} \pm 3\%$	$6.25 \times 10^{-38} \pm 3\%$	$7.08 \times 10^{-38} \pm 3\%$

The uncertainty represents the error resulting from reading the published graph. As previously discussed, $\frac{\sigma_N}{\sigma_P} = .7$ and so $\frac{C_N}{C_P} = .7$. The average C_N for $8.9 \times 10^{14} \text{ Sb/cm}^3$ is $4.6 \times 10^{-38} \pm 25\%$ where the uncertainty reflects the uncertainty in majority dopant, beam measurement ($\pm 15\%$), fringing correction factor ($\pm 1\%$), thickness, and area of the electrode ($\pm .2\%$ for this run). Averaging the C_P 's at 1.40 and 1.45 K, we have $C_P = 5.90 \times 10^{-38} \text{ ohm}^{-1} \text{ cm}^5 \pm 3\%$. This gives C_P near 1.425 K where the measurements of the present experiment were made. Since $0.7 \times 5.9 \times 10^{-38} = 4.1 \times 10^{-38}$, the agreement between this experiment and the results of Golin is good for the low doped samples. From Golin's sample E at 1.5 K, it is found that $C_P = 4.4 \times 10^{-38}$. (Sample E has a majority doping of $2.1 \times 10^{15} \text{ cm}^{-3}$.) To

compare this with the high doped samples of this experiment it should be noted that $\sigma_N(1.5 \text{ K})/\sigma_N(1.42 \text{ K}) \approx 1.5$ for the high doped samples. (This was obtained by extrapolating Figure 6 to 1.5 K.) The average C_N at 1.5 K for these samples is $3.9 \times 10^{-38} \text{ ohm}^{-1} \text{ cm}^5$. Since $C_N = .7 C_P$, we compare $C_N = 3.9 \times 10^{-38}$ with $.7 \times 4.4 \times 10^{-38} = 3.1 \times 10^{-38} \text{ ohm}^{-1} \text{ cm}^5$ where the 4.4×10^{-38} is Golin's C_P . The agreement is not as good as for the low doped samples. However, it should be again noted that in this experiment σ_{dc} was not subtracted from the measured σ as it was in Golin's. Hence there is some ambiguity in how to obtain comparable C_P 's for the high doped samples.

To calculate production rates in low doped ($\sim 1 \times 10^{15} \text{ cm}^{-3}$) germanium, the value of C_P calculated from Golin's sample C at 1.45 K was used since the measurements of the p-type samples used for calculating production rates were made at $1.45 \pm .03 \text{ K}$ (Note: the uncertainty refers to knowledge of the temperature, not its reproducibility.) To find C_P for the high doped samples, C_P for the low doped was multiplied by the ratio of C_N for the high doped n-type to C_N for the low doped n-type samples. The values of C_P used in calculating production rates are shown below.

TABLE 10

Values of C_P used in calculating production rates in p-type samples of this experiment.

Doping range	C_P
Low ($\sim 1 \times 10^{15} \text{ cm}^{-3}$)	$6.25 \times 10^{-38} \pm 3\%$
High ($\sim 6 \times 10^{15} \text{ cm}^{-3}$)	$3.35 \times 10^{-38} \pm 11\%$

The 11% uncertainty for the high doped C_P includes 8% due to doping uncertainty and 3% due to possible variation of the beam across the sample chamber.

Annealing results for the high doped samples are shown below. The samples were annealed to 80 K for 7 minutes. Measurements were taken at 1.4 K. The fraction annealed was found from the formula

$$F_A = \frac{\Delta G_{ANN}}{\Delta G_{IRR}} \quad (33)$$

where

F_A = fraction annealed

ΔG_{ANN} = change in conductance due to anneal

ΔG_{IRR} = change in conductance due to irradiation

TABLE 11

Annealing results for the high doped n-type samples of Run 9.

Sample	Annealing temperature	F_A (10^4 Hz)
2	80 K	$.60 \pm .07$
4	80 K	$.61 \pm .03$

The resulting fraction annealed agrees very roughly with that found by Callcott and MacKay^{1/} and gives confidence in the type of measurement used here.

After the initial irradiation and measurements just discussed the samples were again irradiated after an anneal to 295 K. The hopping conductivity was measured immediately after the irradiation and after an anneal to 10 K. Although the hopping conductivity did increase after the 10 K anneal, it did not double as one might expect due to doubling the charge on the defect sites observed by Callcott and MacKay.^{1/} Results of the several irradiations and anneals done on these samples are summarized in Figures 13-16 and Tables 12-15. Frequency dependence of σ before and after the first

Figure 13: Summary of Run 9, Sample 1, 10^4 Hz, showing conductance on irradiation and annealing.

Figure 14: Summary of Run 9, Sample 2, 10^4 Hz, showing conductance on irradiation and annealing.

Figure 15: Summary of Run 9, Sample 3, 10^4 Hz, showing conductance on irradiation and annealing.

Figure 16: Summary of Run 9, Sample 4, 10^4 Hz, showing conductance on irradiation and annealing.

TABLE 12

Run 9. Summary, Sample 1, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Conductance (micromhos)	Capacitance (picofarads)	Explanation
$.0387 \pm .001$	$4.97 \pm .1$	before irradiation
$.0458 \pm .0003$	$5.36 \pm .01$	after 3×10^{14} e/cm ²
$.0412 \pm .0004$	$5.17 \pm .01$	anneal to 80 K 7 minutes
$.0398 \pm .0002$	$4.99 \pm .01$	anneal to 295 K
$.0456 \pm .0002$	$5.18 \pm .01$	reirradiate 3×10^{14} e/cm ²
$.0462 \pm .0002$	$5.20 \pm .015$	anneal to 10 K 7 minutes

TABLE 13

Run 9. Summary, Sample 2, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Conductance (micromhos)	Capacitance (picofarads)	Explanation
$.404 \pm .01$	$8.2 \pm .1$	before irradiation
$.535 \pm .002$	$9.34 \pm .01$	after 3×10^{14} e/cm ²
$.462 \pm .001$	$8.68 \pm .01$	anneal to 80 K 7 minutes
$.440 \pm .001$	$8.36 \pm .01$	anneal to 295 K
$.560 \pm .002$	$9.36 \pm .01$	reirradiate 3×10^{14} e/cm ²
$.568 \pm .001$	$9.41 \pm .01$	anneal to 10 K 7 minutes

TABLE 14

Run 9. Summary, Sample 3, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Conductance (micromhos)	Capacitance (picofarads)	Explanation
$.0298 \pm .001$	$4.6 \pm .1$	before irradiation
$.0353 \pm .0008$	$5.16 \pm .01$	after 3×10^{14} e/cm ²
$.0313 \pm .0004$	$4.66 \pm .02$	anneal to 80 K 7 minutes
$.030 \pm .001$	$4.63 \pm .01$	anneal to 295 K
$.0345 \pm .002$	$5.12 \pm .02$	reirradiate 3×10^{14} e/cm ²
$.0367 \pm .0008$	$5.15 \pm .01$	anneal to 10 K 7 minutes

TABLE 15

Run 9. Summary, Sample 4, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.4$ K, $T_{\text{IRR}} \approx 3.8$ K.

Conductance (micromhos)	Capacitance (picofarads)	Explanation
$.405 \pm .002$	$8.1 \pm .2$	before irradiation
$.530 \pm .002$	$9.26 \pm .01$	after 3×10^{14} e/cm ²
$.454 \pm .002$	$8.50 \pm .01$	anneal to 80 K 7 minutes
$.432 \pm .001$	$8.35 \pm .01$	anneal to 295 K
$.556 \pm .001$	$9.44 \pm .01$	reirradiate 3×10^{14} e/cm ²
$.565 \pm .001$	$9.49 \pm .01$	anneal to 10 K 7 minutes

irradiation is given in Tables 16-19 and Figures 17-20. In Figures 8-11, some of the points plotted at 1.4 e/cm^2 have very large errors due to "noise" in the measurement. This probably was due to failure to disconnect the cable used to monitor electron fluence. It was discovered later that if the plate used to collect the beam was left connected to the current integrator during conductance measurements a spurious noise signal resulted.

B. P-type Germanium

In calculating production rates for the p-type samples, the uncertainty in the constant C_p does not affect a comparison of the production rates for samples of nearly the same doping. Also, in Runs 10-12 errors in the beam measurement include uncertainties due to the fact that the measurements were carried out inside a chamber filled with exchange gas. Only variations of the beam intensity over the area of the sample chamber should matter in comparing production rates of different samples in the same run. On the other hand, the total uncertainty in the fluence is important in comparing samples from different runs, and of course, the total error is necessary in comparing the results of this experiment with others. Therefore, in tabulating production rates in Table 20 the uncertainties are separated into errors I, II, and III. Error I refers to uncertainties which affect comparison of production rates within a run, error II refers to the total errors which should be considered in comparing samples from different runs, and error III is the estimate of total error in the computed production rate. It should be noted that the production rates in some runs vary widely and this "error" is not reflected in the tabulated errors. The method of choosing the slope of the G versus ϕ curves for use in computing production rates varied from run to run and is explained in the following summaries of each run. It should be

TABLE 16

Run 9. Frequency dependence data, Sample 1, $T_{\text{MEAS}} = 1.4 \text{ K}$, $T_{\text{IRR}} \approx 3.8 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$.000 \pm .001$	10 ± 2
10^3	$.013 \pm .002$	8 ± 1
10^4	$.039 \pm .01$	$4.97 \pm .1$
10^5	$.09 \pm .01$	$4.4 \pm .1$
After $\phi = 3.0 \times 10^{14} \text{ e/cm}^2 \pm 15\%$		
10^2	$.0010 \pm .0008$	11 ± 1
10^3	$.0145 \pm .003$	$7.5 \pm .1$
10^4	$.0458 \pm .003$	$5.36 \pm .01$
10^5	$.177 \pm .004$	$4.86 \pm .02$

TABLE 17

Run 9. Frequency dependence data, Sample 2, $T_{\text{MEAS}} = 1.4 \text{ K}$, $T_{\text{IRR}} \approx 3.8 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$.265 \pm .001$	146 ± 1
10^3	$.30 \pm .01$	$13.9 \pm .1$
10^4	$.40 \pm .01$	$8.2 \pm .1$
10^5	$.87 \pm .01$	$6.03 \pm .02$
After $\phi = 2.9 \times 10^{14} \text{ e/cm}^2 \pm 15\%$		
10^2	$.335 \pm .001$	234 ± 1
10^3	$.415 \pm .001$	$15.50 \pm .02$
10^4	$.535 \pm .002$	$9.34 \pm .01$
10^5	$1.183 \pm .003$	$6.6 \pm .1$

TABLE 18

Run 9. Frequency dependence data, Sample 3, $T_{\text{MEAS}} = 1.4 \text{ K}$, $T_{\text{IRR}} \approx 3.8 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$.000 \pm .003$	9 ± 2
10^3	$.007 \pm .002$	6 ± 1
10^4	$.030 \pm .001$	$4.6 \pm .1$
10^5	$.11 \pm .08$	$4.24 \pm .01$
After $\varphi = 2.7 \times 10^{14} \text{ e/cm}^2 \pm 15\%$		
10^2	$.0010 \pm .0008$	8 ± 1
10^3	$.0099 \pm .0002$	$6.6 \pm .1$
10^4	$.0353 \pm .0008$	$5.16 \pm .01$
10^5	$.150 \pm .001$	$4.70 \pm .01$

TABLE 19

Run 9. Frequency dependence data, Sample 4, $T_{\text{MEAS}} = 1.4 \text{ K}$, $T_{\text{IRR}} \approx 3.8 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$.26 \pm .01$	140 ± 20
10^3	$.30 \pm .01$	14 ± 1
10^4	$.405 \pm .002$	$8.1 \pm .2$
10^5	$.87 \pm .01$	$5.97 \pm .01$
After $\varphi = 2.6 \times 10^{14} \text{ e/cm}^2 \pm 15\%$		
10^2	$.331 \pm .001$	226 ± 1
10^3	$.406 \pm .001$	$15.5 \pm .1$
10^4	$.530 \pm .002$	$9.26 \pm .01$
10^5	$1.19 \pm .01$	$6.4 \pm .1$

Figure 17: Conductance versus frequency, Run 9, Sample 1, before and after 3×10^{14} e/cm².

Figure 18: Conductance versus frequency, Run 9, Sample 2, before and after 3×10^{14} e/cm².

Figure 19: Conductance versus frequency, Run 9, Sample 3, before and after $3 \times 10^{14} \text{ e/cm}^2$.

Figure 20: Conductance versus frequency, Run 9, Sample 4, before and after 3×10^{14} e/cm².

TABLE 20

Production rates calculated using $C_p = 3.53 \times 10^{-38} \text{ ohm}^{-1} \text{ cm}^5$ for high doped samples and $C_p = 6.25 \text{ ohm}^{-1} \text{ cm}^5$ for low doped samples. See text p.68 for explanation of errors. All rates calculated from 1.5 K measurements at 10^4 Hz.

Run	Irradiation series	Sample	Production rate (cm^{-1})	Error I ($\pm \%$)	Error II ($\pm \%$)	Error III ($\pm \%$)
10	1	2	.17	17	+51 -17	+72 -32
11	1	4	.26	18	28	43
		7	.26	19	29	44
		8	.27	22	32	47
		9	.36	22	32	57
12	1	11	.77	18	+38 -18	+53 -33
		4	.49	17	+37 -17	+52 -32
		13	.87	17	+37 -17	+52 -32
		14	.46	18	+38 -17	+53 -33
13	1	12	.73	17	17	33
		15	.60	18	18	34
		16	.83	17	17	33
		18	.24	18	18	34
13	2A	12	.65	17	17	33
		15	.62	18	18	34
		16	.74	17	17	33
		18	.26	18	18	34
13	2B	12	.073	22	22	38
		15	1.5	23	23	39
		16	.047	22	22	38
		18	.068	23	23	39
13	3A	12	.70	17	17	33
		15	.69	18	18	34
		16	.92	17	17	33
		18	.34	18	18	34
13	3B	12	.30	22	22	38
		15	.39	23	23	39
		16	.15	22	22	38
		18	.13	23	23	39
14	1	10	.45	18	18	34
		17	.26	17	17	33
		23	.10	18	18	26
		24	.11	18	18	26
14	2	10	.39	19	19	35
		17	.27	18	18	34
		23	.083	19	19	27
		24	.085	19	19	27

noted that the theory of Golin used to analyze this data may not be obeyed exactly. The errors quoted do not reflect "surface errors" to be discussed.

Run 10. This run was carried out in the "new" dewar with three gallium doped samples. Measurements were made at $1.45 \text{ K} \begin{smallmatrix} +.03 \text{ K} \\ -.01 \text{ K} \end{smallmatrix}$ and $1.981 \text{ K} \pm .002 \text{ K}$. Two samples were doped $8 \times 10^{14}/\text{cm}^3$ and one was doped $7.3 \times 10^{15}/\text{cm}^3$. Production data are shown in Figures 21, 22, and 23 and Tables 21-24, and conductance versus frequency results in Figures 24, 25, and 26 and Tables 25-27. The conductivity of Sample 5 before irradiation is about 12 times that of Sample 3, in spite of the fact that the samples are of the same doping level and cut from the same ingot. The two samples were prepared differently, however. Sample 3 received a second etch in cp-4. Possibly the difference in conductivities between the two samples is due to surface conductance. We assume for now that this is the case. If we consider the changes in conductivities due to a fluence of $1.4 \times 10^{14} \text{ e/cm}^2$ $\begin{smallmatrix} +10\% \\ -50\% \end{smallmatrix}$, $\frac{\Delta\sigma_5}{\Delta\sigma_3} = 2.2$ at 2 K, and $\Delta\sigma_5 = \Delta\sigma_3$ within experimental error at 1.5 K (although the experimental error is large). This indicates that even though surface conductance may affect starting conductivities the production rates measured at low temperatures should be nearly independent of surface conditions. In Run 11, samples of different thicknesses were used to investigate possible surface effects.

Run 11. In this run, four samples doped 7×10^{15} gallium atoms/ cm^3 of thicknesses 254, 252, 91, and 71 microns were irradiated with 1.1 MeV electrons. Measurements were carried out at $1.45 \text{ K} \begin{smallmatrix} +.03 \text{ K} \\ -.01 \text{ K} \end{smallmatrix}$, $1.58 \text{ K} \pm .01 \text{ K}$, and $1.981 \text{ K} \pm .002 \text{ K}$. Some conductance versus frequency curves are shown in Figures 27 and 28. Tables 28 and 31 show changes in total conductances of the samples at 10^4 Hz for increments of irradiation, and also ratios of the

Figure 21: Conductance versus fluence, Run 10, Sample 2, 10^4 Hz, measurement temperature = 2.0 K.

Figure 22: Conductance versus fluence, Run 10, Sample 3, 10^4 Hz, measurement temperature = 2.0 K.

Figure 23: Conductance versus fluence, Run 10, Sample 5, 10^4 Hz, measurement temperature = 2.0 K.

CONDUCTANCE (μMHO)

CONDUCTANCE VS. FLUENCE

RUN 10, SAMPLE 5

 $8 \times 10^{14} \text{ Ga/cm}^3$ $T_{\text{IRR}} < 1.9 \text{ K}$ $T_{\text{MEAS}} = 2.0 \text{ K}$ $f = 10^4 \text{ Hz}$

TABLE 21

Run 10. Production data, Sample 2, $f = 10^4$ Hz, $T_{\text{MEAS}} = 2.0$ K, $T_{\text{IRR}} < 1.9$ K.

Total fluence $\begin{smallmatrix} +10\% \\ -50\% \end{smallmatrix}$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	$3.259 \pm .002$	$10.1 \pm .1$
1.05	$3.29 \pm .01$	$10.1 \pm .1$
2.29	$3.299 \pm .006$	$10.1 \pm .1$
* 2.72	$3.318 \pm .001$	$10.1 \pm .1$
4.78	$3.359 \pm .005$	$10.3 \pm .1$
9.56	$3.475 \pm .003$	$10.8 \pm .1$
14.4	$3.580 \pm .003$	$11.2 \pm .1$
*14.4	$3.683 \pm .002$	$11.2 \pm .1$

* Samples brought up to 4.2 K and kept there overnight after irradiation but before measurement.

TABLE 22

Run 10. Production data, Sample 3, $f = 10^4$ Hz, $T_{\text{MEAS}} = 2.0$ K, $T_{\text{IRR}} < 1.9$ K.

Total fluence $\begin{smallmatrix} +10\% \\ -50\% \end{smallmatrix}$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	$.015 \pm .001$	$6.65 \pm .02$
1.05	$.0154 \pm .0003$	$6.63 \pm .02$
2.29	$.0159 \pm .0003$	$6.67 \pm .01$
2.72	$.0159 \pm .0005$	$6.67 \pm .01$
* 2.72	$.0158 \pm .0003$	$6.67 \pm .02$
4.78	$.016 \pm .001$	$6.69 \pm .02$
9.56	$.0193 \pm .0001$	$6.84 \pm .01$
14.4	$.0217 \pm .0003$	$6.98 \pm .004$
*14.4	$.0213 \pm .0003$	$6.97 \pm .01$

* Samples brought up to 4.2 K and kept there overnight after irradiation but before measurement.

TABLE 23

Run 10. Production data, Sample 5, $f = 10^4$ Hz, $T_{MEAS} = 2.0$ K, $T_{IRR} < 1.9$ K.

Total fluence (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	.201 $\pm$.002	10.07 $\pm$.01
1.05	.205 $\pm$.001	10.06 $\pm$.01
2.29	.205 $\pm$.001	10.23 $\pm$.01
2.72	.201 $\pm$.002	10.01 $\pm$.01
* 2.72	.205 $\pm$.001	10.16 $\pm$.01
4.78	.207 $\pm$.001	10.24 $\pm$.02
9.56	.213 $\pm$.001	10.44 $\pm$.01
14.4	.217 $\pm$.002	10.61 $\pm$.02
*14.4	.215 $\pm$.001	10.60 $\pm$.01

* Samples brought up to 4.2 and kept there overnight after irradiation but before measurement.

TABLE 24

Run 10. Production data; Samples 2, 3 and 5; $f = 10^4$ Hz; $T_{MEAS} = 1.5$ K;

$T_{IRR} < 1.9$ K.

Sample	Total fluence (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
2	9.56	.277 $\pm$.001	8.2 $\pm$.1
2	14.4	.302 $\pm$.004	8.5 $\pm$.1
3	9.56	.0094 $\pm$.0002	6.69 $\pm$.02
3	14.4	.0109 $\pm$.0004	6.84 $\pm$.03
5	9.56	.030 $\pm$.001	8.69 $\pm$.02
5	14.4	.032 $\pm$.001	8.77 $\pm$.03

Figure 24: Conductance versus frequency, Run 10, Sample 2, measurement
temperature = 2.0 K, before and after 1.4×10^{14} e/cm².

Figure 25: Conductance versus frequency, Run 10, Sample 3, measurement
temperature = 2.0 K, before and after $1.4 \times 10^{14} \text{ e/cm}^2$.

Figure 26: Conductance versus frequency, Run 10, Sample 5, measurement temperature = 2.0 K, before and after $1.4 \times 10^{14} \text{ e/cm}^2$.

TABLE 25

Run 10. Frequency dependence data, Sample 2, $T_{\text{MEAS}} = 2.0 \text{ K}$, $T_{\text{IRR}} < 1.9 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$1.01 \pm .02$	2150 ± 2
10^3	$3.127 \pm .002$	$91.9 \pm .2$
10^4	$3.243 \pm .001$	$10.1 \pm .1$
10^5	$3.680 \pm .008$	$7.4 \pm .2$
After $\phi = 1.4 \times 10^{14} \text{ e/cm}^2 \begin{matrix} +10\% \\ -50\% \end{matrix}$		
10^2	$.986 \pm .001$	2243 ± 1
10^3	$3.359 \pm .007$	$111.0 \pm .1$
10^4	$3.583 \pm .002$	$11.2 \pm .1$
10^5	$4.22 \pm .01$	$7.2 \pm .2$

TABLE 26

Run 10. Frequency dependence data, Sample 3, $T_{\text{MEAS}} = 2.0 \text{ K}$, $T_{\text{IRR}} < 1.9 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$.0070 \pm .0003$	8 ± 1
10^3	$.0089 \pm .0001$	$6.97 \pm .02$
10^4	$.016 \pm .001$	$6.65 \pm .02$
10^5	$.045 \pm .001$	$6.544 \pm .005$
After $\phi = 1.4 \times 10^{14} \text{ e/cm}^2 \begin{matrix} +10\% \\ -50\% \end{matrix}$		
10^2	$.0066 \pm .0004$	$8.9 \pm .3$
10^3	$.0100 \pm .0003$	$7.470 \pm .002$
10^4	$.0212 \pm .003$	$6.97 \pm .01$
10^5	$.076 \pm .001$	$6.773 \pm .002$

TABLE 27

Run 10. Frequency dependence data, Sample 5, $T_{\text{MEAS}} = 2.0 \text{ K}$, $T_{\text{IRR}} < 1.9 \text{ K}$.

Before irradiation		
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
10^2	$.0087 \pm .0005$	19 ± 1
10^3	$.0230 \pm .008$	$16.6 \pm .1$
10^4	$.202 \pm .002$	$10.07 \pm .01$
10^5	$.304 \pm .003$	$8.50 \pm .01$
After $\phi = 1.4 \times 10^{14} \text{ e/cm}^2 \begin{matrix} + 10\% \\ - 50\% \end{matrix}$		
10^2	$.0079 \pm .0003$	$19.2 \pm .3$
10^3	$.0228 \pm .0004$	$17.0 \pm .2$
10^4	$.215 \pm .001$	$10.60 \pm .01$
10^5	$.359 \pm .002$	$8.65 \pm .02$

Figure 27: Conductance versus frequency, Run 11, Sample 4, measurement temperature = 2.0 K, before irradiation.

Figure 28: Conductance versus frequency, Run 11, Sample 9, measurement temperature = 2.0 K, before irradiation.

TABLE 28

Run 11. Change in conductance for increments of fluence; Samples 4, 7, 8, and 9; $T_{MEAS} = 1.5$ K.

Increment of fluence (10^{13} e/cm ²)	Sample 4 ΔG (micromhos)	Sample 7 ΔG (micromhos)	Sample 8 ΔG (micromhos)	Sample 9 ΔG (micromhos)	Irradiation temperature (K)
.2	.012 $\pm$.003	.025 $\pm$.002	.019 $\pm$.002	.024 $\pm$.002	<1.5
3.6	.014 $\pm$.001	.013 $\pm$.002	.032 $\pm$.001	.054 $\pm$.002	1.5
3.6	.003 $\pm$.001	.004 $\pm$.001	.013 $\pm$.001	.025 $\pm$.002	1.6
1.8	.008 $\pm$.001	.008 $\pm$.002	.016 $\pm$.001	.0240 $\pm$.001	1.4
1.4	.000 $\pm$.001	.0005 $\pm$.001	.0037 $\pm$.001	.0053 $\pm$.001	1.6
1.4	.002 $\pm$.002	.003 $\pm$.001	.0047 $\pm$.001	.0059 $\pm$.001	1.6
1.4	.006 $\pm$.001	.006 $\pm$.001	.0109 $\pm$.001	.015 $\pm$.002	1.4

TABLE 29

Run 11. Ratios of conductance changes in Samples 7, 8, and 9 to changes in Sample 4 for increments of fluence (calculated from Table 28).

Increment of fluence (10^{13} e/cm ²)	$\frac{\Delta G_7}{\Delta G_4}$	$\frac{\Delta G_8}{\Delta G_4}$	$\frac{\Delta G_9}{\Delta G_4}$	Irradiation temperature (K)
.2	2.1 $\pm$.9 - .6	1.6 $\pm$.8 - .5	2.0 $\pm$.9 - .6	<1.5
3.6	.9 $\pm$.2	2.3 $\pm$.2	3.9 $\pm$.4	1.5
3.6	1.3 $\pm$ 1.2 - .6	4.3 $\pm$ 3 - 1	8.3 $\pm$ 5 - 2.6	1.6
1.8	1.0 $\pm$.4 - .5	2.0 $\pm$.8 - .4	3.0 $\pm$.6 - .4	1.4
1.4	--	--	--	1.6
1.4	1.5 $\pm$ 2.5 - .8	2.4 $\pm$ 3.3 - 1.2	3.0 $\pm$ 3.9 - 1.4	1.6
1.4	1.0 $\pm$.4 - .3	1.8 $\pm$.2	2.5 $\pm$.9	1.4

TABLE 30

Run 11. Change in conductance for increments of fluence; Samples 4, 7, 8, and 9; $T_{\text{MEAS}} = 2.0 \text{ K}$; $T_{\text{IRR}} < 1.7 \text{ K}$.

Increment of fluence (10^{13} e/cm^2)	Sample 4 ΔG (micromhos)	Sample 7 ΔG (micromhos)	Sample 8 ΔG (micromhos)	Sample 9 ΔG (micromhos)
.2	.16 $\pm$.03	.10 $\pm$.04	.18 $\pm$.03	.16 $\pm$.04
3.6	.08 $\pm$.02	.10 $\pm$.02	.40 $\pm$.02	.71 $\pm$.03
3.6	.02 $\pm$.01	.02 $\pm$.008	.15 $\pm$.02	.19 $\pm$.04
6.0	.11 $\pm$.01	.10 $\pm$.01	.46 $\pm$.03	.59 $\pm$ 0.14
Total excluding the first increment	.21 $\pm$.03	.24 $\pm$.03	1.01 $\pm$.03	1.49 $\pm$ 0.14

TABLE 31

Run 11. Ratios of conductance changes in Samples 7, 8, and 9 to changes in Sample 4 for increments of fluence (calculated from Table 30).

Increment of fluence (10^{13} e/cm^2)	$\frac{\Delta G_7}{\Delta G_4}$	$\frac{\Delta G_8}{\Delta G_4}$	$\frac{\Delta G_9}{\Delta G_4}$
.2	.63 $\pm$.45 - .31	1.1 $\pm$.5 - .3	1.0 $\pm$.5 - .4
3.6	1.3 $\pm$.7 - .5	5.0 $\pm$.2 - 1.2	8.9 $\pm$ 3.4 - 2.1
3.6	1.0 $\pm$ 1.8 - .6	7.5 $\pm$ 9.5 - 3.2	9.5 $\pm$ 14 - 4.5
6.0	.91 $\pm$.10 - .16	4.2 $\pm$.7 - .6	5.4 $\pm$ 1.9 - 1.7
Total excluding the first increment	1.1 $\pm$.4 - .2	4.8 $\pm$ 1.0 - .7	7.1 $\pm$ 2.0 - 1.5

conductance changes of Samples 7, 8, and 9 to changes of Sample 4. See also Tables 32 and 33 for data of this run. The change in conductance due to the first irradiation increment, which consisted of $1.6 \times 10^{12} \text{ e/cm}^2$, appears to be due to surface changes because 1) the conductances of Samples 7, 8, and 9 are nearly the same; 2) the change in conductance is very high for such small fluence. Therefore this first increment is subtracted from changes due to the total irradiation before ratios of conductance changes of the samples were computed. The ratios of the conductance changes after $\phi = 13.2 \times 10^{13} \text{ e/cm}^2$ were then $\frac{\Delta G_7}{\Delta G_4} = 1.0 \pm .1$, $\frac{\Delta G_8}{\Delta G_4} = 2.5 \pm 1.5$, and $\frac{\Delta G_9}{\Delta G_4} = 4.2 \pm .2$ at $T = 1.45 \text{ K}$. In calculating $\Delta \sigma_i$, we use $\Delta \sigma_i = \frac{Z_i l_i \Delta G_i}{A}$, where Z_i is a factor which corrects for fringing fields, l_i is the thickness, $\Delta \sigma_i$ = change in conductivity, and ΔG_i = change in conductance of the i^{th} sample. If $\Delta \sigma_i = \Delta \sigma$ independent of the sample, then

$$\frac{\Delta G_i}{\Delta G_j} = \frac{Z_i l_i}{Z_j l_j} \quad (34)$$

Since $Z_4 = .856$, $Z_7 = .856$, $Z_8 = .939$, $Z_9 = .952$, we should have $\frac{\Delta G_7}{\Delta G_4} = 1.01$, $\frac{\Delta G_8}{\Delta G_4} = 2.54$, $\frac{\Delta G_9}{\Delta G_4} = 3.22$. If one tries to take into account a smaller average beam energy and hence smaller average production rates in the thicker samples, the calculated ratios $\frac{\Delta G_i}{\Delta G_j}$ would be somewhat smaller. To get some idea of the magnitude of this effect consider the results for production rate versus thickness shown in Figure 12 for n-type samples. It is found that $\frac{P_8}{P_4} = \frac{P_9}{P_4} = 1.1$ where P_i is the production rate in the i^{th} sample. Therefore the calculated values of $\frac{\Delta G_7}{\Delta G_4}$ and $\frac{\Delta G_9}{\Delta G_4}$ should be multiplied by 1.1 to compare with experimental values. The largest error obtained is $\frac{4.2-3.5}{3.5} = .2$ or +20%. The average error is $\frac{.00+.11+.20}{3} = .10$, or 10%. Therefore errors in the production of about $\pm 10\%$ due to surface conductance change can be expected in the calculation of production rates in p-type germanium in this experiment.

TABLE 32

Run 11. Production data; some annealing data; Samples 4, 7, 8, and 9;

$$f = 10^4 \text{ Hz}; T_{\text{IRR}} < 1.7 \text{ K.}$$

Before irradiation

Sample	Conductance (micromhos)	Capacitance (picofarads)	Measurement temperature (K)
4	.446 $\pm$.002	8.57 $\pm$.01	1.5
7	.416 $\pm$.001	8.23 $\pm$.01	1.5
8	.407 $\pm$.001	16.9 $\pm$.1	1.5
9	.808 $\pm$.001	22.5 $\pm$.1	1.5
4	5.32 $\pm$.02	14.8 $\pm$.1	2.0
7	4.96 $\pm$.02	13.0 $\pm$.1	2.0
8	5.86 $\pm$.01	26.9 $\pm$.1	2.0
9	11.60 $\pm$.02	35 $\pm$ 1	2.0

$$\text{After } \varphi = .16 \times 10^{13} \text{ e/cm}^2 \pm 40\%$$

4	.457 $\pm$.002	9.11 $\pm$.01	1.5
7	.439 $\pm$.001	9.01 $\pm$.01	1.5
8	.425 $\pm$.001	17.17 $\pm$.02	1.5
9	.911 $\pm$.001	22.75 $\pm$.01	1.5
4	5.477 $\pm$.002	15.8 $\pm$.1	2.0
7	4.992 $\pm$.002	15.1 $\pm$.1	2.0
8	6.064 $\pm$.002	27.8 $\pm$.1	2.0
9	11.78 $\pm$.02	43 $\pm$ 1	2.0

Samples brought up to 4.2 K for 2 days

4	5.446 $\pm$.003	16.5 $\pm$.1	2.0
7	5.051 $\pm$.003	15.8 $\pm$.1	2.0
8	6.026 $\pm$.002	28.5 $\pm$.1	2.0
9	11.75 $\pm$.02	43 $\pm$ 1	2.0

After $\varphi = 1.3 \times 10^{14} \text{ e/cm}^2$ (TOTAL) $\pm 20\%$

Sample	Conductance (micromhos)	Capacitance (picofarads)	Measurement Temperature (K)
4	.489 $\pm$.01	9.30 $\pm$.01	1.5
7	.472 $\pm$.001	9.23	1.5
8	.507 $\pm$.001	17.81 $\pm$.01	1.5
9	1.053 $\pm$.002	23.51 $\pm$.01	1.5
4	5.700 $\pm$.005	17.6 $\pm$.1	2.0
7	5.300 $\pm$.004	16.4 $\pm$.1	2.0
8	7.058 $\pm$.005	30.5 $\pm$.1	2.0
9	13.25 $\pm$.04	47 $\pm$ 1	2.0

Samples brought up to 4.2 K for one day

4	.491 $\pm$.002	9.30 $\pm$.02	1.5
7	.472 $\pm$.001	9.20 $\pm$.02	1.5
8	.510 $\pm$.001	17.82 $\pm$.02	1.5
9	1.053 $\pm$.0015	23.51 $\pm$.02	1.5

Anneal 10 K for 16 minutes

8	1.10 $\pm$.01	20.0 $\pm$.1	1.6
9	2.16 $\pm$.01	26.3 $\pm$.1	
4	5.700 $\pm$.005	17.5 $\pm$.1	2.0
7	5.303 $\pm$.004	16.3 $\pm$.1	2.0
8	7.098 $\pm$.005	30.4 $\pm$.1	2.0
9	13.46 $\pm$.06	46 $\pm$ 1	2.0
4	1.001 $\pm$.0015	9.97 $\pm$.01	1.6
7	.958 $\pm$.002	10.01 $\pm$.05	1.6
8	1.093 $\pm$.003	20.0 $\pm$.1	1.6
9	2.192 $\pm$.006	26.2 $\pm$.1	1.6

Anneal 300 K

4	.490 $\pm$.001	9.23 $\pm$.03	1.5
7	.464 $\pm$.003	9.8 $\pm$.1	1.5
8	.535 $\pm$.003	17.75 $\pm$.04	1.5
9	1.234 $\pm$.002	24.5 $\pm$.1	1.5

Sample	Conductance (micromhos)	Capacitance (picofarads)	Measurement temperature (K)
4	$1.072 \pm .004$	$10.2 \pm .1$	1.6
7	$.925 \pm .001$	$9.99 \pm .01$	1.6
8	$1.132 \pm .002$	$19.2 \pm .1$	1.6
9	$2.538 \pm .003$	$25.4 \pm .1$	1.6
4	$5.51 \pm .01$	$16.8 \pm .2$	2.0
7	$4.96 \pm .01$	$16.3 \pm .1$	2.0
8	$7.356 \pm .003$	$30.2 \pm .1$	2.0
9	$15.23 \pm .03$	43 ± 1	2.0

TABLE 33

Run 11. Frequency dependence data, Samples 4 and 9, $T_{\text{MEAS}} = 2.0 \text{ K}$,
 $T_{\text{IRR}} < 1.7 \text{ K}$.

Before irradiation

Sample	Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)
4	10^3	$4.64 \pm .01$	$234.1 \pm .2$
4	10^4	$5.32 \pm .02$	$14.8 \pm .1$
4	10^5	$6.04 \pm .01$	$7.3 \pm .1$
9	10^2	$.333 \pm .001$	2464 ± 1
9	10^3	$7.01 \pm .01$	842 ± 1
9	10^4	$11.60 \pm .02$	35 ± 1
9	10^5	$13.6 \pm .1$	11 ± 1

TABLE 34

Experimental and calculated conductance change ratios. See text.

Experimental			Calculated		
$\frac{\Delta G_7}{\Delta G_4}$	$\frac{\Delta G_8}{\Delta G_4}$	$\frac{\Delta G_9}{\Delta G_4}$	$\frac{\Delta G_7}{\Delta G_4}$	$\frac{\Delta G_8}{\Delta G_4}$	$\frac{\Delta G_9}{\Delta G_4}$
$1.0 \pm .1$	$2.5 \pm .15$	$4.2 \pm .2$	1.01	2.8	3.5

The conductance ratios obtained at increments of fluence for measurements at 2 K do not agree with the calculated results very well at all. This means that the lower temperature measurements are more reliable.

Anneals to 10 K, 30 K, 56 K, 80 K, 100 K, and 295 K were made for these samples. Results are given in Tables 35 and 36. The annealing changes are not in agreement with the thickness ratios. It is not certain, therefore, how much of the annealing stages represent true bulk annealing.

It is instructive to try to estimate the magnitude of the surface conductance and its temperature dependence. Before irradiation, the bulk conductivity σ_B should be the same in all samples. Now

$$G_i = \frac{A_i \sigma_B}{Z_i t_i} + G_{S_i} \quad (35)$$

where G_i = bulk-surface conductance
 Z_i = correction factor for fringing fields
 t_i = thickness
 G_{S_i} = surface conductance
 σ_B = bulk conductivity
 A_i = electrode area

for the i^{th} sample. Consider also

TABLE 35

Run 11. Annealing; Samples 4, 7, 8, and 9; $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.6$ K;

$T_{\text{IRR}} < 1.7$ K; $\phi = 1.32 \times 10^{14}$ e/cm² $\pm$ 20%.

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
4	$1.001 \pm .0015$		10
7	$.958 \pm .02$		
8	$1.092 \pm .003$		
9	$2.20 \pm .006$		
4	$1.004 \pm .002$	$+.003 \pm .0035$	30
7	$.957 \pm .002$	$-.001 \pm .02$	
8	$1.098 \pm .0025$	$+.006 \pm .0055$	
9	$2.202 \pm .002$	$+.001 \pm .008$	
4	$.975 \pm .001$	$-.029 \pm .003$	56
7	$.942 \pm .002$	$-.015 \pm .004$	
8	$1.061 \pm .003$	$-.037 \pm .006$	
9	$2.24 \pm .02$	$-.04 \pm .02$	
4	$.968 \pm .002$	$-.007 \pm .003$	80
7	$.941 \pm .002$	$-.001 \pm .004$	
8	$1.042 \pm .004$	$-.019 \pm .007$	
9	$2.283 \pm .01$	$+.04 \pm .03$	
4	$1.072 \pm .003$	$+.120 \pm .005$	100
7	$1.004 \pm .005$	$+.069 \pm .007$	
8	$1.256 \pm .002$	$+.214 \pm .006$	
9	$2.67 \pm .01$	$.39 \pm .01$	
4	$.987 \pm .008$	$-.085 \pm .013$	295
7	$.925 \pm .002$	$-.079 \pm .007$	
8	$1.132 \pm .002$	$-.124 \pm .004$	
9	$2.538 \pm .003$	$-.13 \pm .01$	

TABLE 36

Run 11. Annealing; Samples 4, 7, 8, and 9; $f = 10^4$ Hz; $T_{\text{MEAS}} = 2.0$ K;

$T_{\text{IRR}} < 1.7$ K; $\varphi = 1.32 \times 10^{14}$ e/cm² $\pm 20\%$.

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
4	$5.691 \pm .003$		4.2
7	$5.305 \pm .004$		
8	$7.058 \pm .004$		
9	$13.25 \pm .04$		
4	$5.700 \pm .005$	$+.009 \pm .008$	10
7	$5.309 \pm .004$	$+.004 \pm .008$	
8	$7.098 \pm .005$	$+.040 \pm .009$	
9	$13.46 \pm .06$	$+.21 \pm .1$	
4	$5.702 \pm .003$	$+.002 \pm .008$	30
7	$5.307 \pm .004$	$-.002 \pm .008$	
8	$7.111 \pm .004$	$+.013 \pm .009$	
9	$13.4 \pm .05$	$-.06 \pm .1$	
4	$5.537 \pm .003$	$-.165 \pm .006$	56
7	$5.212 \pm .004$	$-.095 \pm .008$	
8	$6.87 \pm .01$	$-.24 \pm .01$	
9	$13.88 \pm .03$	$+.48 \pm .08$	
4	$5.52 \pm .01$	$-.01 \pm .013$	80
7	$5.209 \pm .005$	$-.003 \pm .012$	
8	$6.87 \pm .01$	$.00 \pm .02$	
9	$13.88 \pm .03$	$.00 \pm .06$	
4	$5.51 \pm .01$	$-.01 \pm .02$	295
7	$4.96 \pm .01$	$-.25 \pm .015$	
8	$7.356 \pm .003$	$+.53 \pm .03$	
9	$15.23 \pm .03$	$+1.35 \pm .06$	

$$G_j = \frac{A_j \sigma_B}{Z_j t_j} + G_{S_j} \quad (36)$$

We can eliminate σ_B as shown below.

$$\frac{A_i G_i}{Z_j t_j} - \frac{A_i G_j}{Z_i t_i} = \frac{A_i A_j \sigma_B}{Z_i Z_j t_i t_j} - \frac{A_i A_j \sigma_B}{Z_i Z_j t_i t_j} + \frac{A_j G_{S_i}}{Z_j t_j} - \frac{A_i G_{S_j}}{Z_i t_i} \quad (37)$$

and so

$$\frac{A_j G_i}{Z_j t_j} - \frac{A_i G_j}{Z_i t_i} = \frac{A_j G_{S_i}}{Z_j t_j} - \frac{A_i G_{S_j}}{Z_i t_i} \quad (38)$$

or

$$G_i - \frac{A_i Z_j t_j}{A_j Z_i t_i} G_j = G_{S_i} - \frac{A_i Z_j t_j}{A_j Z_i t_i} G_{S_j} \quad (39)$$

Define

$$\Gamma_{ij} \equiv G_i - \frac{A_i Z_j t_j}{A_j Z_i t_i} G_j \quad (40)$$

The above quantity Γ_{ij} has the advantages that the bulk conductance has been eliminated, and for some cases $\frac{Z_j t_j}{Z_i t_i} G_{S_j}$ is small so that $\Gamma_{ij} \approx G_{S_i}$. Results are shown in Table 37.

The temperature dependence of the bulk conductivity can be found by considering $G_i = \frac{A_i}{T_i Z_i} \sigma_B + G_{S_i}$ at two different temperatures for the same sample. This is illustrated below for Sample 4.

$$G_4(1.45 \text{ K}) = \frac{A_4}{t_4 Z_4} \sigma_B(1.45 \text{ K}) + G_{S_4}(1.45 \text{ K}) \quad (41)$$

$$G_4(2.0 \text{ K}) = \frac{A_4}{t_4 Z_4} \sigma_B(2.0 \text{ K}) + G_{S_4}(2.0 \text{ K}) \quad (42)$$

Note that

$$\frac{\Gamma_{47}(2.0 \text{ K})}{\Gamma_{47}(1.45 \text{ K})} = 12 \quad (43)$$

TABLE 37

Γ_{ij} in Run 11. See text.

Before irradiation					
ij	Γ_{ij} (micromhos) at 1.5 K	Γ_{ij} (micromhos) at 2.0 K		$\frac{\Gamma_{ij}(2.0 \text{ K})}{\Gamma_{ij}(1.5 \text{ K})}$	
47	.033 $\pm$.003	.40 $\pm$.04			12
89	-.295 $\pm$.002	-3.29 $\pm$.03			11.5
49	.171 $\pm$.002	1.73 $\pm$.03			10.1
78	.256 $\pm$.001	2.65 $\pm$.03			10.4
79	.139 $\pm$.001	1.34 $\pm$.03			9.64
48	.287 $\pm$.002	3.03 $\pm$.03			10.6

After irradiation ($\phi = 1.3 \times 10^{14} \text{ e/cm}^2$)					
ij	Γ_{ij} (micromhos) at 1.5 K	Γ_{ij} (micromhos) at 1.6 K	Γ_{ij} (micromhos) at 2.0 K	$\frac{\Gamma_{ij}(1.6)}{\Gamma_{ij}(1.5)}$	$\frac{\Gamma_{ij}(2.0)}{\Gamma_{ij}(1.5)}$
47	.023 $\pm$.003	.051 $\pm$.0035	.442 $\pm$.01	2.22	19
89	-.317 $\pm$.0025	-.638 $\pm$.01	-3.41 $\pm$.045	2.01	10.8
49	.167 $\pm$.003	.316 $\pm$.0075	1.60 $\pm$.015	1.89	9.58
78	.271 $\pm$.001	.520 $\pm$.003	2.51 $\pm$.006	1.92	9.26
79	.145 $\pm$.002	.266 $\pm$.004	1.16 $\pm$.014	1.83	8.00
48	.292 $\pm$.002	.567 $\pm$.003	2.94 $\pm$.007	1.94	10.1

If we assume that all G_{S_i} have the same temperature dependence then

$$\frac{G_{S_4}(2.0 \text{ K})}{G_{S_4}(1.45 \text{ K})} = 12 \quad (44)$$

Now we can write

$$G_4(2.0) = \frac{A_4}{t_4 Z_4} \sigma_B(2.0 \text{ K}) + 12 G_{S_4}(1.45 \text{ K}) \quad (45)$$

Since $G_4(1.45)$, $G_4(2.0)$, A_4 , t_4 , and Z_4 are all known, the relation between $\sigma_B(2.0 \text{ K})$ and $\sigma_B(1.45 \text{ K})$ can be found using equations 41 and 45 to eliminate the surface term. The result is

$$\sigma_B(2.0 \text{ K}) \cong 12 \sigma_B(1.45 \text{ K}) \quad (46)$$

If we use the temperature dependence obtained from Γ_{79} then we would have

$$\sigma_B(2.0 \text{ K}) \cong 9.7 \sigma_B(1.45 \text{ K}) \quad (47)$$

To summarize the results of Run 11, we can say that although a large part of the initial conductance of these samples is due to surface effects, changes in conductance observed on irradiation are for the most part due to changes in the bulk conductivity. We assume that surface effects lead to errors of $\pm 10\%$ in attempts to calculate production rates. Although there seems to be a dependence of production rate on irradiation temperature, this was not reproduced in later runs. The fluence measurements for this run were made by picking up the beam on a small beam monitor inside the sample can. Ionization of the exchange gas can lead to spurious effects, so that fluence measurements in Runs 10, 11, and 12 are not as reliable as those of Runs 13 and 14, where the fluence was monitored by measuring the beam collected by the entire dewar. The annealing measurements in Run 11 do not prove that the annealing stages seen are due to bulk changes.

The production rate listed in Table 20. was obtained by using the points at $.16 \times 10^{13} \text{ e/cm}^2$ and $1.3 \times 10^{13} \text{ e/cm}^2$ to determine the slope of the production curve.

Run 12. Four gallium doped samples ($5.2 \times 10^{15} \text{ cm}^{-3}$, $7.0 \times 10^{15} \text{ cm}^{-3}$, $5.0 \times 10^{15} \text{ cm}^{-3}$, and $4.7 \times 10^{15} \text{ cm}^{-3}$) were irradiated with 1.1 MeV electrons and annealed. Two measurements were taken at $1.45 \text{ K} \begin{smallmatrix} +.03 \text{ K} \\ -.01 \text{ K} \end{smallmatrix}$ and $1.58 \text{ K} \pm .01 \text{ K}$. Sample 4 is the same sample used in Run 11. It was remounted for use in this run. A carbon resistance thermometer was varnished to the back of the sample within the $\frac{1}{4}$ " electrode. This resistor was used to determine the temperature difference during irradiation between the samples and the carbon resistance thermometer normally used to measure the temperature. Conductance versus fluence is shown in Figures 29-36. See also Tables 38-41. Annealing results are given Figures 37-44 and Tables 42-44. Conductance versus frequency curve after irradiation is given in Figure 45 for Sample 11.

The production curves in this run are erratic. The first and last measurement points were used to determine the slope of the curve for the purpose of calculating P for Table 20.

Run 13. Again in this run, four gallium doped samples were irradiated with 1.1 MeV electrons. The doping levels were $5.7 \times 10^{15} \text{ cm}^{-3}$, $6.0 \times 10^{15} \text{ cm}^{-3}$, $7.6 \times 10^{15} \text{ cm}^{-3}$, and $8.8 \times 10^{15} \text{ cm}^{-3}$. This was the first run in which the entire dewar was used to monitor the beam. The relationship between the charge collected by the dewar in coulombs and the fluence in e/cm^2 is $\phi = 3.7 \times 10^{16} Q_d$ at 1.1 MeV. There was a $\pm 5\%$ variation in beam intensity over the sample chamber, so that the value given above is an average value for all samples. The current integrator has an accuracy of 1%. The reproducibility of the beam on the samples is about 5%, so that the total accuracy

Figure 30: Conductance versus fluence, Run 12, Sample 4, 10^4 Hz.

Figure 31: Conductance versus fluence, Run 12, Sample 13, 10^4 Hz.

Figure 32: Conductance versus fluence, Run 12, Sample 14, 10^4 Hz.

Figure 33: Conductance versus fluence, Run 12, Sample 11, 10^2 Hz.

Figure 34: Conductance versus fluence, Run 12, Sample 4, 10^2 Hz.

Figure 35: Conductance versus fluence, Run 12, Sample 13, 10^2 Hz.

TABLE 38

Run 12. Production and frequency data, some annealing data, Sample 11,
 $T_{IRR} < 2.0 \text{ K}$.

Before irradiation

Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Measurement temperature (K)
10^2	$.3882 \pm .0003$	140 ± 1	1.5
10^4	$.526 \pm .001$	$8.56 \pm .01$	1.5
* 10^4	$.529 \pm .001$	$8.45 \pm .01$	1.5

After $\varphi = 1.46 \times 10^{14} \text{ e/cm}^2$ $\begin{matrix} +10\% \\ -30\% \end{matrix}$

10^4	$.599 \pm .001$	$9.10 \pm .01$	1.5
† 10^4	$.596 \pm .001$	$9.13 \pm .01$	1.5
‡ 10^4	$.598 \pm .001$	$9.06 \pm .01$	1.5
10^2	$.426 \pm .001$	177 ± 2	1.5
10^3	$.4972 \pm .0002$	$16.77 \pm .02$	1.5
10^5	$1.037 \pm .001$	$7.12 \pm .01$	1.5

Anneal 10 K for 15 minutes

10^2	$.425 \pm .001$	176 ± 1	1.5
10^4	$.601 \pm .001$	$9.06 \pm .01$	1.5
10^4	$1.209 \pm .003$	$10.0 \pm .1$	1.6

* About one hour later

† Samples at 4.2 K for ten days

‡ About $1\frac{1}{2}$ hours later

TABLE 39

Run 12. Production and frequency data, some annealing data, Sample 4,
 $T_{IRR} < 2.0$ K.

Before irradiation			
Frequency (Hz)	Conductance (micromhos)	Capacitance (pico farads)	Measurement temperature (K)
10^2	.357 $\pm$.001	147 $\pm$ 1	1.5
10^4	.470 $\pm$.001	8.56 $\pm$.01	1.5
$\dagger 10^4$	.472 $\pm$.001	8.12 $\pm$.01	1.5
After $\phi = 1.46 \times 10^{14}$ e/cm ² $\begin{smallmatrix} +10\% \\ -30\% \end{smallmatrix}$			
10^4	.539 $\pm$.0015	8.73 $\pm$.01	1.5
* 10^4	.529 $\pm$.001	8.67 $\pm$.01	1.5
‡ 10^4	.531 $\pm$.001	8.51 $\pm$.01	1.5
10^2	.393 $\pm$.001	181 $\pm$ 1	1.5
10^3	.4481 $\pm$.0002	13.51 $\pm$.03	1.5
10^5	.939 $\pm$.001	6.67 $\pm$.01	1.5
Anneal 10 K for 15 minutes			
10^2	.391 $\pm$.001	180 $\pm$ 1	1.5
10^4	.528 $\pm$.001	8.50 $\pm$.01	1.5
10^4	1.08 $\pm$.01	9.3 $\pm$.1	1.6

* Samples brought up to 4.2 K for ten days.

† About one hour later.

‡ About $1\frac{1}{2}$ hours later.

TABLE 40

Run 12. Production and frequency data, some annealing data, Sample 13,
 $T_{IRR} < 2.0$ K.

Before irradiation			
Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Measurement temperature (K)
10^2	$.4983 \pm .0004$	233 ± 1	1.5
10^4	$.668 \pm .001$	$10.35 \pm .01$	1.5
$^\dagger 10^4$	$.673 \pm .001$	$10.31 \pm .01$	1.5
After $\phi = 1.46 \times 10^{14} \text{ e/cm}^2 \begin{smallmatrix} +10\% \\ -30\% \end{smallmatrix}$			
10^4	$.772 \pm .001$	$10.98 \pm .01$	1.5
$^* 10^4$	$.771 \pm .001$	$11.05 \pm .01$	1.5
$^\ddagger 10^4$	$.774 \pm .001$	$10.95 \pm .01$	1.5
10^2	$.553 \pm .001$	299 ± 1	1.5
10^3	$.6591 \pm .0003$	$19.76 \pm .015$	1.5
10^5	$1.43 \pm .01$	$7.7 \pm .1$	1.5
Anneal 10K for 15 minutes			
10^4	$.776 \pm .001$	$10.95 \pm .02$	1.5
10^2	$.550 \pm .0015$	$296. \pm 1$	1.5
10^4	$1.568 \pm .002$	$11.9 \pm .1$	1.6

* Samples brought up to 4.2 K for 10 days

† About one hour later

‡ About $1\frac{1}{2}$ hours later

TABLE 41

Run 12. Production and frequency data, some annealing data, Sample 14,
 $T_{IRR} < 2.0$ K.

Before irradiation

Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Measurement temperature (K)
10^2	.308 $\pm$.001	92 $\pm$ 1	1.5
10^4	.415 $\pm$.001	9.78 $\pm$.01	1.5
$^{\dagger}10^4$	.418 $\pm$.001	9.74 $\pm$.01	1.5

After $\phi = 1.46 \times 10^{14}$ e/cm² $\begin{smallmatrix} +10\% \\ -3\% \end{smallmatrix}$

10^4	.485 $\pm$.001	10.24 $\pm$.01	1.5
* 10^4	.482 $\pm$.001	10.23 $\pm$.01	1.5
$^{\dagger}10^4$	.483 $\pm$.001	10.19 $\pm$.01	1.5
10^2	.355 $\pm$.001	123 $\pm$ 1	1.5
10^3	.3924 $\pm$.0003	14.92 $\pm$.01	1.5
10^5	.883 $\pm$.001	8.84 $\pm$.01	1.5

Anneal 10 K for 15 minutes

10^4	.484 $\pm$.001	10.19 $\pm$.01	1.5
10^2	.353 $\pm$.001	122 $\pm$ 1	1.5
10^4	.980 $\pm$.001	10.89	1.6

* Samples brought up to 4.2 K for ten days

† About one hour later

‡ About $1\frac{1}{2}$ hours later

Figure 37: Annealing, Run 12, Sample 11, 10^4 Hz.

ANNEALING

RUN 12, SAMPLE 11

$$5 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} < 2.0 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

○ WITHIN $\frac{1}{2}$ HOUR AFTER PUMPDOWN

x UP TO 5 HOURS LATER

Figure 38: Annealing, Run 12, Sample 4, 10^4 Hz.

ANNEALING

RUN 12, SAMPLE 4

$$7 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} < 2.0 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

○ WITHIN $\frac{1}{2}$ HOUR AFTER PUMPDOWN

x UP TO 5 HOURS LATER

Figure 39: Annealing, Run 12, Sample 13, 10^4 Hz.

Figure 40: Annealing, Run 12, Sample 14, 10^4 Hz.

Figure 41: Annealing, Run 12, Sample 11, 10^2 Hz.

Figure 42: Annealing, Run 12, Sample 4, 10^2 Hz.

ANNEALING

RUN 12, SAMPLE 4

$$7 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} < 2.0 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^2 \text{ Hz}$$

Figure 43: Annealing, Run 12, Sample 13, 10^2 Hz.

Figure 44: Annealing, Run 12, Sample 14, 10^2 Hz.

ANNEALING

RUN 12, SAMPLE 14

$$6 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} < 2.0 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^2 \text{ Hz}$$

TABLE 42

Run 12. Annealing; Samples 11, 4, 13, and 14; $f = 10^4$ Hz; $T_{\text{MEAS}} = 1.5$ K;

$$T_{\text{IRR}} < 2.0 \text{ K}; \varphi = 1.46 \times 10^{13} \text{ e/cm}^2 \begin{matrix} +10\% \\ -30\% \end{matrix}$$

Sample	Conductance (micromhos)	Change in Conductance (micromhos)	Annealing temperature (K)
11	.596 $\pm$.001		4.2
4	.531 $\pm$.001		
13	.774 $\pm$.001		
14	.483 $\pm$.001		
11	.601 $\pm$.001	+.005 $\pm$.002	10
4	.532 $\pm$.001	+.003 $\pm$.002	
13	.776 $\pm$.001	+.014 $\pm$.002	
14	.484 $\pm$.001	+.002 $\pm$.002	
11	.598 $\pm$.001	-.003 $\pm$.002	30
4	.528 $\pm$.001	-.004 $\pm$.002	
13	.770 $\pm$.002	-.015 $\pm$.002	
14	.482 $\pm$.001	-.002 $\pm$.002	
11	.568 $\pm$.001	-.030 $\pm$.002	56
4	.512 $\pm$.001	-.016 $\pm$.0025	
13	.730 $\pm$.001	-.034 $\pm$.002	
14	.462 $\pm$.001	-.020 $\pm$.002	
11	.559 $\pm$.001	-.009 $\pm$.002	80
4	.507 $\pm$.001	-.005 $\pm$.002	
13	.724 $\pm$.001	-.007 $\pm$.002	
14	.459 $\pm$.001	-.003 $\pm$.002	
11	.629 $\pm$.001	+.070 $\pm$.002	100
4	.569 $\pm$.0015	+.062 $\pm$.0025	
13	.829 $\pm$.001	+.105 $\pm$.002	
14	.571 $\pm$.001	+.112 $\pm$.002	
11	.588 $\pm$.001	-.041 $\pm$.003	295
4	.532 $\pm$.001	-.037 $\pm$.0015	
13	.763 $\pm$.001	-.066 $\pm$.002	
14	.491 $\pm$.002	-.080 $\pm$.003	

TABLE 43

Run 12. Annealing; Samples 11, 4, 13, and 14; $f = 10^2$ Hz; $T_{\text{MEAS}} = 1.5$ K;

$$T_{\text{IRR}} < 2.0 \text{ K}; \varphi = 1.46 \times 10^{13} \text{ e/cm}^2 \begin{matrix} +10\% \\ -30\% \end{matrix}$$

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
11	.426 $\pm$.001		4.2
4	.393 $\pm$.001		
13	.553 $\pm$.001		
14	.355 $\pm$.001		
11	.425 $\pm$.001	-.001 $\pm$.002	10
4	.391 $\pm$.001	-.002 $\pm$.002	
13	.550 $\pm$.001	-.003 $\pm$.002	
14	.353 $\pm$.001	-.002 $\pm$.002	
11	.417 $\pm$.001	-.008 $\pm$.002	56
4	.386 $\pm$.0014	-.005 $\pm$.0024	
13	.539 $\pm$.001	-.011 $\pm$.002	
14	.347 $\pm$.001	-.006 $\pm$.002	
11	.414 $\pm$.001	-.003 $\pm$.002	80
4	.384 $\pm$.001	-.002 $\pm$.002	
13	.537 $\pm$.001	-.002 $\pm$.002	
14	.345 $\pm$.001	-.002 $\pm$.002	
11	.464 $\pm$.001	+.050 $\pm$.002	100
4	.427 $\pm$.0015	+.043 $\pm$.0025	
13	.602 $\pm$.001	+.065 $\pm$.002	
14	.400 $\pm$.0015	+.055 $\pm$.0025	
11	.434 $\pm$.0015	-.030 $\pm$.0025	295
4	.403 $\pm$.001	-.024 $\pm$.0025	
13	.564 $\pm$.001	-.038 $\pm$.002	
14	.370 $\pm$.001	-.030 $\pm$.002	

TABLE 44

Run 12. Annealing; Samples 11, 4, 13, and 14; $f = 10^4$ Hz; $T_{MEAS} = 1.6$ K;

$$T_{IRR} < 2.0 \text{ K}; \varphi = .1.46 \times 10^{13} \text{ e/cm}^2 \begin{matrix} +10\% \\ -30\% \end{matrix}$$

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
11	$1.219 \pm .003$		10
4	$1.08 \pm .01$		
13	$1.568 \pm .002$		
14	$.980 \pm .001$		
11	$1.197 \pm .003$	$-.012 \pm .003$	30
4	$1.072 \pm .003$	$-.01 \pm .01$	
13	$1.554 \pm .004$	$-.014 \pm .006$	
14	$.983 \pm .0015$	$+.003 \pm .006$	
11	$1.139 \pm .002$	$-.058 \pm .005$	56
4	$1.043 \pm .002$	$-.029 \pm .005$	
13	$1.477 \pm .01$	$-.077 \pm .014$	
14	$.946 \pm .001$	$-.037 \pm .0025$	
11	$1.139 \pm .005$	$-.000 \pm .007$	80
4	$1.046 \pm .004$	$+.003 \pm .006$	
13	$1.468 \pm .01$	$-.009 \pm .02$	
14	$.945 \pm .001$	$-.001 \pm .001$	
11	$1.220 \pm .003$	$+.081 \pm .008$	100
4	$1.124 \pm .003$	$+.078 \pm .007$	
13	$1.619 \pm .002$	$+.151 \pm .012$	
14	$1.038 \pm .008$	$+.093 \pm .009$	
11	$1.186 \pm .003$	$-.034 \pm .006$	300
4	$1.08 \pm .01$	$-.04 \pm .01$	
13	$1.561 \pm .005$	$-.058 \pm .007$	
14	$1.00 \pm .015$	$-.038 \pm .023$	

Figure 45: Conductance versus frequency, Run 12, Sample 11, after a
fluence of 1.5×10^{14} e/cm².

of the beam measurement is $\pm 11\%$. This run consisted of three series of irradiations. Anneals up to 295 K were done after each series. After the first series, the samples were at room temperature for about seven days. The samples were removed from the dewar and remounted with new wiring before the second series of irradiations. The samples were at room temperature four days between the second and third series. The results of the first irradiations are given in Figures 46-53 and Tables 45-48.

In the first series, the irradiations were made at temperatures of 1.8, 2.1, 2.3, and 4.3 K. The increase in conductance at 10^4 Hz was smaller for the irradiation increment at 4.3 K. Unfortunately, measurements at 10^2 Hz are not available for this increment because the conductance at 10^2 Hz became too noisy for meaningful measurements to be taken.

Production rates for this set of irradiations were estimated by using the points at 1.24×10^{13} e/cm² and 8.7×10^{13} e/cm².

The results of the second series of irradiations and anneals is given in Figures 54-69 and Tables 49-58. This irradiation was carried out at 1.8 K except for one increment at 4.3 K. The 10^4 Hz measurements show no decrease in production with this higher temperature, but the 10^2 Hz measurements do. Note that the production rate curves at 10^4 Hz have an "s" shape between 3.7×10^{13} e/cm² and 18.5×10^{13} e/cm². The production rate reaches a maximum near 1×10^{14} e/cm². In the final part of this series of irradiations the production was much smaller than initially. Note that Sample 15 has a higher production rate than the other three samples, which are in reasonable agreement in this region. In Table 20, the production rates tabulated in irradiation series 2A were calculated using points at 1.24×10^{13} e/cm² and 11.2×10^{13} e/cm² (near the beginning of the run). The production rates in

Figure 46: Conductance versus fluence, Run 13, Sample 12, 10^4 Hz.

Figure 48: Conductance versus fluence, Run 13, Sample 16, 10^4 Hz.

Figure 49: Conductance versus fluence, Run 13, Sample 18, 10^4 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 18

$$9 \times 10^{15} \text{ Ga/cm}^3$$

 $T_{\text{IRR}} = (\text{AS NOTED})$
 $T_{\text{MEAS}} = 1.5 \text{ K}$

$$f = 10^4 \text{ Hz}$$

 $\odot$ AFTER IRRADIATION

 $\times$ AFTER ANNEAL TO 10 K

Figure 50: Conductance versus fluence, Run 13, Sample 12, 10^2 Hz.

Figure 51: Conductance versus fluence, Run 13, Sample 15, 10^2 Hz.

Figure 52: Conductance versus fluence, Run 13, Sample 16, 10^2 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 16

 $8 \times 10^{15} \text{ Ga/cm}^3$ $T_{\text{IRR}} = (\text{AS NOTED})$ $T_{\text{MEAS}} = 1.5 \text{ K}$ $f = 10^2 \text{ Hz}$

Figure 53: Conductance versus fluence, Run 13, Sample 18, 10^2 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 18

 $9 \times 10^{15} \text{ Ga/cm}^3$ $T_{\text{IRR}} = (\text{AS NOTED})$ $T_{\text{MEAS}} = 1.5 \text{ K}$ $f = 10^2 \text{ Hz}$

TABLE 45

Run 13. Production data at 10^2 Hz and 10^4 Hz, Sample 12, $T_{\text{MEAS}} = 1.5$ K.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	10^4	$.513 \pm .0015$	$8.65 \pm .02$	
1.24	10^4	$.528 \pm .001$	$8.70 \pm .01$	1.8
3.77	10^4	$.540 \pm .001$	$8.80 \pm .01$	1.8
6.25	10^4	$.552 \pm .001$	$9.02 \pm .01$	2.1
8.70	10^4	$.569 \pm .001$	$9.16 \pm .01$	2.3
* 8.70	10^4	$.566 \pm .001$	$9.13 \pm .01$	
11.2	10^4	$.570 \pm .001$	$9.17 \pm .01$	4.3
13.7	10^4	$.583 \pm .001$	$9.19 \pm .01$	1.8
0	10^2	$.382 \pm .001$	136 ± 1	
1.24	10^2	$.393 \pm .001$	143 ± 1	1.8
3.77	10^2	$.398 \pm .001$	148 ± 2	1.8
6.25	10^2	$.403 \pm .001$	157 ± 1	2.1
8.70	10^2	$.406 \pm .001$	162 ± 1	2.3

* Anneal 10 K for 30 minutes

TABLE 46

Run 13. Production data at 10^2 Hz and 10^4 Hz, Sample 15, $T_{MEAS} = 1.5$ K.

Total fluence $\pm 11\%$	Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	10^4	$.556 \pm .001$	$7.75 \pm .02$	
1.24	10^4	$.569 \pm .001$	$7.81 \pm .01$	1.8
3.77	10^4	$.583 \pm .001$	$7.84 \pm .01$	1.8
6.25	10^4	$.595 \pm .001$	$8.14 \pm .01$	2.1
8.70	10^4	$.600 \pm .001$	$8.18 \pm .01$	2.3
* 8.70	10^4	$.602 \pm .001$	$8.18 \pm .01$	
11.2	10^4	$.601 \pm .001$	$8.14 \pm .01$	4.3
13.7	10^4	$.608 \pm .001$	$8.22 \pm .01$	1.8
0	10^2	$.456 \pm .001$	156 ± 2	
1.24	10^2	$.468 \pm .001$	163 ± 1	1.8
3.77	10^2	$.473 \pm .001$	171 ± 2	1.8
6.25	10^2	$.477 \pm .001$	176 ± 1	2.1
8.70	10^2	$.480 \pm .001$	182 ± 1	2.3

* Anneal 10 K for 30 minutes

TABLE 47

Run 13. Production data at 10^2 Hz and 10^4 Hz, Sample 16, $T_{\text{MEAS}} = 1.5$ K.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	10^4	$.563 \pm .0015$	$8.01 \pm .01$	...
1.24	10^4	$.577 \pm .0012$	$8.06 \pm .01$	1.8
3.77	10^4	$.597 \pm .001$	$8.26 \pm .01$	1.8
6.25	10^4	$.617 \pm .001$	$8.46 \pm .01$	2.1
8.70	10^4	$.630 \pm .001$	$8.65 \pm .01$	2.3
* 8.70	10^4	$.631 \pm .001$	$8.61 \pm .01$	
11.2	10^4	$.634 \pm .001$	$8.63 \pm .01$	4.3
13.7	10^4	$.644 \pm .001$	$8.71 \pm .01$	1.8
0	10^2	$.440 \pm .001$	143 ± 1	
1.24	10^2	$.450 \pm .001$	150 ± 1	1.8
3.77	10^2	$.458 \pm .001$	159 ± 1	1.8
6.25	10^2	$.462 \pm .001$	170 ± 2	2.1
8.70	10^2	$.465 \pm .001$	176 ± 1	2.3

* Anneal 10 K for 30 minutes

TABLE 48

Run 13. Production data at 10^2 Hz and 10^4 Hz, Sample 18, $T_{\text{MEAS}} = 1.5$ K.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Frequency (Hz)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0				
1.24	10^4	$.274 \pm .001$	$7.44 \pm .01$	1.8
3.77	10^4	$.281 \pm .001$	$7.51 \pm .01$	1.8
6.25	10^4	$.292 \pm .001$	$7.85 \pm .01$	2.1
8.70	10^4	$.295 \pm .001$	$7.91 \pm .01$	2.3
* 8.70	10^4	$.295 \pm .001$	$7.91 \pm .01$	
11.2	10^4	$.295 \pm .001$	$7.88 \pm .01$	4.3
13.7	10^4	$.301 \pm .001$	$7.96 \pm .01$	1.8
0				
1.24	10^2	$.192 \pm .001$	45 ± 1	1.8
3.77	10^2	$.195 \pm .001$	48 ± 1	1.8
6.25	10^2	$.200 \pm .001$	52 ± 1	2.1
8.70	10^2	$.202 \pm .001$	54 ± 1	2.3

* Anneal 10 K for 30 minutes

Figure 54: Conductance versus fluence, Run 13, second irradiation series,
Sample 12, 10^4 Hz.

Figure 55: Conductance versus fluence, Run 13, second irradiation series,
Sample 15, 10^4 Hz.

Figure 56: Conductance versus fluence, Run 13, second irradiation series,
Sample 16, 10^4 Hz.

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Figure 57: Conductance versus fluence, Run 13, second irradiation series,
Sample 18, 10^4 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 18

2nd IRRADIATION SERIES

$$8.8 \times 10^{15} \text{ Ga/cm}^3$$

$T_{\text{IRR}} = 1.8 \text{ K}$ EXCEPT AS NOTED

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^4 \text{ Hz}$

Figure 58: Conductance versus fluence, Run 13, second irradiation series,
Sample 12, 10^2 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 12

2nd IRRADIATION SERIES

$5.7 \times 10^{15} \text{ Ga/cm}^3$

$T_{\text{IRR}} = 1.8 \text{ K EXCEPT AS NOTED}$

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^2 \text{ Hz}$

Figure 59: Conductance versus fluence, Run 13, second irradiation series,
Sample 15, 10^2 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 15

2nd IRRADIATION SERIES

$5.7 \times 10^{15} \text{ Ga/cm}^3$

$T_{\text{IRR}} = 1.8 \text{ K EXCEPT AS NOTED}$

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^2 \text{ Hz}$

Figure 60: Conductance versus fluence, Run 13, second irradiation series,
Sample 16, 10^2 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 16

2nd IRRADIATION SERIES

$$7.6 \times 10^{15} \text{ Ga/cm}^3$$

$T_{\text{IRR}} = 1.8 \text{ K}$ EXCEPT AS NOTED

$T_{\text{MEAS}} = 1.5 \text{ K}$

$$f = 10^2 \text{ Hz}$$

Figure 61: Conductance versus fluence, Run 13, second irradiation series,
Sample 18, 10^2 Hz.

CONDUCTANCE VS. FLUENCE

RUN 13, SAMPLE 18

2nd IRRADIATION SERIES

$$8.8 \times 10^{15} \text{ Ga/cm}^3$$

$T_{\text{IRR}} = 1.8 \text{ K EXCEPT AS NOTED}$

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^2 \text{ Hz}$

Figure 62: Annealing, Run 13, second irradiation series, Sample 12, .

10^4 Hz.

Figure 63: Annealing, Run 13, second irradiation series, Sample 15,
 10^4 Hz.

Figure 64: Annealing, Run 13, second irradiation series, Sample 16,
 10^4 Hz.

Figure 65: Annealing, Run 13, second irradiation series, Sample 18, 10^4 Hz.

Figure 66: Annealing, Run 13, second irradiation series, Sample 12,
 10^2 Hz.

Figure 67: Annealing, Run 13, second irradiation series, Sample 15,
 10^2 Hz.

Figure 68: Annealing, Run 13, second irradiation series, Sample 16,
 10^2 Hz.

Figure 69: Annealing, Run 13, second irradiation series, Sample 18,
 10^2 Hz.

TABLE 49

Run 13, second irradiation series. Production data, Sample 12, $f = 10^4$ Hz,
 $T_{MEAS} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	.572 $\pm$.001	8.89 $\pm$.01	
1.24	.580 $\pm$.001	8.94 $\pm$.01	1.8
3.70	.587 $\pm$.001	8.97 $\pm$.01	1.8
6.18	.597 $\pm$.001	9.06 $\pm$.01	1.8
*6.18	.599 $\pm$.001	9.05 $\pm$.01	
8.73	.616 $\pm$.001	9.34 $\pm$.01	4.3
11.2	.629 $\pm$.001	9.42 $\pm$.01	1.8
*11.2	.630 $\pm$.001	9.42 $\pm$.01	
13.7	.635 $\pm$.001	9.43 $\pm$.01	1.8
16.2	.641 $\pm$.001	9.40 $\pm$.01	1.8
21.1	.648 $\pm$.001	9.47 $\pm$.01	1.8
+21.1	.649 $\pm$.001	9.46 $\pm$.01	
26.1	.657 $\pm$.001	9.51 $\pm$.01	1.8
31.0	.663 $\pm$.001	9.53 $\pm$.01	1.8
*31.0	.664 $\pm$.001	9.53 $\pm$.01	
45.8	.679 $\pm$.001	9.61 $\pm$.01	1.8
*45.8	.682 $\pm$.001	9.62 $\pm$.01	
60.6	.692 $\pm$.001	9.69 $\pm$.01	1.8
#60.6	.697 $\pm$.001	9.69 $\pm$.01	
75.3	.705 $\pm$.001	9.74 $\pm$.01	1.8
*75.3	.711 $\pm$.001	9.74 $\pm$.01	
90.0	.717 $\pm$.001	9.78 $\pm$.01	1.8
*90.0	.719 $\pm$.001	9.79 $\pm$.01	
97.5	.721 $\pm$.001	9.80 $\pm$.01	1.8

* Samples brought up to 4.2 K overnight before this measurement

+ Samples brought up to 4.2 K for 11 days before this measurement

Samples brought up to 4.2 K for 3 days before this measurement

TABLE 50

Run 13, second irradiation series. Production data, Sample 15, $f = 10^4$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	.603 $\pm$.001	8.31 $\pm$.02	...
1.24	.612 $\pm$.001	8.36 $\pm$.01	1.8
3.70	.617 $\pm$.001	8.38 $\pm$.01	1.8
6.18	.627 $\pm$.001	8.44 $\pm$.01	1.8
* 6.18	.627 $\pm$.001	8.41 $\pm$.01	...
8.73	.643 $\pm$.001	8.97 $\pm$.01	4.3
11.2	.655 $\pm$.001	9.02 $\pm$.01	1.8
*11.2	.657 $\pm$.001	9.02 $\pm$.01	
13.7	.660 $\pm$.001	9.04 $\pm$.01	1.8
16.2	.667 $\pm$.001	9.00 $\pm$.01	1.8
21.1	.673 $\pm$.001	9.06 $\pm$.01	1.8
†21.1	.677 $\pm$.0015	9.06 $\pm$.01	
26.1	.682 $\pm$.001	9.08 $\pm$.01	1.8
31.0	.685 $\pm$.001	9.10 $\pm$.01	1.8
*31.0	.688 $\pm$.001	9.09 $\pm$.01	
45.8	.702 $\pm$.001	9.16 $\pm$.01	1.8
*45.8	.704 $\pm$.001	9.17 $\pm$.01	
60.6	.723 $\pm$.001	9.40 $\pm$.01	1.8
#60.6	.724 $\pm$.0015	9.35 $\pm$.01	
75.3	.785 $\pm$.001	10.19 $\pm$.01	1.8
*75.3	.779 $\pm$.001	10.05 $\pm$.01	
90.0	.888 $\pm$.001	11.58 $\pm$.01	1.8
*90.0	.869 $\pm$.001	11.34 $\pm$.01	
#97.5	.963 $\pm$.001	12.48 $\pm$.01	1.8
**97.5	.951 $\pm$.001	12.30 $\pm$.01	

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K for 11 days before this measurement

Samples brought up to 4.2 K for 3 days before this measurement

** About 2½ hours later

Immediately after irradiation

TABLE 51

Run 13, second irradiation series. Production data, Sample 16, $f = 10^4$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm 2)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0.	.612 $\pm$.001	8.27 $\pm$.02	
1.24	.621 $\pm$.0015	8.30 $\pm$.01	1.8
3.70	.632 $\pm$.0015	8.39 $\pm$.01	1.8
6.18	.646 $\pm$.0015	8.52 $\pm$.01	1.8
*6.18	.642 $\pm$.001	8.42 $\pm$.01	
8.73	.673 $\pm$.001	8.86 $\pm$.01	4.3
11.2	.684 $\pm$.001	8.90 $\pm$.01	1.8
*11.2	.685 $\pm$.001	8.89 $\pm$.01	
13.7	.690 $\pm$.001	8.93 $\pm$.01	1.8
16.2	.696 $\pm$.001	8.89 $\pm$.01	1.8
21.1	.703 $\pm$.001	8.97 $\pm$.01	1.8
† 21.1	.706 $\pm$.001	8.95 $\pm$.01	
26.1	.712 $\pm$.001	8.99 $\pm$.01	1.8
31.0	.716 $\pm$.001	9.02 $\pm$.01	1.8
*31.0	.717 $\pm$.001	9.03 $\pm$.01	
45.8	.731 $\pm$.001	9.07 $\pm$.01	1.8
*45.8	.733 $\pm$.001	9.08 $\pm$.01	
60.6	.743 $\pm$.0015	9.08 $\pm$.01	1.8
‡ 60.6	.747 $\pm$.0015	9.13 $\pm$.01	
75.3	.754 $\pm$.001	9.17 $\pm$.01	1.8
*75.3	.759 $\pm$.001	9.17 $\pm$.01	
90.0	.763 $\pm$.001	9.19 $\pm$.01	1.8
*90.0	.766 $\pm$.001	9.21 $\pm$.01	
97.5	.766 $\pm$.001	9.22 $\pm$.01	1.8

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K for 11 days before this measurement

‡ Samples brought up to 4.2 K for 3 days before this measurement

TABLE 52

Run 13, second irradiation series. Production data, Sample 18, $f = 10^4$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm 2)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	.301 $\pm$.001	7.66 $\pm$.01	
1.24	.308 $\pm$.001	7.69 $\pm$.01	1.8
3.70	.313 $\pm$.001	7.72 $\pm$.01	1.8
6.18	.322 $\pm$.001	7.83 $\pm$.01	1.8
* 6.18	.322 $\pm$.001	7.80 $\pm$.01	
8.73	.328 $\pm$.001	8.16 $\pm$.01	4.3
11.2	.338 $\pm$.001	8.21 $\pm$.01	1.8
*11.2	.339 $\pm$.001	8.22 $\pm$.01	
13.7	.343 $\pm$.001	8.23 $\pm$.01	1.8
16.2	.348 $\pm$.001	8.21 $\pm$.01	1.8
21.1	.353 $\pm$.001	8.26 $\pm$.01	1.8
† 21.1	.355 $\pm$.001	8.27 $\pm$.01	
26.1	.360 $\pm$.0015	8.30 $\pm$.01	1.8
31.0	.364 $\pm$.001	8.32 $\pm$.01	1.8
*31.0	.365 $\pm$.001	8.32 $\pm$.01	
45.8	.378 $\pm$.001	8.40 $\pm$.01	1.8
*45.8	.379 $\pm$.001	8.42 $\pm$.01	
60.6	.392 $\pm$.0015	8.54 $\pm$.01	1.8
‡ 60.6	.393 $\pm$.001	8.53 $\pm$.01	
75.3	.404 $\pm$.001	8.69 $\pm$.01	1.8
*75.3	.406 $\pm$.001	8.68 $\pm$.01	
90.0	.417 $\pm$.001	8.87 $\pm$.01	1.8
*90.0	.417 $\pm$.001	8.85 $\pm$.01	
97.5	.423 $\pm$.001	8.97 $\pm$.01	1.8

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K for 11 days before this measurement

‡ Samples brought up to 4.2 K for 3 days before this measurement

TABLE 53

Run 13, second irradiation series. Production data, Sample 12, $f = 10^2$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	.424 $\pm$.001	168 $\pm$ 1	
1.24	.432 $\pm$.001	173 $\pm$ 1	1.8
3.70	.436 $\pm$.001	176 $\pm$ 1	1.8
6.18	.441 $\pm$.0015	182 $\pm$ 1	1.8
* 6.18	.442 $\pm$.001	183 $\pm$ 2	
8.73	.443 $\pm$.001	191 $\pm$ 1	4.3
11.2	.452 $\pm$.001	198 $\pm$ 1	1.8
*11.2	.453 $\pm$.001	198 $\pm$ 1	
13.7	.456 $\pm$.001	201 $\pm$ 1	1.8
16.2	.459 $\pm$.001	205 $\pm$ 1	1.8
21.1	.463 $\pm$.001	209 $\pm$ 1	1.8
†21.1	.466 $\pm$.001	211 $\pm$ 1	
26.1	.470 $\pm$.001	214 $\pm$ 1	1.8
31.0	.473 $\pm$.001	216 $\pm$ 2	1.8
*31.0	.474 $\pm$.001	219 $\pm$ 1	
45.8	.482 $\pm$.001	227 $\pm$ 1	1.8
*45.8	.485 $\pm$.001	230 $\pm$ 1	
60.6	.492 $\pm$.001	236 $\pm$ 1	1.8
‡60.6	.496 $\pm$.0015	240 $\pm$ 1	
75.3	.501 $\pm$.001	245 $\pm$ 1.5	1.8
*75.3	.505 $\pm$.001	249 $\pm$ 2	
90.0	.507 $\pm$.001	252 $\pm$ 1	1.8
*90.0	.510 $\pm$.0015	254 $\pm$ 1	
97.5	.510 $\pm$.001	255 $\pm$ 1	1.8

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K for 11 days before this measurement

‡ Samples brought up to 4.2 K for 3 days before this measurement

TABLE 54

Run 13, second irradiation series. Production data, Sample 15, $f = 10^2$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	.482 $\pm$.001	184 $\pm$ 1	
1.24	.491 $\pm$.001	189 $\pm$ 1	1.8
3.70	.494 $\pm$.001	193 $\pm$ 1	1.8
6.18	.501 $\pm$.001	197 $\pm$ 1	1.8
* 6.18	.502 $\pm$.001	198 $\pm$ 1	
8.73	.502 $\pm$.001	207 $\pm$ 1	4.3
11.2	.509 $\pm$.001	213 $\pm$ 1	1.8
* 11.2	.512 $\pm$.001	213 $\pm$ 1	
13.7	.515 $\pm$.001	216 $\pm$ 1	1.8
16.2	.518 $\pm$.001	220 $\pm$ 1	1.8
21.1	.522 $\pm$.001	223 $\pm$ 1	1.8
† 21.1	.524 $\pm$.001	225 $\pm$ 1	
26.1	.529 $\pm$.001	229 $\pm$ 2	1.8
31.0	.531 $\pm$.001	231 $\pm$ 2	1.8
* 31.0	.533 $\pm$.001	233 $\pm$ 2	
45.8	.542 $\pm$.001	241 $\pm$ 1	1.8
* 45.8	.544 $\pm$.001	244 $\pm$ 1	
60.6	.552 $\pm$.001	252 $\pm$ 1	1.8
‡ 60.6	.556 $\pm$.002	255 $\pm$ 1	
75.3	.563 $\pm$.001	271 $\pm$ 1	1.8
* 75.3	.566 $\pm$.001	271 $\pm$ 1	
90.0	.567 $\pm$.001	286 $\pm$ 1	1.8
* 90.0	.569 $\pm$.001	288 $\pm$ 1	
97.5	.569 $\pm$.001	292 $\pm$ 1	1.8

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K for 11 days before this measurement

‡ Samples brought up to 4.2 K for 3 days before this measurement

TABLE 55

Run 13, second irradiation series. Production data, Sample 16, $f = 10^2$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance: (picofarads)	Irradiation temperature (K)
0	.477 $\pm$.001	168 $\pm$ 1	
1.24	.484 $\pm$.001	172 $\pm$ 1	1.8
3.70	.491 $\pm$.001	179 $\pm$ 1	1.8
6.18	.496 $\pm$.0015	184 $\pm$ 2	1.8
* 6.18	.497 $\pm$.0015	185 $\pm$ 1	
8.73	.498 $\pm$.001	199 $\pm$ 1	4.3
11.2	.505 $\pm$.001	206 $\pm$ 1	1.8
*11.2	.507 $\pm$.001	205 $\pm$ 1	
13.7	.510 $\pm$.001	208 $\pm$ 1	1.8
16.2	.513 $\pm$.001	211 $\pm$ 2	1.8
21.1	.516 $\pm$.001	214 $\pm$ 1	1.8
+ 21.1	.520 $\pm$.001	215 $\pm$ 1	
26.1	.522 $\pm$.001	219 $\pm$ 1	1.8
31.0	.523 $\pm$.001	222 $\pm$ 1	1.8
*31.0	.526 $\pm$.001	223 $\pm$ 1	
45.8	.533 $\pm$.001	229 $\pm$ 1	1.8
*45.8	.535 $\pm$.001	231 $\pm$ 1	
60.6	.541 $\pm$.001	236 $\pm$ 1	1.8
*60.6	.544 $\pm$.001	239 $\pm$ 1	
75.3	.548 $\pm$.001	243 $\pm$ 1.5	1.8
*75.3	.552 $\pm$.001	245 $\pm$ 1	
90.0	.553 $\pm$.001	248 $\pm$ 1	1.8
*90.0	.556 $\pm$.001	250 $\pm$ 2	
97.5	.556 $\pm$.001	251 $\pm$ 1	1.8

* Samples brought up to 4.2 K overnight before this measurement

+ Samples brought up to 4.2 K for 11 days before this measurement

* Samples brought up to 4.2 K for 3 days before this measurement.

TABLE 56

Run 13, second irradiation series. Production data, Sample 18, $f = 10^2$ Hz,
 $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
0	.211 $\pm$.001	54 $\pm$ 1	
1.24	.217 $\pm$.001	56 $\pm$ 1	1.8
3.70	.222 $\pm$.001	58 $\pm$ 1	1.8
6.18	.227 $\pm$.001	62 $\pm$ 1.5	1.8
* 6.18	.228 $\pm$.001	61 $\pm$ 1	
8.73	.227 $\pm$.001	65 $\pm$ 1	4.3
11.2	.235 $\pm$.001	68 $\pm$ 1	1.8
* 11.2	.236 $\pm$.001	68 $\pm$ 1	
13.7	.239 $\pm$.001	70 $\pm$ 1	1.8
16.2	.242 $\pm$.001	71 $\pm$ 1	1.8
21.1	.246 $\pm$.001	73 $\pm$ 1	1.8
† 21.1	.248 $\pm$.0015	74 $\pm$ 2	
26.1	.252 $\pm$.001	76 $\pm$ 1	1.8
31.0	.255 $\pm$.001	77 $\pm$ 1	1.8
* 31.0	.256 $\pm$.001	78 $\pm$ 1	
45.8	.265 $\pm$.001	82 $\pm$ 1	1.8
* 45.8	.267 $\pm$.001	83 $\pm$ 1	
60.6	.274 $\pm$.001	88 $\pm$ 2	1.8
‡ 60.6	.275 $\pm$.0015	90 $\pm$ 1	
75.3	.282 $\pm$.001	93 $\pm$ 1	1.8
* 75.3	.284 $\pm$.001	94 $\pm$ 1	
90.0	.288 $\pm$.001	97 $\pm$ 1	1.8
* 90.0	.289 $\pm$.001	96 $\pm$ 1	
97.5	.291 $\pm$.001	98 $\pm$ 1	1.8

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K for 11 days before this measurement

‡ Samples brought up to 4.2 K for 3 days before this measurement

TABLE 57

Run 13, second irradiation series. Anneals; Samples 12, 15, 16, and 18;
 $f = 10^4$ Hz; $T_{\text{MEAS}} = 1.5$ K; $T_{\text{IRR}} = 1.8$ K except for 1.5×10^{13} e/cm²
 at 4.2 K; $\varphi = 9.75 \times 10^{14}$ e/cm² $\pm 11\%$.

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
12	.728 $\pm$.001		4.2
*15	.905 $\pm$.001		
16	.776 $\pm$.001		
18	.426 $\pm$.001		
12	.727 $\pm$.001	-.001 $\pm$.002	30
15	.870 $\pm$.001	-.035 $\pm$.002	
16	.773 $\pm$.001	-.003 $\pm$.002	
18	.423 $\pm$.001	-.003 $\pm$.002	
12	.704 $\pm$.001	-.023 $\pm$.002	56
15	.795 $\pm$.001	-.075 $\pm$.002	
16	.755 $\pm$.001	-.018 $\pm$.002	
18	.408 $\pm$.001	-.015 $\pm$.002	
12	.689 $\pm$.001	-.015 $\pm$.002	80
15	.772 $\pm$.001	-.023 $\pm$.002	
16	.751 $\pm$.001	-.004 $\pm$.002	
18	.411 $\pm$.001	+.003 $\pm$.002	
12	1.014 $\pm$.001	+.325 $\pm$.002	100
15	1.044 $\pm$.001	+.272 $\pm$.002	
16	1.009 $\pm$.001	+.258 $\pm$.002	
18	.648 $\pm$.001	+.237 $\pm$.002	
12	.908 $\pm$.001	-.106 $\pm$.002	295
15	.951 $\pm$.001	-.093 $\pm$.002	
16	.924 $\pm$.001	-.085 $\pm$.002	
18	.576 $\pm$.001	-.072 $\pm$.002	

* This sample was .963 $\pm$.001 micromhos immediately after irradiation before warming to 4.2 K.

TABLE 58

Run 13, second irradiation series. Anneals; Samples 12, 15, 16, and 18;

$f = 10^2$ Hz; $T_{\text{MEAS}} = 1.5$ K; $T_{\text{IRR}} = 1.8$ K except for 1.5×10^{13}

e/cm^2 at 4.2 K. $\phi = 9.7 \times 10^{14} e/\text{cm}^2 \pm 11\%$.

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
12	.516 $\pm$.001		4.2
15	.576 $\pm$.001		
16	.561 $\pm$.001		
18	.295 $\pm$.001		
12	.515 $\pm$.001	-.001 $\pm$.002	30
15	.575 $\pm$.001	-.001 $\pm$.002	
16	.560 $\pm$.001	-.001 $\pm$.002	
18	.294 $\pm$.001	-.001 $\pm$.002	
12	.504 $\pm$.001	-.011 $\pm$.002	56
15	.567 $\pm$.001	-.008 $\pm$.002	
16	.553 $\pm$.001	-.007 $\pm$.002	
18	.286 $\pm$.001	-.008 $\pm$.002	
12	.505 $\pm$.001	+.001 $\pm$.002	80
15	.581 $\pm$.001	+.014 $\pm$.002	
16	.554 $\pm$.001	+.001 $\pm$.002	
18	.291 $\pm$.001	+.005 $\pm$.002	
12	.707 $\pm$.001	+.202 $\pm$.002	100
15	.786 $\pm$.0015	+.205 $\pm$.002	
16	.748 $\pm$.0015	+.194 $\pm$.002	
18	.472 $\pm$.001	+.181 $\pm$.002	
12	.651 $\pm$.001	-.056 $\pm$.002	295
15	.738 $\pm$.001	-.048 $\pm$.0025	
16	.703 $\pm$.001	-.045 $\pm$.0025	
18	.417 $\pm$.001	-.055 $\pm$.002	

series 2B were calculated using the last two irradiation points at 9.00×10^{14} e/cm² and 9.75 e/cm². In this run, somewhat more attention was paid to variation of conductance with time after irradiation. Measurements were made soon after irradiation (usually within 15-30 minutes), and several more measurements were made during a time period of up to four hours. At the end of a day samples were brought up to 4.2 K and held there overnight.

After the irradiations in the second series were carried out, the samples were annealed to 30, 56, 80, 100, and 295 K. The most striking feature of these anneals is the large size of the 100 K peak compared to the 56 K peak.

Following the above anneals a third series of irradiations was performed. The results, including anneals which followed, are given in Tables 59-64. Figures 70 and 71 show the results for Sample 12. The first irradiation increment was performed at 10.4 K and the second at 1.7 K. We expect the production rate at 1.7 K to be smaller than at 10.4 K because of the dependence of the production rate on fluence. To see if there is temperature effect, we need to compare with the production rates in the second irradiation series. This is done in Table 65. We see that there is no significant temperature dependence. The annealing is interesting because there is a less pronounced 100 K peak, but more annealing at 56 K and below as compared to the second series. (Note that instead of 80 K an anneal at 90 K was used.) The ratio of the fluences for the two series of irradiations is $9.7/2.3 = 4.2$. Some of the 100 K change has been lost due to the 90 K anneal. If we assume that there would have been the same decrease at 80 K as in the second series, then for the third series 100 K changes, we have the results shown in Table 66.

TABLE 59

Run 13, third irradiation series. Production data at 10^2 Hz and 10^4 Hz, Sample 12, $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Frequency (Hz)	Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
10^4	0	$.908 \pm .001$	$10.04 \pm .01$	
10^4	11.2	$.967 \pm .001$	$10.44 \pm .01$	10.4
10^4	22.4	$.992 \pm .001$	$10.61 \pm .01$	1.7
* 10^4	22.4	$.994 \pm .001$	$10.60 \pm .01$	
† 10^4	22.4	$.999 \pm .001$	$10.61 \pm .01$	
‡ 10^4	22.4	$1.005 \pm .001$	$10.61 \pm .01$	
10^2	0	$.651 \pm .001$	400 ± 1	
10^2	11.2	$.674 \pm .001$	441 ± 3	10.4
* 10^2	22.4	$.688 \pm .001$	463 ± 1	1.7
† 10^2	22.4	$.691 \pm .001$	467 ± 1	

* Samples brought up to 4.2 K for one day after irradiation, but before this measurement

† About $2\frac{1}{2}$ hours later

‡ About 13 hours later

TABLE 60

Run 13, third irradiation series. Production data at 10^2 Hz and 10^4 Hz,
 Sample 15, $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after
 irradiation.

Frequency (Hz)	Total fluence +11% (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
10^4	0	$.952 \pm .001$	$9.31 \pm .01$	
10^4	11.2	$1.006 \pm .001$	$9.69 \pm .01$	10.4
10^4	22.4	$1.036 \pm .001$	$10.17 \pm .01$	1.7
* 10^4	22.4	$1.045 \pm .001$	$10.14 \pm .01$	
† 10^4	22.4	$1.050 \pm .001$	$10.15 \pm .01$	
10^2	0	$.738 \pm .001$	424 ± 1	
10^2	11.2	$.763 \pm .001$	464 ± 1	10.4
* 10^2	22.4	$.779 \pm .001$	494 ± 1	1.7
† 10^2	22.4	$.783 \pm .001$	497 ± 1	

* Samples brought up to 4.2 K for one day after irradiation, but before this measurement

† About 13 hours later

TABLE 61

Run 13, third irradiation series. Production data at 10^2 Hz and 10^4 Hz,
 Sample 16, $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after
 irradiation.

Frequency (Hz)	Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
10^4	0	$.924 \pm .001$	$9.24 \pm .01$	
10^4	11.2	$1.012 \pm .001$	$9.93 \pm .01$	10.4
10^4	22.4	$1.026 \pm .001$	$9.99 \pm .01$	1.7
* 10^4	22.4	$1.033 \pm .001$	$9.99 \pm .01$	
† 10^4	22.4	$1.039 \pm .001$	$10.00 \pm .01$	
10^2	0	$.703 \pm .001$	355 ± 1	
10^2	11.2	$.729 \pm .001$	407 ± 3	10.4
* 10^2	22.4	$.743 \pm .001$	424 ± 1	1.7
† 10^2	22.4	$.747 \pm .001$	427 ± 1	

* Samples brought up to 4.2 K for one day after irradiation, but before this measurement

† About 13 hours later

TABLE 62

Run 13, third irradiation series. Production data at 10^2 Hz and 10^4 Hz, Sample 18, $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after irradiation.

Frequency (Hz)	Total fluence +11% (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)	Irradiation temperature (K)
10^4	0	$.576 \pm .001$	$8.84 \pm .01$	
10^4	11.2	$.620 \pm .001$	$9.29 \pm .01$	10.4
10^4	22.4	$.639 \pm .001$	$9.49 \pm .01$	1.7
* 10^4	22.4	$.644 \pm .001$	$9.49 \pm .01$	
† 10^4	22.4	$.646 \pm .001$	$9.49 \pm .01$	
10^2	0	$.416 \pm .001$	180 ± 1	
10^2	11.2	$.451 \pm .001$	207 ± 3	10.4
* 10^2	22.4	$.466 \pm .001$	221 ± 1	1.7
† 10^2	22.4	$.468 \pm .001$	223 ± 1	

* Samples brought up to 4.2 K for one day after irradiation, but before this measurement

† About 13 hours later

TABLE 63

Run 13, third irradiation series. Anneals; Samples 12, 15, 16, and 18;
 $f = 10^4$ Hz; $T_{\text{MEAS}} = 1.5$ K; $T_{\text{IRR}} = 10.4$ K and 1.7 K; $\varphi = 2.3 \times$
 10^{14} e/cm² $\pm 11\%$.

Sample	Conductance (micromhos) $\pm .001$	Change in conductance (micromhos) $\pm .002$	Annealing temperature (K)
12	.999		4.2
15	1.045		
16	1.033		
18	.644		
12	.988	-.011	30
15	1.044	-.001	
16	1.029	-.004	
18	.642	-.002	
12	.959	-.029	56
15	1.029	-.017	
16	.999	-.030	
18	.623	-.019	
12	.977	+.018	90
15	1.026	+.027	
16	.991	-.008	
18	.624	+.001	
12	1.020	+.043	100
15	1.062	+.035	
16	1.029	+.038	
18	.670	+.046	
12	.986	-.034	295
15	1.041	-.020	
16	.994	-.035	
18	.649	-.021	

TABLE 64

Run 13, third irradiation series. Anneals; Samples 12, 15, 16, and 18;

$f = 10^2$ Hz; $T_{\text{MEAS}} = 1.5$ K; $T_{\text{IRR}} = 10.4$ K and 1.7 K; $\varphi = 2.3 \times$

10^{14} e/cm² $\pm 11\%$.

Sample	Conductance (micromhos)	Change in conductance (micromhos)	Annealing temperature (K)
12	.688 $\pm$.001		4.2
15	.779 $\pm$.001		
16	.743 $\pm$.001		
18	.466 $\pm$.001		
12	.686 $\pm$.001	-.002 $\pm$.002	30
15	.778 $\pm$.001	-.001 $\pm$.002	
16	.742 $\pm$.001	-.001 $\pm$.002	
18	.466 $\pm$.001	-.000 $\pm$.002	
12	.678 $\pm$.001	-.018 $\pm$.002	56
15	.773 $\pm$.001	-.005 $\pm$.002	
16	.736 $\pm$.001	-.006 $\pm$.002	
18	.458 $\pm$.001	-.008 $\pm$.001	
12	.690 $\pm$.001	+.012 $\pm$.002	90
15	.784 $\pm$.001	+.011 $\pm$.002	
16	.747 $\pm$.001	+.011 $\pm$.002	
18	.469 $\pm$.002	+.011 $\pm$.002	
12	.714 $\pm$.001	+.024 $\pm$.002	100
15	.810 $\pm$.0015	+.026 $\pm$.0025	
16	.770 $\pm$.0015	+.028 $\pm$.0025	
18	.491 $\pm$.0015	+.022 $\pm$.0035	
12	.697 $\pm$.001	-.017 $\pm$.002	295
15	.795 $\pm$.001	-.015 $\pm$.0025	
16	.754 $\pm$.001	-.016 $\pm$.0025	
18	.479 $\pm$.0015	-.012 $\pm$.003	

Figure 70: Conductance versus fluence, annealing, Run 13, third irradiation series, Sample 12, 10^4 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 13, SAMPLE 12

3rd IRRADIATION SERIES

$5.7 \times 10^{15} \text{ Ga/cm}^3$

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^4 \text{ Hz}$

○ IMMEDIATELY AFTER IRRADIATION
OR PUMPDOWN

x ONE TO FOUR HOURS LATER

Δ OVERNIGHT AT 1.5 K

Figure 71: Conductance versus fluence, annealing, Run 13, third irradiation series, Sample 12, 10^2 Hz.

TABLE 65

Comparison of production rates of the second irradiation series and the third (P is given in cm^{-1}).

Sample	Second irradiation		Third irradiation	
	1.24×10^{13} to $11.2 \times 10^{13} \text{ e/cm}^2$	11.2×10^{13} to $21.1 \times 10^{13} \text{ e/cm}^2$	$T_{\text{IRR}} = 10.4 \text{ K}$ 0 to $11.2 \times 10^{13} \text{ e/cm}^2$	$T_{\text{IRR}} = 1.7 \text{ K}$ 11.2×10^{13} to $22.4 \times 10^{13} \text{ e/cm}^2$
12	.65	.26	.70	.30
15	.62	.27	.69	.30
16	.74	.23	.92	.15
18	.26	.20	.34	.13

TABLE 66

Correction of the 100 K annealing in the third series to compensate for having a 90 K anneal instead of an 80 K anneal.

Sample	Change in conductance
12	$+.043 + .033 = .076$
15	$+.035 + .040 = .075$
16	$+.038 - .004 = .034$
18	$+.046 - .002 = .044$

Then the ratios of the 100 K stage in series 2 to series 3 are given below.

TABLE 67

Ratios of the change in conductivity in the 100 K annealing in the second irradiation series to the change in the conductivity in the 100 K annealing in the third using the results in Table 66.

Sample	$\Delta G_2 / \Delta G_3$ Corrected
12	4.3
15	3.6
16	7.6
18	5.4

Run 14. Four gallium doped samples were irradiated with 1.1 MeV electrons. The doping levels were 5.6×10^{15} , 8.0×10^{14} , 8.3×10^{15} , and 8.4×10^{14} . In this run, the sapphire sample mounting was used as previously described. Some difficulty was encountered in using this configuration. Because the exchange gas was pumped out to at least 20 microns to isolate the sample plate from the rest of the dewar during anneals, temperature gradients appeared across the advance alloy wires and terminal pins connecting to the carbon resistance thermometers. As a result spurious emf's appeared which caused the measured temperature to be higher than the actual temperature. The corrections made for these spurious emf's were 5.3 K at 100 K and .6 K at 30 K. Somewhat smaller corrections were made for the second anneal because a higher exchange gas pressure was used leading to smaller emfs. In addition, some difficulty was experienced in controlling the annealing temperature. In the first set of anneals, the temperature ran away to 84 K for one minute at the beginning of the "54 K" anneal. During the second set of anneals, the temperature ran away to 64 K for $\frac{1}{2}$ minute at the beginning of the "54 K" anneal. In comparing annealing results from this run with previous runs, it should be remembered that the times required to reach annealing temperature and come back down to 4.2 K were longer in the previous runs.

The data for Run 14 is presented in Figures 72-83 and Tables 68-80. There were two irradiation series performed to 3.3×10^{14} e/cm², and each of these was followed by a set of anneals. After the first series, anneals were done to 4.2 K, 10 K, 30 K, "54 K", 100 K, and 295 K. In the first series of irradiations, the production curves show a decreased production rate above 1.9×10^{14} e/cm². This is particularly evident in Sample 23, Figure 74. This effect is also seen in Sample 10, Figure 78, in the second

Figure 72: Conductance versus fluence, annealing, Run 14, Sample 10,
 10^4 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 10

$$6 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

○ IMMEDIATELY AFTER IRRADIATION
OR PUMPDOWN

x ONE TO THREE HOURS LATER

□ OVERNIGHT AT 4.2 K

Figure 73: Conductance versus fluence, annealing, Run 14, Sample 17,
 10^4 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 17

$$8 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

○ ONE TO THREE HOURS AFTER
IRRADIATION OR PUMPDOWN

□ OVERNIGHT AT 4.2 K

Figure 74: Conductance versus fluence, annealing, Run 14, Sample 23,
 10^4 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 23

$$8 \times 10^{14} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

○ ONE TO THREE HOURS AFTER
IRRADIATION OR PUMPDOWN

□ OVERNIGHT AT 4.2 K

Figure 75: Conductance versus fluence, annealing, Run 14, Sample 24,
 10^4 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 24

$$8 \times 10^{14} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

○ ONE TO THREE HOURS AFTER
IRRADIATION OR PUMPDOWN

□ OVERNIGHT AT 4.2 K

Figure 76: Conductance versus fluence, annealing, Run 14, Sample 10,
 10^2 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 10

$$6 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^2 \text{ Hz}$$

○ IMMEDIATELY AFTER IRRADIATION
OR PUMPDOWN

x ONE TO THREE HOURS LATER

□ OVERNIGHT AT 4.2 K

Figure 77: Conductance versus fluence, annealing, Run 14, Sample 17,
 10^2 Hz.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 17

$$8 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^2 \text{ Hz}$$

○ ONE TO THREE HOURS AFTER
IRRADIATION OR PUMPDOWN

□ OVERNIGHT AT 4.2 K

Figure 78: Conductance versus fluence, annealing, Run 14, second irradiation series, Sample 10, 10^4 Hz. Samples brought up to 4.2 K overnight after each irradiation but before measurement.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 10

2nd IRRADIATION SERIES

 $6 \times 10^{15} \text{ Ga/cm}^3$ $T_{\text{IRR}} = 1.8 \text{ K}$ $T_{\text{MEAS}} = 1.5 \text{ K}$ $f = 10^4 \text{ Hz}$

○ IMMEDIATELY AFTER PUMPDOWN

x TWO TO FOUR HOURS AFTER PUMPDOWN

Figure 79: Conductance versus fluence, annealing, Run 14, second irradiation series, Sample 17, 10^4 Hz. Samples brought up to 4.2 K overnight after each irradiation but before measurement.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 17

2nd IRRADIATION SERIES

$$8 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

TWO TO FOUR HOURS AFTER
PUMPDOWN

Figure 80: Conductance versus fluence, annealing, Run 14, second irradiation series, Sample 23, 10^4 Hz. Samples brought up to 4.2 K overnight after each irradiation but before measurement.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 23

2nd IRRADIATION SERIES

$8 \times 10^{14} \text{ Ga/cm}^3$

$T_{\text{IRR}} = 1.8 \text{ K}$

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^4 \text{ Hz}$

TWO TO FOUR HOURS AFTER
PUMPDOWN

Figure 81: Conductance versus fluence, annealing, Run 14, second irradiation series, Sample 24, 10^4 Hz. Samples brought up to 4.2 K overnight after each irradiation but before measurement.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 24

2nd IRRADIATION SERIES

$$8 \times 10^{14} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^4 \text{ Hz}$$

TWO TO FOUR HOURS AFTER
PUMPDOWN

Figure 82: Conductance versus fluence, annealing, Run 14, second irradiation series, Sample 10, 10^2 Hz. Samples brought up to 4.2 K overnight after each irradiation but before measurement.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 10

2nd IRRADIATION SERIES

$$6 \times 10^{15} \text{ Ga/cm}^3$$

$$T_{\text{IRR}} = 1.8 \text{ K}$$

$$T_{\text{MEAS}} = 1.5 \text{ K}$$

$$f = 10^2 \text{ Hz}$$

○ IMMEDIATELY AFTER PUMPDOWN
OR IRRADIATION

x UP TO THREE HOURS LATER

Figure 83: Conductance versus fluence, annealing, Run 14, second irradiation series, Sample 17, 10^2 Hz. Samples brought up to 4.2 K overnight after each irradiation but before measurement.

CONDUCTANCE VS. FLUENCE;

ANNEALING

RUN 14, SAMPLE 17

2nd IRRADIATION SERIES

$8 \times 10^{15} \text{ Ga/cm}^3$

$T_{\text{IRR}} = 1.8 \text{ K}$

$T_{\text{MEAS}} = 1.5 \text{ K}$

$f = 10^2 \text{ Hz}$

TWO TO FOUR HOURS AFTER PUMPDOWN

TABLE 68

Run 14. Production data at 10^2 Hz and 10^4 Hz, Sample 10, $T_{MEAS} = 1.5$ K,
 $T_{IRR} = 1.8$ K. Data taken at least one hour after irradiation.

Frequency (Hz)	Total fluence +11% (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
10^4	0	$.647 \pm .001$	$8.89 \pm .01$
10^4	1.24	$.659 \pm .001$	$8.97 \pm .01$
10^4	3.73	$.667 \pm .001$	$8.99 \pm .01$
* 10^4	3.73	$.667 \pm .001$	$8.99 \pm .01$
10^4	11.1	$.686 \pm .001$	$9.09 \pm .01$
10^4	18.5	$.713 \pm .001$	$9.31 \pm .01$
* 10^4	18.5	$.716 \pm .001$	$9.31 \pm .01$
10^4	33.3	$.736 \pm .001$	$9.37 \pm .01$
* 10^4	33.3	$.740 \pm .001$	$9.39 \pm .01$
10^2	0	$.495 \pm .001$	216 ± 3
10^2	1.4	$.504 \pm .001$	222 ± 2
† 10^2	3.73	$.511 \pm .001$	229 ± 2
10^2	11.1	$.523 \pm .0015$	241 ± 2
10^2	18.5	$.534 \pm .002$	258 ± 2
* 10^2	18.5	$.56 \pm .01$	330 ± 1
10^2	33.3	$.549 \pm .001$	273 ± 2
* 10^2	33.3	$.552 \pm .001$	276 ± 2

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K overnight after this measurement

TABLE 69

Run 14. Production data at 10^2 Hz and 10^4 Hz, Sample 17, $T_{\text{MEAS}} = 1.5$ K,
 $T_{\text{IRR}} = 1.8$ K. Data taken at least one hour after irradiation.

Frequency (Hz)	Total fluence +11% (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
10^4	0	$.556 \pm .001$	$7.54 \pm .01$
10^4	1.24	$.565 \pm .001$	$7.59 \pm .01$
10^4	3.73	$.570 \pm .001$	$7.63 \pm .02$
* 10^4	3.73	$.569 \pm .001$	$7.62 \pm .02$
10^4	11.1	$.588 \pm .0015$	$7.76 \pm .02$
10^4	18.5	$.604 \pm .001$	$7.89 \pm .02$
* 10^4	18.5	$.605 \pm .0015$	$7.87 \pm .02$
10^4	33.3	$.625 \pm .002$	$8.06 \pm .02$
* 10^4	33.3	$.628 \pm .0015$	$8.06 \pm .02$
10^2	0	$.426 \pm .003$	153 ± 5
10^2	1.24	$.430 \pm .003$	158 ± 4
† 10^2	3.73	$.436 \pm .001$	162 ± 2
10^2	11.1	$.446 \pm .001$	174 ± 3
10^2	18.5	$.454 \pm .003$	182 ± 3
* 10^2	18.5	$.456 \pm .003$	181 ± 1
10^2	33.3	$.465 \pm .001$	192 ± 1
* 10^2	33.3	$.466 \pm .001$	194 ± 1

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K overnight after this measurement

TABLE 70

Run 14. Production data at 10^2 Hz and 10^4 Hz, Sample 23, $T_{MEAS} = 1.5$ K,
 $T_{IRR} = 1.8$ K. Data taken at least one hour after irradiation.

Frequency (Hz)	Total fluence $\pm 11\%$ (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
10^4	0	$.0030 \pm .0002$	$7.37 \pm .02$
10^4	1.24	$.0039 \pm .0003$	$7.40 \pm .02$
10^4	3.73	$.0045 \pm .0002$	$7.41 \pm .03$
* 10^4	3.73	$.0045 \pm .0002$	$7.41 \pm .03$
10^4	11.1	$.0072 \pm .0002$	$7.50 \pm .02$
10^4	18.5	$.0082 \pm .0002$	$7.56 \pm .02$
* 10^4	18.5	$.0084 \pm .00025$	$7.55 \pm .02$
10^4	33.3	$.0115 \pm .00025$	$7.64 \pm .02$
* 10^4	33.3	$.0118 \pm .0005$	$7.65 \pm .02$
10^2	0	$.001 \pm .001$	7 ± 1
10^2	1.24	$.0008 \pm .0004$	$9.0 \pm .5$
† 10^2	3.73	$.0008 \pm .0005$	7 ± 1.5
10^2	11.1	$.0009 \pm .0004$	8 ± 1
10^2	18.5	$.001 \pm .001$	8 ± 1
* 10^2	18.5	$.001 \pm .001$	8 ± 2
10^2	33.3	$.002 \pm .001$	8 ± 1

* Samples brought up to 4.2 K overnight before this measurement

† Samples brought up to 4.2 K overnight after this measurement

TABLE 71

Run 14. Production data, Sample 24, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.5$ K, $T_{\text{IRR}} = 1.8$ K.

Data taken at least one hour after irradiation.

Total fluence +11% (10^{13} e/cm ²)	Conductance (micromhos)	Capacitance (picofarads)
0	.0030 $\pm$.0005	6.84 $\pm$.02
1.24	.0036 $\pm$.0003	6.88 $\pm$.02
3.73	.0039 $\pm$.00015	6.88 $\pm$.02
* 3.73	.0040 $\pm$.0002	6.88 $\pm$.02
11.1	.0067 $\pm$.00025	6.94 $\pm$.02
18.5	.0080 $\pm$.0004	7.03 $\pm$.02
*18.5	.0082 $\pm$.0002	7.02 $\pm$.02
33.3	.0115 $\pm$.0003	7.15 $\pm$.03
*33.3	.0113 $\pm$.0003	7.14 $\pm$.03

* Samples brought up to 4.2 K overnight before this measurement

TABLE 72

Run 14. Annealing data, Sample 10, $T_{\text{MEAS}} = 1.5 \text{ K}$. Data taken at least one hour after pumpdown. $\phi = 3.3 \times 10^{14} \text{ e/cm}^2 \pm 11\%$.

Frequency (Hz)	Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
10^4	4.2	$.740 \pm .001$	$9.39 \pm .01$
10^4	10	$.739 \pm .002$	$9.37 \pm .02$
10^4	30	$.736 \pm .001$	$9.36 \pm .01$
* 10^4	"54"	$.713 \pm .001$	$9.18 \pm .01$
* 10^4	95	$.800 \pm .001$	$9.49 \pm .01$
10^4	295	$.829 \pm .001$	$9.48 \pm .01$
10^2	4.2	$.552 \pm .001$	276 ± 2
10^2	10	$.552 \pm .001$	276 ± 3
10^2	30	$.551 \pm .001$	273 ± 1
* 10^2	"54"	$.542 \pm .001$	258 ± 1
* 10^2	95	$.602 \pm .001$	318 ± 4
10^2	295	$.625 \pm .0015$	344 ± 2

* See text for a discussion of this annealing step.

TABLE 73

Run 14. Annealing data, Sample 17, $T_{\text{MEAS}} = -1.5 \text{ K}$. Data taken at least one hour after pumpdown. $\phi = 3.3 \times 10^{14} \text{ e/cm}^2 \pm 11\%$.

Frequency (Hz)	Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
10^4	4.2	$.628 \pm .0015$	$8.06 \pm .01$
10^4	10	$.628 \pm .0015$	$8.06 \pm .01$
10^4	30	$.609 \pm .001$	$7.82 \pm .01$
* 10^4	"54"	$.602 \pm .002$	$7.77 \pm .01$
* 10^4	95	$.680 \pm .001$	$8.09 \pm .01$
10^4	295	$.689 \pm .001$	$8.03 \pm .01$
10^2	4.2	$.466 \pm .001$	194 ± 1
10^2	10	$.466 \pm .001$	194 ± 1
10^2	30	$.460 \pm .001$	182 ± 1
* 10^2	"54"	$.458 \pm .0015$	178 ± 1
* 10^2	95	$.513 \pm .001$	222 ± 2
10^2	295	$.522 \pm .0015$	228 ± 2

* See text for a discussion of this annealing step

TABLE 74

Run 14. Annealing data, Sample 23, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after pumpdown. $\phi = 3.3 \times 10^{14}$ e/cm² $\pm 11\%$.

Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
4.2	.0118 $\pm$.0005	7.65 $\pm$.02
10	.0120 $\pm$.0003	7.65 $\pm$.02
30	.0107 $\pm$.00035	7.65 $\pm$.02
*"54"	.0110 $\pm$.0004	7.60 $\pm$.02
* 95	.0113 $\pm$.0005	7.61 $\pm$.02
295	.0100 $\pm$.0005	7.58 $\pm$.01

* See text for a discussion of this annealing step

TABLE 75

Run 14. Annealing data, Sample 24, $f = 10^4$ Hz, $T_{\text{MEAS}} = 1.5$ K. Data taken at least one hour after pumpdown. $\phi = 3.3 \times 10^{14}$ e/cm² $\pm 11\%$.

Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
4.2	.0113 $\pm$.0003	7.14 $\pm$.01
10	.0110 $\pm$.0004	7.14 $\pm$.02
30	.0105 $\pm$.0004	7.07 $\pm$.02
*"54"	.0100 $\pm$.0004	7.09 $\pm$.01
* 95	.0109 $\pm$.0002	7.09 $\pm$.01
295	.0090 $\pm$.0004	7.03 $\pm$.02

* See text for a discussion of this annealing step

TABLE 76

Run 14, second irradiation series. Production data; Samples 10, 17, 23, and 24; $T_{\text{MEAS}} = 1.5 \text{ K}$; $T_{\text{IRR}} = 1.8 \text{ K}$. Data taken at least one hour after pumpdown.

Sample	Frequency (Hz)	Total fluence $\pm 11\%$ (10^{13} e/cm^2)	Conductance (micromhos)	Capacitance (picofarads)
10	10^4	0	$.830 \pm .001$	$9.47 \pm .01$
*10	10^4	8.88	$.859 \pm .001$	$9.57 \pm .01$
*10	10^4	33.3	$.927 \pm .001$	$9.93 \pm .01$
10	10^2	0	$.625 \pm .0015$	344 ± 2
*10	10^2	8.88	$.643 \pm .001$	367 ± 2
*10	10^2	33.3	$.675 \pm .001$	417 ± 2
17	10^4	0	$.689 \pm .001$	$8.03 \pm .01$
*17	10^4	8.88	$.712 \pm .001$	$8.13 \pm .01$
*17	10^4	33.3	$.769 \pm .0012$	$8.51 \pm .01$
17	10^2	0	$.523 \pm .0015$	228 ± 2
*17	10^2	8.88	$.535 \pm .0015$	243 ± 1
*17	10^2	33.3	$.563 \pm .001$	278 ± 1
23	10^4	0	$.0100 \pm .0005$	$7.58 \pm .01$
*23	10^4	8.88	$.0120 \pm .00025$	$7.64 \pm .01$
*23	10^4	33.3	$.0169 \pm .0005$	$7.79 \pm .01$
24	10^4	0	$.0090 \pm .0004$	$7.03 \pm .02$
*24	10^4	8.88	$.0109 \pm .0003$	$7.09 \pm .01$
*24	10^4	33.3	$.0159 \pm .0004$	$7.29 \pm .02$

* Samples brought up to 4.2 K overnight after irradiation, but before measurement

TABLE 77

Run 14, second irradiation series. Annealing data, Sample 10, $T_{\text{MEAS}} = 1.5 \text{ K}$.
 Data taken at least two hours after pumpdown. $\phi = 3.3 \times 10^{14} \text{ e/cm}^2$
 $\pm 11\%$.

Frequency (Hz)	Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
10^4	4.2	$.927 \pm .001$	$9.93 \pm .01$
10^4	10	$.926 \pm .001$	$9.90 \pm .01$
10^4	30	$.925 \pm .001$	$9.88 \pm .01$
$*10^4$	"54"	$.917 \pm .001$	$9.85 \pm .01$
10^4	76	$.899 \pm .001$	$9.71 \pm .01$
10^4	100	$.913 \pm .001$	$9.71 \pm .01$
10^4	295	$.959 \pm .0015$	$9.83 \pm .01$
10^2	4.2	$.675 \pm .001$	417 ± 2
10^2	10	$.675 \pm .0025$	419 ± 4
10^2	30	$.675 \pm .001$	415 ± 2
$*10^2$	"54"	$.673 \pm .0015$	410 ± 2
10^2	76	$.665 \pm .001$	397 ± 1
10^2	100	$.678 \pm .001$	411 ± 2
10^2	295	$.705 \pm .0015$	450 ± 2

* See text for a discussion of this annealing step

TABLE 78

Run 14, second irradiation series. Annealing data, Sample 17, $T_{\text{MEAS}} = 1.5 \text{ K}$.
 Data taken at least two hours after pumpdown. $\phi = 3.3 \times 10^{14} \text{ e/cm}^2$
 $\pm 11\%$.

Frequency (Hz)	Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
10^4	4.2	$.769 \pm .001$	$8.51 \pm .01$
10^4	10	$.768 \pm .0015$	$8.47 \pm .01$
10^4	30	$.763 \pm .001$	$8.40 \pm .01$
* 10^4	"54"	$.749 \pm .001$	$8.29 \pm .01$
10^4	76	$.734 \pm .001$	$8.19 \pm .01$
10^4	100	$.747 \pm .001$	$8.22 \pm .01$
10^4	295	$.786 \pm .001$	$8.35 \pm .01$
10^2	4.2	$.563 \pm .001$	278 ± 1
10^2	10	$.563 \pm .001$	274 ± 5
10^2	30	$.562 \pm .001$	274 ± 2
* 10^2	"54"	$.556 \pm .001$	266 ± 1
10^2	76	$.550 \pm .001$	257 ± 1
10^2	100	$.561 \pm .002$	267 ± 1
10^2	300	$.588 \pm .0015$	293 ± 1

* See text for a discussion of this annealing step

TABLE 79

Run 14, second irradiation series. Annealing data, Sample 23, $f = 10^4$ Hz,

$T_{\text{MEAS}} = 1.5$ K. Data taken at least two hours after pumpdown.

$\varphi = 3.3 \times 10^{14}$ e/cm² $\pm 11\%$.

Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
4.2	$.0169 \pm .0005$	$7.81 \pm .02$
10	$.0169 \pm .0005$	$7.79 \pm .02$
30	$.0170 \pm .0002$	$7.80 \pm .01$
*"54"	$.0165 \pm .0002$	$7.78 \pm .02$
76	$.0163 \pm .0002$	$7.76 \pm .02$
100	$.0174 \pm .0003$	$7.76 \pm .02$
295	$.0145 \pm .0004$	$7.67 \pm .01$

* See text for a discussion of this annealing step

TABLE 80

Run 14, second irradiation series. Annealing data, Sample 24, $f = 10^4$ Hz,

$T_{\text{MEAS}} = 1.5$ K. Data taken at least two hours after pumpdown.

$\varphi = 3.3 \times 10^{14}$ $\pm 11\%$.

Annealing temperature (K)	Conductance (micromhos)	Capacitance (picofarads)
4.2	$.0159 \pm .0004$	$7.29 \pm .02$
10	$.0160 \pm .0003$	$7.27 \pm .01$
30	$.0165 \pm .0003$	$7.25 \pm .01$
*"54"	$.0157 \pm .0003$	$7.22 \pm .01$
76	$.0156 \pm .0003$	$7.20 \pm .01$
100	$.0157 \pm .0003$	$7.19 \pm .01$
300	$.0134 \pm .0003$	$7.13 \pm .01$

* See text for a discussion of this annealing step

series of irradiations fit a straight line. Production rates given in Table 20 were found as follows. In the first series points at $1.24 \times 10^{13} \text{ e/cm}^2$ and $18.5 \times 10^{13} \text{ e/cm}^2$ were used. In the second series, the points at $8.83 \times 10^{13} \text{ e/cm}^2$ and $33.3 \times 10^{13} \text{ e/cm}^2$ were used.

The most striking feature of the first set of anneals is that the very large change near 100 K in the samples doped $5.6 \times 10^{15}/\text{cm}^3$ and $8.3 \times 10^{15}/\text{cm}^3$ is much reduced in the samples doped $8.3 \times 10^{14}/\text{cm}^3$ and $8.4 \times 10^{14}/\text{cm}^3$. Also in the high doped samples the conductance after an anneal to 295 K is much higher than the conductance after the last irradiation point, while in the low doped samples the conductance after an anneal to 295 K is lower. In the second set of anneals, the high doped samples do not show as large a 100 K increase as in the first set.

In the previous data, a decrease in conductivity was seen in high doped samples after an anneal to 295 K when a 100 K anneal was done before the 295 K anneal. The reverse is seen in Run 14. Therefore one suspects that due to the shorter up and down time for the anneals in this run not all of the stage near 100 K was seen. The difference in the size of the change near 100 K in the two sets of anneals in this run could be understood if the actual temperature of the "100 K" anneal in the first set were higher, or if the warming up and cooling down times were significantly different. The actual temperature of the first "100 K" anneal was $95 \text{ K} \pm 1.5 \text{ K}$ except for an initial rise in temperature to 100 K which took about two minutes to recover to 95 K. The actual temperature of the second anneal was $100 \text{ K} \pm 2 \text{ K}$. Also, the up and down times are not very different. Therefore it does not seem that the difference between these two anneals can be understood on the basis of temperature or time. The first set of anneals for the high doped samples is reasonably

consistent with the results obtained in the other runs. The second set of anneals is not.

C. Summary of Experimental Results

The main features of the results are as follows.

1. If we use Golin's^{8/} expression, i.e.,

$$\sigma = C_N \frac{N_D N_A}{D_A} \quad (48)$$

where N_D and N_A are the concentrations of donors and acceptors, then for the low doped n-type specimens (8.9×10^{14} Sb/cm³) C_N is 0.7 of Golin's C_p , as expected from Golin's results.

2. When 5.3×10^{15} Sb/cm³ doped samples are irradiated and annealed to 80 K, the fraction of the conductance change on irradiation which recovers is $.61 \pm .03$. This is in fair agreement with Callcott and MacKay^{1/} who got 80% recovery.

3. Production rates in p-type germanium average $.56 \text{ cm}^{-1}$ for samples doped 6×10^{15} Ga/cm³ in the first irradiations of Runs 13 and 14. Run 12 showed somewhat erratic production curves, and Run 11 had an apparent temperature dependent production rate so these runs were not used in computing the above average. Samples close to 6×10^{15} Ga/cm³ were chosen to avoid possible complications due to deviations from Golin's^{8/} expression for the majority site concentration dependence. The first irradiation series are chosen to avoid possible complications from defects remaining after a previous series of irradiations and anneals.

4. Production rates for the samples doped 8×10^{14} Ga/cm³ in the first part of Run 14 average $.105 \approx .11 \text{ cm}^{-1}$.

5. The samples in Run 13, second irradiation series, show much smaller production rates at large fluence than initially. The production curve bends over at 1×10^{14} e/cm² in this series.

6. In Runs 11-13, anneals show decreases in conductance at 56 K and 80 K, a large increase at 100 K, and in Runs 12 and 13 a decrease after an anneal to 295 K. The first irradiation series of Run 14 is similar to other runs for the high doped samples show very small changes on annealing compared to the high doped. The second series anneals of Run 14 are not consistent with the other runs.

7. No reproducible temperature dependence of production was seen in this experiment.

8. In n-type samples, which had been irradiated below 4 K, a small increase in conductance was seen on annealing to 10 K. From the work of Hyatt and Koehler,^{23/} we expect that a 10 K anneal is sufficient to cause the negative defects observed by Callcott and MacKay^{1/} to capture another electron and become doubly negative. The increase in conductance observed in the present experiment in n-type germanium is in agreement with this, but the conductivity increase was not equal to the change due to irradiation as one might expect if doubling the charge on a center doubles its contribution to the hopping conductance. Actually, the double negative charge remains stationary in the lattice and the positive charges on two nearby donor atoms do the hopping. Their like charge will tend to keep them separated and thus their motion under an applied field will be more restricted than if the two charges were on widely separated sites. Possibly this accounts for the smaller increase observed than expected on annealing to 10 K in n-type germanium.

9. The 100 K change in Run 13 scaled directly as the fluence. This was in spite of the fact that the apparent production rate decreased after 1×10^{14} e/cm² fluence and that the 56 K stage was about the same in the second and third series (discounting Sample 15). In connection with the 100 K stage, the following should be noted. In Run 10 during an anneal to 30 K, the helium exchange gas was inadvertently admitted to the dewar vacuum and the temperature of the samples rose to 100 K for about 15 minutes after which time the inner dewar volume was filled with liquid nitrogen. This unintentional anneal had the interesting result that Sample 5, which is shown to have a large surface conductance in Chapter V, showed an increase of $.085 \pm .002$ micromhos at 2 K and $.008 \pm .0015$ micromhos at 1.5 K. The total increase due to irradiation was only $.013 \pm .003$ micromhos at 2 K. Sample 3, which had a low surface conductance decreased by $.0040 \pm .0006$ micromhos. Therefore it appears that much of the large increase in conductance at 100 K in this experiment may be due to a surface effect. The low doped samples in Run 14 do not show the 100 K increase presumably because they are nearly free of spurious surface effects, as will be discussed in Chapter V. One rather puzzling fact, however, is that in Run 11 Sample 8 had the lowest surface conductance, but Sample 7 had the lowest change on annealing to 100 K. Whether or not this annealing is the same stage as seen by Flanagan and Klontz^{2/} can be checked by exposing the annealed sample to ionizing radiation. If the defects of Flanagan and Klontz are present, the defects should then become neutral and the conductivity should decrease. Reheating should re-ionize the defects as in Flanagan and Klontz experiment. This test was not carried in the present work.

V. DISCUSSION

A. Defects in Valence IV Semiconductors

The present research was undertaken to clarify our knowledge of simple defects in semiconductors. At the present time, the situation is as follows.

Self-diffusion has been measured in silicon and in germanium. The activation energies are $Q_{Si} = 4.8 \pm .3 \text{ eV}$ ^{24/} and $Q_{Ge} = 2.98 \pm .04 \text{ eV}$.^{25/} In germanium, doping experiments suggest that diffusion occurs by means of lattice vacancies or divacancies which act as acceptors.^{26/} No measurements of the equilibrium vacancy concentrations have been made. No reliable quenching measurements exist.

In silicon, Watkins^{3/} has used EPR on n- and p-type silicon. He believes that vacancies exist in four different charge states from doubly negative to singly positive, and he has observed V^+ and V^- by EPR. He observes impurity-vacancy complexes after various annealing treatments. From such experiments, he concludes that $E_M^{Vo} = 0.33 \pm .03 \text{ eV}$ and $E_M^{V=}$ = $0.18 \pm .02 \text{ eV}$. The temperatures at which the migration is observed to occur is 60 - 80 K for the doubly negative vacancy and 170 K for the neutral vacancy.

Watkins did not observe the silicon interstitial, but after an irradiation of aluminum doped p-type silicon at 4.5 K, he saw aluminum interstitials. He believes that a silicon interstitial migrates during electron irradiation and then trades places with the substitutional aluminum atom. McKeighen and Koehler^{27/} proposed athermal migration of the interstitial. During irradiation electrons and holes are generated.

They recombine at the interstitial releasing energy which is available to produce migration of the interstitial.

In germanium, considerable research has been done on n-type material. Callcott and MacKay^{1/} have shown that electron irradiation at 4.2 K in the dark produces a reduction in the carrier concentration of germanium doped $\sim 10^{14}$ donors per cm^3 . The defects produced captured an additional electron on annealing to 15 K thus becoming doubly negative. MacKay and Klontz^{28/} believe this defect is the vacancy. Upon annealing vacancy-interstitial recombination occurs at 65 K. About 5 eV is released for each annihilation event.^{29/} The observed production in n-type germanium near 4.2 K is 1.4 cm^{-1} for 1.1 MeV electrons.^{1/} This reasonably large production rate suggests that perhaps the defects in n-type are immobile up to the 65 K stage. The kinetics observed is appropriate for correlated I-V recombination (the time dependence of the fraction of defects annealed goes as $1/\sqrt{t}$ at long times). Also, the defects appear to be about 16 Å apart.^{23/} The activation energy observed was $0.15 \pm 0.01 \text{ eV}$.^{30/} No identification of the moving defect was made. Arimura and MacKay^{31/} have used filtered light to cause annealing of defects at 4.5 K. Presumably this is due to an alteration of the defect charge state by the illumination. Hyatt and Koehler^{23/} use sub-threshold electrons to obtain annealing between 5 and 10 K with an activation energy of $0.0044 \pm .0004 \text{ eV}$. MacKay and Klontz^{28/} believe the interstitial in

n-type germanium is neutral. In degenerate n-type, additional processes occur.^{28/} Also, high energy irradiation appears to generate divacancies.^{2/}

In lightly doped p-type germanium electron irradiation at 10 K in the dark does not alter the carrier concentration.^{2/} However, defects are generated since illumination with germanium filtered light at 5 K causes the hole concentration to decrease. Flanagan and Klontz^{2/} propose that V^- and I^+ pairs are introduced upon irradiation. Using 1.0 MeV electrons, their production rate was about 0.6 cm^{-1} after illumination in $5 \times 10^{15} \text{ cm}^{-3}$ doped samples. They observe a "transformation" for specimens annealed to about 130 K in the dark which gives a decrease in hole concentration ($E = 0.10 \text{ eV}$, first order kinetics). They also observed that the defects produced by the 100 - 150 K transformation break up near 200 K with an activation energy of 0.40 eV (first order kinetics). In illuminated specimens, they see annealing in the range 40 K to 70 K. No stored energy release was observed in p-type germanium between 20 K and 90 K for samples annealed in the dark.^{29/} MacKay and Klontz believe that interstitials are mobile in all charge states at 4.2 K and that a neutral interstitial can be captured by a group V impurity.^{28/} They believe that interstitial-vacancy recombination is unlikely unless the interstitial and vacancy have a Coulomb attraction.

B. Production Rates

Before discussing the implications of production rates, it should be noted that the conductance of the low doped samples in Run 14 and their changes due to irradiation are relatively free of surface effects. This is shown in the discussion below.

Consider first the starting conductivities of these samples of $.618 \times 10^{-9}$ mhos/cm $\pm 10\%$ for Sample 23 and $.655 \times 10^{-9}$ mhos/cm $\pm 21\%$ for Sample 24, which are doped 8.0×10^{14} cm $^{-3}$ and 8.4×10^{14} cm $^{-3}$, respectively. Now

$$N_D = \frac{\sigma}{C_p N_A} \quad (49)$$

where $C_p = 6.25 \times 10^{-38}$, and so we get $N_D = 1.2 \times 10^{13}$ cm $^{-3}$ for both samples. This is a reasonable minority doping concentration. Consider also the temperature dependence of samples in Run 10 summarized below in Tables 81 and 82.

TABLE 81

Temperature dependence of conductances for Samples 3 and 5 in Run 10 measured at 10^4 Hz.

Fluence (10^{13} e/cm 2)	Sample	Conductance at 1.5 K (micromhos)	Conductance at 2.0 K (micromhos)
9.6	3	.0094 $\pm$.0002	.0193 $\pm$.0001
14.4	3	.0109 $\pm$.0004	.0215 $\pm$.0002
9.6	5	.030 $\pm$.001	.213 $\pm$.001
14.4	5	.032 $\pm$.001	.217 $\pm$.0015

TABLE 82

Temperature dependence for conductance ratios and ratios of ΔG due to irradiation for the above samples.

	$\varphi = 9.6 \times 10^{13} \text{ e/cm}^2$		$\varphi = 14.4 \times 10^{13} \text{ e/cm}^2$	
Sample	$\frac{G_{2.0}}{G_{1.5}}$		$\frac{G_{2.0}}{G_{1.5}}$	$\frac{\Delta G_{2.0}}{\Delta G_{1.5}}$
3	2.06		1.97	1.5
5	7.2		6.9	--

If we make an analysis using Γ_i , as in Run 11, we find that $\Gamma_{35}(2.0)/\Gamma_{35}(1.5) = 9.0$ at $9.6 \times 10^{13} \text{ e/cm}^2$, and 8.6 at $14.4 \times 10^{13} \text{ e/cm}^2$. This is in agreement with results obtained for Γ_i , in Run 11 after irradiation so it appears that the difference in the conductance of Samples 3 and 5 is due to the same mechanism as in the higher doped samples. The $\Delta G_{2.0}/\Delta G_{1.5} = 1.5$ obtained in this run is nearly the same temperature dependence as obtained for Golin's⁸ sample C of $G_{2.0}/G_{1.5} = 1.7$. Therefore it is reasonable to say that $\Delta G_{2.0}/\Delta G_{1.5}$ is almost entirely bulk change since its temperature dependence is that of the bulk mechanism rather than the surface mechanism. We can find the amount of surface conductance in each sample. As before we assume that the surface conductance has the same temperature dependence in every sample so that it is the same as for Γ_{ij} . Let

$$\begin{aligned}
 G_i &= \text{the total conductance of the } i^{\text{th}} \text{ sample} \\
 G_{S_i} &= \text{the surface conductance of the } i^{\text{th}} \text{ sample} \\
 G_{B_i} &= \text{the bulk conductance of the } i^{\text{th}} \text{ sample}
 \end{aligned}$$

Then

$$\frac{G_{S_i}(2.0 \text{ K})}{G_{S_i}(1.5 \text{ K})} = 9.0 \text{ at } \phi = 9.6 \times 10^{13} \text{ e/cm}^2 \quad (50)$$

We assume

$$\frac{G_{B_i}(2.0 \text{ K})}{G_{B_i}(1.5 \text{ K})} = 1.5 \quad (51)$$

Then for Sample 3,

$$G_3(2.0 \text{ K}) = 1.5 G_{B_3}(1.5 \text{ K}) + 9.0 G_{S_3}(1.5 \text{ K}) \quad (52)$$

and

$$G_3(1.5 \text{ K}) = G_{B_3}(1.5 \text{ K}) + G_{S_3}(1.5 \text{ K}) \quad (53)$$

Since $G_3(2.0 \text{ K})$ and $G_3(1.5 \text{ K})$ are known, $G_{B_3}(1.5 \text{ K})$ and $G_{S_3}(1.5 \text{ K})$ can be found. The result is $G_{S_3}(1.5 \text{ K}) = .0007 \times 10^{-6}$ mhos or 7.4% of the total. Similarly, for Sample 5, $G_{S_5} = .022 \times 10^{-6}$ mhos or 75% of the conductance. Since the starting conductance of the samples in Run 14 is even lower than Sample 3, we assume that surface contribution to the total conductance before irradiation is less than 7.4%.

Next let us consider the implications of the magnitude of the production rate. In the low doped samples $P = .11 \text{ cm}^{-1} \pm 27\%$ in Run 14, first irradiation series. Flanagan and Klontz^{2/} irradiated p-type germanium doped $4 \times 10^{14} \text{ cm}^{-3}$ to $4 \times 10^{15} \text{ cm}^{-3}$ with 1.0 MeV electrons at 10 K and measured Hall coefficient and electrical conductivity using a reference temperature of 30 K. By measuring the carrier concentration between 30 K and 60 K as a function of temperature and using the equation

$$p + N_d = N_a / [1 + (4p/N_v) e^{e/kt}] \quad (54)$$

where

p = carrier concentration

N_d = donor concentration

N_a = acceptor concentration

N_v = density of states in the valence band

ϵ = acceptor activation energy

k = Boltzmann's constant

T = absolute temperature ,

Flanagan and Klontz obtained both the acceptor concentration and the donor concentrations. Immediately after a 1.0 MeV irradiation, they saw essentially no charged defects introduced. On subsequent illumination with light filtered through a germanium filter charged defects appeared. The production rate before illumination was less than 3×10^{-4} (holes/cm³)/(electrons/cm²). After 98 hours of illumination, the production (using their Figure 7) was 18 cm^{-1} for a sample doped $1.3 \times 10^{15} \text{ cm}^{-3}$. The results of this experiment and that of Flanagan and Klontz are consistent if the defect introduced by irradiation is neutral at 30 K and positively charged at 1.5 K. This would imply that the defect is a deep donor with a level near that of the chemical acceptor. Suppose that the defect has a level at the same level as the acceptor. The ionization of the donor at 30 K is calculated from

$$\frac{n}{N_D} = \frac{1}{1 + \frac{1}{2} \exp((E_D - E_F)/kT)}$$

where

$\frac{n}{N_D}$ = fraction unionized

E_D = energy of donor level

E_F = Fermi energy .

The Fermi energy is calculated from^{32/}

$$E_F = \frac{1}{2}E_A - \frac{kT}{2} \ln\left(\frac{N_A}{2U_V}\right) + kT \sinh^{-1} \left\{ \sqrt{\frac{U_V}{8N_A}} e^{E_A/2kT} \right\} \quad (55)$$

where

$$E_A = .010 \text{ eV}$$

$$k = .861 \times 10^{-4} \text{ eV/}^\circ\text{K}$$

$$U_V = 4.82 \times 10^{15} \left(\frac{m_p^*}{m_o} \right)^{3/2} T^{3/2}$$

$$\frac{m_p^*}{m_o} = 0.39$$

The concentration of defects is assumed small compared to N_A for this calculation. For $T = 30 \text{ K}$, $N_A = 1 \times 10^{15} \text{ cm}^{-3}$, we get $E_F - E_D \approx .0136$, and $1 - \frac{n}{N_D} = .003$. Our observed production rate is .11, so the production rate which would be observed at $T = 30$ is $.003 \times .11 = .00033$, in agreement with Flanagan and Klontz.

The value of $P = .11 \text{ cm}^{-1}$ has another implication. In n-type material, production rates of 1.4 cm^{-1} would be expected for singly ionized defects. Therefore, either the defects observed have migrated and are not the supposedly simple defects observed in n-type material, or not all the defects are ionized at 1.5 K. One might wonder at first if it is possible that defects might be trapped in non-equilibrium charge states during irradiations at low temperatures. However, anneals to 30 K usually produce a decrease in conductance so that this occasional change is in the wrong direction to account for the small production. Another possibility is that the donor level of the defect is between the gallium level and the valence band. One could arrange matters so that only a fraction of the defects

would be ionized. This would enable one to understand why P is small. The model also predicts that apparent production rates should depend on minority compensation of the crystals, and temperature, and this provides a test of this model. This is discussed below.

The position of the Fermi level at low temperatures is given by^{33/}

$$\frac{E_F}{kT} = \frac{E_A}{kT} - \ln\left(\frac{N_A - N_D}{2N_D}\right) \quad (56)$$

for $N_A \gg N_D$

where E_A is the acceptor ionization energy. The fraction of neutral donors is given by

$$n_D = \frac{1}{1 + \frac{1}{2}e^{(E_D - E_F)/kT}} \quad (57)$$

The effective production rate P_{EFF} is then given by

$$P_{EFF} = Px(1 - n_D) \quad (58)$$

where P is the production rate in n-type material. Since $P_{EFF} = 0.11$ and $P = 1.4$, we get $1 - n_D = .0785$. In Sample 23, $N_A = 8.0 \times 10^{14} \text{ cm}^{-3}$, $N_D = 1.2 \times 10^{13}$. Take the acceptor level E_A as the zero of energy; then $E_F/kT = -3.48$. This enables us to calculate E_D using Equation (57) and $n_D = .9215$. We find $E_D/kT = -5.25 \pm .2$. After an irradiation of $3.3 \times 10^{13} \text{ e/cm}^2$ and an anneal to 295 K, the conductance of Sample 23 is $.0100 \pm .0005$ micromhos. Flanagan and Klontz^{2/} show the effect of an irradiation followed by an anneal to 300 K in their Figure 10. Before irradiation, they had $N_A = 1.19 \times 10^{15} \text{ cm}^{-3}$, $N_D = 4.2 \times 10^{13} \text{ cm}^{-3}$. After an irradiation of $6 \times 10^{15} \text{ e/cm}^2$, they found $N_A = 1.10 \times 10^{15} \text{ cm}^{-3}$ and $N_D = 2.3 \times 10^{14} \text{ cm}^{-3}$. Therefore for a fluence of $3.3 \times 10^{14} \text{ e/cm}^2$, we should have $\Delta N_D = +1 \times 10^{13}$.

The N_D estimated for Sample 23 after being irradiated and annealed to 295 K is $\frac{.0100}{.003} \times 1.2 \times 10^{13} = 4.0 \times 10^{13}$. Therefore $\Delta N_D = 3 \times 10^{13}$, about three times the observation of Flanagan and Klontz.^{2/} Using $N_D = 4 \times 10^{13}$ and $E_D/kT = -5.25$, we can now calculate the effective production rate for the second irradiation. The number ionized is .024 and so the effective production rate should be $P_{EFF} = .033 \pm .010$. The observed production rate in the second irradiation was $P_{EFF} = .083 \pm .016$. These do not agree with 1m the experimental error. If one takes $P_{EFF} = .9$ as one would expect from the data of Hyatt,^{23/} then the P_{EFF} obtained for the second irradiation would be $P_{EFF} = .035 \pm .010$, and $E_D/kT = -4.76 \pm .2$. The level model does not appear to fit for $\Delta N_D = 3 \times 10^{13}$. If $\Delta N_D = 1 \times 10^{13}$, then using $P = 0.9$ we would get $P_{EFF} = .078$ for the second run which is within experimental error. Now let us consider the higher doped samples. Since these samples have an appreciable surface conductivity, we get only an upper estimate for N_D before irradiation by using the initial conductance of Sample 17. The calculated N_D is 6.5×10^{14} . This is about a factor of 10 higher than we expect the concentration to be. Therefore to estimate N_D , we calculate it using the measured production rate. For $P = 1.4$ and $E_D/kT = -5.25 \pm .2$, and $P_{EFF} = .45$ we get $N_D = 1.5 \times 10^{13}$, which is reasonable. For $P = .9$ and $E_D/kT = -4.76$, $N_D = 2.4 \times 10^{13} \text{ cm}^{-3}$, which also is reasonable. Now consider Sample 12 of Run 13. For this sample using $P = .9$, $E_D/kT = -4.76$, and $P_{EFF} = .73 \pm 17\%$, we find $N_D = 3.0 \times 10^{12} \text{ cm}^{-3}$, ($7.1 \times 10^{11} \leq N_D \leq 5.8 \times 10^{12}$). This seems a bit too small. By the time the third irradiation is performed there should be at least $3 \times 10^{13} \text{ cm}^{-3}$ donors. The effective production rate should be $P_{EFF} = .26$ as opposed to $.73 \pm 17\%$ observed. This is outside the experimental error.

Now we examine the effect of varying the measurement temperature on the apparent production rate. Consider again Sample 3 of Run 10, for which $N_D = 2.5 \times 10^{13} \text{ cm}^{-3}$, $N_A = 7.8 \times 10^{14} \text{ cm}^{-3}$. We take $P = 0.9$ and so $E_D/kT = -4.76 \pm .2$ at 1.5 K. What we want to do is to calculate the ratio of the effective production rate at 2.0 K to the effective production rate at 1.5 K. To do this, we need an equation for the Fermi level which includes the effect of the defects with energy level E_D . To get this equation, we write the equation for electrical neutrality at low temperatures:

$$N_D - \frac{N_D}{1 + \frac{1}{2} \exp\left(\frac{E_D - E_F}{kT}\right)} + N_{D_0} = N_A - \frac{N_A}{1 + \frac{1}{2} \exp\left(\frac{E_F - E_A}{kT}\right)} \quad (59)$$

where N_D = concentration of defects with energy level E_D

N_{D_0} = concentration of chemical donors

N_A = concentration of chemical acceptors with level E_A .

Let $\alpha = \exp(E_F/kT)$

$\beta_A = \exp(E_A/kT)$

$\beta_D = \exp(-E_D/kT)$.

The above equation is a quadratic equation in α . It can be written as

$$\alpha^2 (-2N_A \beta_D + 2N_{D_0} \beta_D) + \alpha (N_D - N_A + N_{D_0} + 4N_{D_0} \beta_A \beta_D) + 2N_D \beta_A + 2N_{D_0} \beta_A = 0. \quad (60)$$

The solution is

$$\alpha = \frac{N_D - (N_A - N_{D_0} - 4N_{D_0} \beta_A \beta_D)}{4\beta_D (N_A - N_{D_0})} + \left[\frac{(N_D - (N_A - N_{D_0} - 4N_{D_0} \beta_A \beta_D))^2}{16(\beta_D (N_A - N_{D_0}))^2} + \frac{N_D + N_{D_0}}{N_A - N_{D_0}} \frac{\beta_A}{\beta_D} \right]^{\frac{1}{2}}. \quad (61)$$

The plus sign in front of the square root is chosen to ensure that α is positive. From this equation, E_F can be found and used along with E_D to calculate the ionization of the defects at the two doses given in Table 81. The result is shown below.

TABLE 83

Calculation of the fraction of defects ionized for Sample 3, Run 10, using $E_D/kT = -4.76$ at 1.5 K.

Fluence (10^{13} e/cm ²)	Temperature (K)	Fraction ionized
9.6	1.45 $\pm$.03 - .01	.052
14.4	1.45 $\pm$.03 - .01	.049
9.6	1.981 $\pm$.005	.135
14.4	1.981 $\pm$.005	.122

The average production rate at 2.0 K divided by the average production rate at 1.5 K is 2.5. This ratio can vary by $\pm .1$ due to experimental uncertainties. Using $E_D/kT = -5.25$ at 1.5 K gives an even larger ratio. Therefore the apparent production rate should go up by at least a factor of 2.5 if one compares measurements at 2.0 K and 1.5 K. However, in Table 82, we showed that $\Delta G_{2.0}/\Delta G_{1.5} = 1.5^{+1.3}_{-.6}$. We expect from Golin's measurements that $G_{2.0}/G_{1.5} = 1.7$. The errors given for $\Delta G_{2.0}/\Delta G_{1.5}$ are outside limits and overestimate the probable error. Thus we can say temperature dependence observed is just due to the temperature dependence of the hopping mechanism, and not due to any level effect.

To summarize, this model does not fit the experimental results. It predicts that the defect energy level should be between 4.76 and 5.25 kT

units below the chemical acceptor level at 1.5 K. As a result of donors introduced after an irradiation and an anneal to 295 K, the production rate on a succeeding run should be smaller. The observed production rates in Runs 13 and 14 are larger than those calculated using this model. In addition, the production rates as measured at 1.5 K and 2.0 K (but one irradiation temperature) in Run 10, Sample 3 should differ by a factor of $2.5 \pm .1$. The upper limit for this ratio experimentally is 1.1. Since the above model was unsuccessful in describing the experimental results, we are left with the alternative that the defect moves at the irradiation temperature.

One feature of the production data that has not been discussed as yet is the bending over of the production curve in Run 13 near 1×10^{14} e/cm² and the small production rate at large doses. From Golin's expression^{8/} $\sigma = C \frac{N_D}{N_A} (N_A - N_D)$ we would expect a maximum in the production curve when $N_D/N_A = \frac{1}{2}$, or $N_D \approx 3 \times 10^{15}$ cm⁻³. For a production rate of .7, this would correspond to 4.3×10^{15} e/cm². However, if there were 6.5×10^{14} donors present initially (previously estimated as an upper limit), the dose corresponding to the maximum would be 3.3×10^{15} e/cm². This is too far from 1×10^{14} e/cm² to explain the bend in the production rate seen there. We used $P = \frac{1}{C \frac{N_D}{N_A}} \frac{\Delta \sigma}{\Delta \phi}$ to calculate the production rate P, as tabulated in Table 20. For $N_D \ll N_A$, this reduces to

$$P = \frac{\Delta N_D}{\Delta \phi} \quad (62)$$

For N_D large, we have

$$P = \frac{\Delta N_D}{\Delta \phi} - \frac{2N_D}{N_A} \frac{\Delta N_D}{\Delta \phi} \quad (63)$$

If we assume that $\frac{\Delta N_D}{\Delta \phi} \approx .7$ throughout the irradiation, then at $\phi = 9.8 \times 10^{14}$ e/cm², the donor concentration produced by irradiation would be 6.9×10^{14} cm⁻³. Adding to this the upper limit for chemical donors present, we have a total of 1.4×10^{15} cm⁻³. The production at $\phi = 9.8 \times 10^{14}$ e/cm² as tabulated in Run 13, Series 2B should then be

$$P = .7 - 2 \times \frac{1.4}{6} \times .7 = .37 \text{ cm}^{-1}.$$

Excluding Sample 15 the production rates were less than $.07 \text{ cm}^{-1}$. Therefore the expression of Golin^{8/} does not predict such low production rates. The theory of Scher and Lax^{10/} is not sufficiently elaborated to permit a calculation of the dependence of σ on N_D in germanium for large N_D .

The bending over of the production rate at $\sim 10^{14}$ e/cm² in Run 13, second irradiation series, could be understood in the following way. Suppose, as previously discussed that the defects are mobile during irradiation and that they can be preferentially trapped by one type of impurity present in quantities of $\sim 7 \times 10^{13}$ cm⁻³. When these traps become filled, the apparent production rate decreases. The remaining production rate could be due to traps with a smaller cross section or perhaps due to defect-defect complexes. In this model, the electrically active defects would be defect-impurity complexes. Since the production rates in Run 14 are higher for the higher doped samples, it is tempting to identify the traps as gallium atoms. This is probably not the case, however, because Sample 18 in Run 13 had a smaller production rate than the other samples, but had a doping of 8.8×10^{15} Ga/cm³ compared to 7.6×10^{15} Ga/cm³ for the next highest sample. Sample 17 (8.3×10^{15} Ga/cm³) in Run 14 had a lower production rate than Sample 10 (5.6×10^{15} Ga/cm³). Since Samples 17 and 18 were cut from near

the end of the horizontally grown ingot, it is quite possible to have a different concentration of neutral impurities than in the samples cut from the middle. Therefore we hypothesize that the higher production rate observed in the samples of somewhat lower doping is due to a high concentration of a certain type of neutral impurities. The difference in production rates between samples doped $\sim 9 \times 10^{15} \text{ cm}^{-3}$ and those doped $\sim 6 \times 10^{15} \text{ cm}^{-3}$ would then be explained by a higher concentration of the unknown neutral impurity by roughly a factor of four or five. According to this explanation the production rate in Sample 18, Run 13, second irradiation series, should begin to decrease at about $\frac{1}{2}$ the fluence at which this is seen in the other samples. It did not. Whether this is due to a failure of the expression of Golin used to calculate production rates, or a failure of the model is not clear. One does expect that σ depends less strongly on the majority doping at high doping levels. It was observed in this experiment for n-type crystals that C in

$$\sigma = C N_{\text{MIN}} (N_{\text{MAJ}} - N_{\text{MIN}})$$

decreased by a factor of 1.8 between samples doped $9 \times 10^{14} \text{ cm}^{-3}$ and samples doped $5 \times 10^{15} \text{ cm}^{-3}$. It is not known how rapidly C should decrease between $8 \times 10^{15} \text{ cm}^{-3}$ and $9 \times 10^{15} \text{ cm}^{-3}$. In summary, the idea that defects run to a fixed number of traps and that this limits the production rate is consistent with the bending over of the production curve in Run 13 and with the variation of the production rate in different samples, but it is not clear if it agrees with the fact that the production rate of Sample 18 of Run 13, second series, bends over at about the same place as the other samples.

In p-type degenerate material, the production rate under 1.10 MeV electron irradiation is less than $10^{-2}/\text{cm}^{34/}$ at 4.2 K. In this material, we would expect the defect levels of the present experiment to be ionized. However, the production rate in Run 13 was observed to decrease at fluences above 10^{14} e/cm^2 (except for one sample which was anomalous) so that for the large fluences (greater than 10^{16} e/cm^2) reported in their experiment it is reasonable that such a low production rate would be obtained.

C. Suggestion for Understanding Radiation Damage in Germanium in Relation to Defects in Silicon

In this research, the production rates in p-type germanium were higher for higher doped samples. (This is probably due to a higher concentration of a neutral impurity rather than due to the higher gallium concentration.) Also, as we have seen one cannot explain the data by assuming the deep donor level associated with the defects introduced by irradiation lies below the Fermi level so that only some of the defects are ionized. Instead it seems necessary to suppose that defects migrate during or after the electron irradiation at 1.8 K and some or all are trapped by some neutral impurity. This is similar to what McKeighen and Koehler^{4/} found in the case of p-type silicon, namely that the production rate depended on impurity concentration, implying a migration of defects at the irradiation temperature. This leads one to make the suggestion that germanium and silicon behave similarly, both as far as interstitials and as far as vacancies are concerned. This idea leads on to suggest that the mobile entity in p-type germanium at 1.8 K is the interstitial. The suggestion also leads one to suspect that the mobile species in n-type

germanium at 65 K could be the vacancy, similar to the 60 - 80 K migration of $V^{\cdot\cdot}$ in silicon. The activation energy of $0.15 \pm .01$ eV for the 65 K stage in germanium compares well with $E_M^{V^{\cdot\cdot}} = 0.18 \pm .02$ eV in silicon. A criticism of this suggestion for the 65 K stage is that it has been observed by Bourgoin and Mollot^{35/} that the annealing takes place when the Fermi level goes through a level between .33 and .55 MeV below the conduction band suggesting that a defect becomes mobile when it loses an electron. Since it is assumed that I^0 and $V^{\cdot\cdot}$ are present before the anneal,^{28/} the mobile defect would then be I^+ or V^- . However, Bourgoin and Mollot also observed that in heavily doped n-type germanium where the Fermi level never reaches .33 MeV below the conduction band the annealing takes place at 65 K whatever doping concentration in this high doped range is used. Thus their conclusion does not appear to be correct. Finally, one wonders if there is a stage in germanium corresponding to the migration of the neutral vacancy at 170 K in silicon. The break up of defects observed by Flanagan and Klontz^{2/} near 200 K is a possibility. The activation energy observed was .40 eV which is not far from $E_M^{V^0} = 0.33 \pm .03$ eV in silicon.

APPENDIX

This appendix shows the method of calculation for obtaining Figure 12, which gives the variation of production rate with thickness in n-type germanium. First, Callcott and MacKay's^{1/} data for production versus energy is assumed correct and a first approximation for the production versus thickness curve obtained. Second, the finite size of Callcott and MacKay's samples was taken into account and a small correction obtained.

Consider a 1.1 MeV beam of electrons incident on a 100 micron thick sample of germanium. The energy loss/micron is calculated from the tables of Berger and Selzer^{36/} by taking the collision and radiation loss terms for copper and using

$$\left. \frac{dE}{dx} \right|_{\text{collision}} \propto NZ$$

$$\left. \frac{dE}{dx} \right|_{\text{radiation}} \propto NZ^2$$

where N = number of atoms per unit volume,

Z = atomic number,

to convert to the values for germanium. $\left. \frac{dE}{dx} \right|_{\text{total}}$ for germanium is thus found to be 700 eV/micron. The effective thickness of the sample is increased by multiple scattering. The extra path length due to this effect is

$$\Delta_w = \theta_w^2 \frac{\chi}{8}$$

where Δ_w = increase in thickness

χ = sample thickness

θ_w = mean scattering angle .

The mean scattering angle as a function of thickness was obtained using the tables and graphs in Corbett.^{37/} A table of x versus Δ_w is given below.

TABLE 84

Thickness x versus scattering angle Δ_w for a 1.1 MeV incident beam of electrons. Decrease of beam energy with thickness was ignored in calculating these results.

x (microns)	Δ_w (microns)
100	6
150	13
200	24
250	38
300	56
350	79
400	106

The energy loss for the 100 μ sample can be computed from $\Delta E = \frac{dE}{dx} [x + \Delta_w]$.

The average energy in the sample is $\sim 1.1 - \frac{\Delta E}{2}$. Using Callcott and MacKay's^{1/} production versus energy curve (their Figure 11) a production rate can be found which corresponds to this average. Next the energy loss for 150 μ is computed. The average energy in the last 50 microns was computed by the formula

$$\text{average energy } 100\text{-}150\mu = \frac{[\text{energy at } 100 + \text{energy at } 150]}{2}$$

A production rate for the average energy in the last 50 microns was found from Callcott and MacKay's graph and the production rate for the first 100 μ and the last 50 averaged according to the formula

$$P_{0-100} \left(\frac{100}{150} \right) + P_{100-150} \left(\frac{50}{150} \right) = P_{av}$$

This process was repeated for 200, 250, 300, 350, and 400 μ . Results are tabulated below.

TABLE 85

Average production rate versus thickness for n-type samples and a 1.1 MeV incident electron beam. See Figure 12 for a correction to the results given here.

$P_{av} \pm .1 \text{ cm}^{-1}$	T (microns)
2.69	100
2.60	150
2.48	200
2.33	250
2.19	300
2.04	350
1.88	400

Callcott and MacKay's^{1/} samples were 150 μ before etching. After etching the thickness is not given, but a reasonable assumption is 100 μ . The energy loss for 100 μ at 1.1 MeV including the correction for multiple scattering is .037 MeV. Therefore the average energy in the crystal is 1.06 MeV and the average energy loss is .04 MeV. We find from Callcott and MacKay's^{1/} Figure 11 that .04 MeV implies a change of .18 cm^{-1} near 1.1 MeV. Therefore to get the production rate in a sample of zero thickness, we add the production rate for their sample of 2.85 cm^{-1} to .18 cm^{-1} to get 3.0 cm^{-1} . For the average energy of the 300 and 400 μ samples, .04 MeV corresponds to .32 cm^{-1} . An approximate correction for the finite thickness of the test sample is therefore obtained and is given in Figure 12.

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