GENERAL DYNAMICS
General Atomic Division

SPECIAL NUCLEAR EFFECTS LABORATORY

P.O. BOX 608, SAN DIEGO, CALIFORNIA 92112

GACD-6249
(6/30/66)

Copy No.

RADIATION EFFECTS ON SILICON

Sixth Quarterly Progress Report Covering the Period
April 1, 1966, through June 30, 1966

Work done by:

J. B. Bryant
H. Horiye
J. A. Naber
E. G. Wikner

Report written by:

H. Horiye
J. A. Naber
E. G. Wikner

National Aeronautics and Space Administration
Contract NAS7-289
General Atomic Project 430

July 11, 1966

1. INTRODUCTION

This sixth quarterly progress report on Contract NAS7-289, "Radiation Effects in Silicon Solar Cells," covers the period April 1, 1966, through June 30, 1966.

During this period studies were made of the damage and annealing properties of high-purity n-type silicon after irradiation at 4.2°K with 25 MeV electrons, and further investigations were made of the annealing characteristics of the E center.

2. MICROWAVE CONDUCTIVITY

Work during this quarter has been concentrated on investigating the damage and annealing properties of the high-purity n-type silicon after the sample has been irradiated at 4.2°K with electrons of approximately 25 MeV.

2.1 IRRADIATION AT 4.2°K

At room temperature the high-purity n-type silicon has a conductivity of 10^{-4} (ohm-cm)$^{-1}$, a Hall mobility of about 2000 cm^2/volt-sec,[1] and a carrier concentration of approximately 3×10^{11} carriers/cm^3. Recent publications[2] indicate that n-type silicon, when bombarded with electrons at 4.2°K, is very insensitive to damage when the electrical properties of the material are used as the damage indicators.

Prior to irradiation, the excess carriers excited by a 0.1 μsec 25 MeV electron pulse (low injection level equivalent to 0.5 rad Si) decay with two time constants--one about 0.2 μsec, followed by a longer one of approximately 3 μsec. At high injection levels (0.1 μsec pulse of 25 MeV electrons equivalent to 10 rads Si), the excess carriers decay with the same two time constants. Measurements during irradiation show that up to integrated fluxes of 1.45×10^{12} electrons/cm^2 there is no noticeable change in the decay lifetime of either the high- or low-injection-level carriers at 4.2°K. This is in agreement with the published data that the electrical properties of the silicon show no observable changes due to electron bombardment at 4.2°K.

The sample was then warmed to liquid nitrogen temperature (77.5°K) and kept there for 36 hours while the microwave equipment was moved to the flash x-ray facility, where it was subsequently subjected to dose levels of 5 mR or less.

2.2 ANNEALING

Even though there was no observable effect in the properties of the sample irradiated at 4.2°K, considerable changes at liquid nitrogen temperature were observed. The pre-irradiation electrical conductivity at liquid nitrogen temperature is 8×10^{-4} (ohm-cm)$^{-1}$; after irradiation at 4.2°K it is $< 2 \times 10^{-5}$ (ohm-cm)$^{-1}$ at liquid nitrogen temperature. The pre-irradiation lifetime of excess carriers at liquid nitrogen temperature is 20 μsec, and the lifetime after the 4.2°K bombardment is 2 x 10^4 μsec at liquid nitrogen temperature. The pre-irradiation temperature dependence of the excess-carrier lifetime (τ) and the electrical conductivity as a function of $10^3/T$ are given in Figs. 3 and 4 of Reference 3. Prior to annealing, the injection-level dependence of the excess-carrier lifetime is obtained at liquid nitrogen temperature. It is found that over the range of injection levels possible at the flash x-ray there is no noticeable injection level dependence of the excess-carrier lifetime. The sample is then heated to 101°K for 10 minutes and then returned to liquid nitrogen temperature. This type of anneal is known as an isochronal anneal.

The electrical conductivity measurements are made at the reference temperature of liquid nitrogen. The sample is then annealed at 20°K temperature intervals up to 310°K. After each anneal the τ versus $10^3/T$ characteristics and an isochronal anneal measurement of the electrical conductivity are taken.

Figure 1 shows the excess-carrier lifetime as a function of $10^3/T$ after the 101°K anneal. Figure 2 shows the τ versus $10^3/T$ characteristics after the sample is heated to 310°K. Figure 3 shows the isochronal anneal characteristics of the sample.

All of the excess-carrier decay lifetimes are first order, i.e., they can be analyzed by using the relationship

$$\frac{\sigma_f - \sigma_t}{\sigma_f - \sigma_o} = e^{-t/\tau}$$

where σ_o and σ_f are initial and final conductivities, respectively, and σ_t is the conductivity at any time t. Further scrutiny shows that there is only this one observable decay time constant. There is no shorter time constant for decay of excess carriers.

2.3 ANALYSIS OF ANNEALING DATA

The most striking observation of the 4.2°K bombardment is that the lifetime measurements do not show the presence of damage at 4.2°K, but upon heating the sample to liquid nitrogen temperature the electrical properties of the sample at liquid nitrogen temperature are greatly affected. This could be due to the temperature dependence of the charge state of the defect or to the migration of the inactive centers upon

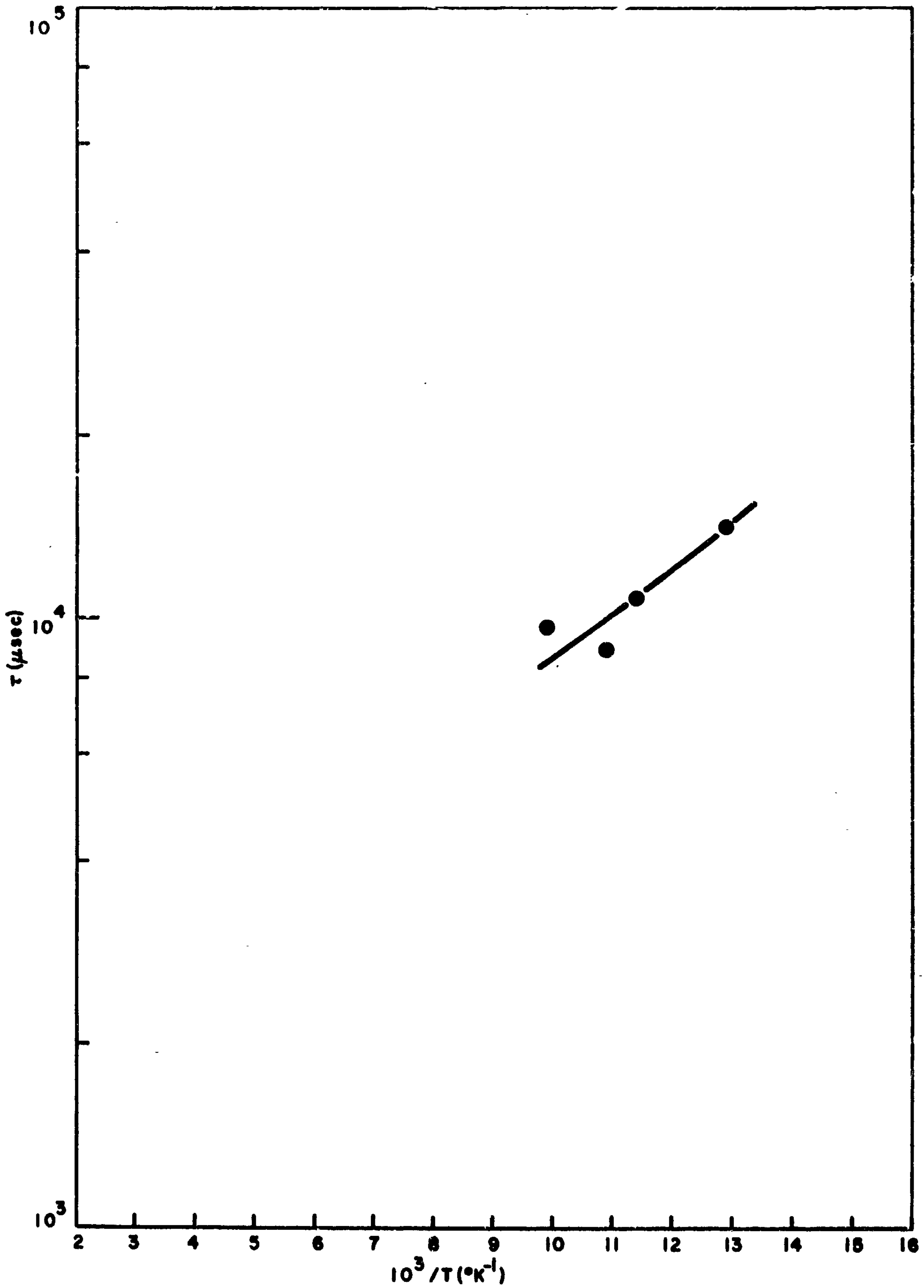

Fig. 1--Excess carrier lifetime after annealing n-type silicon to 101°K

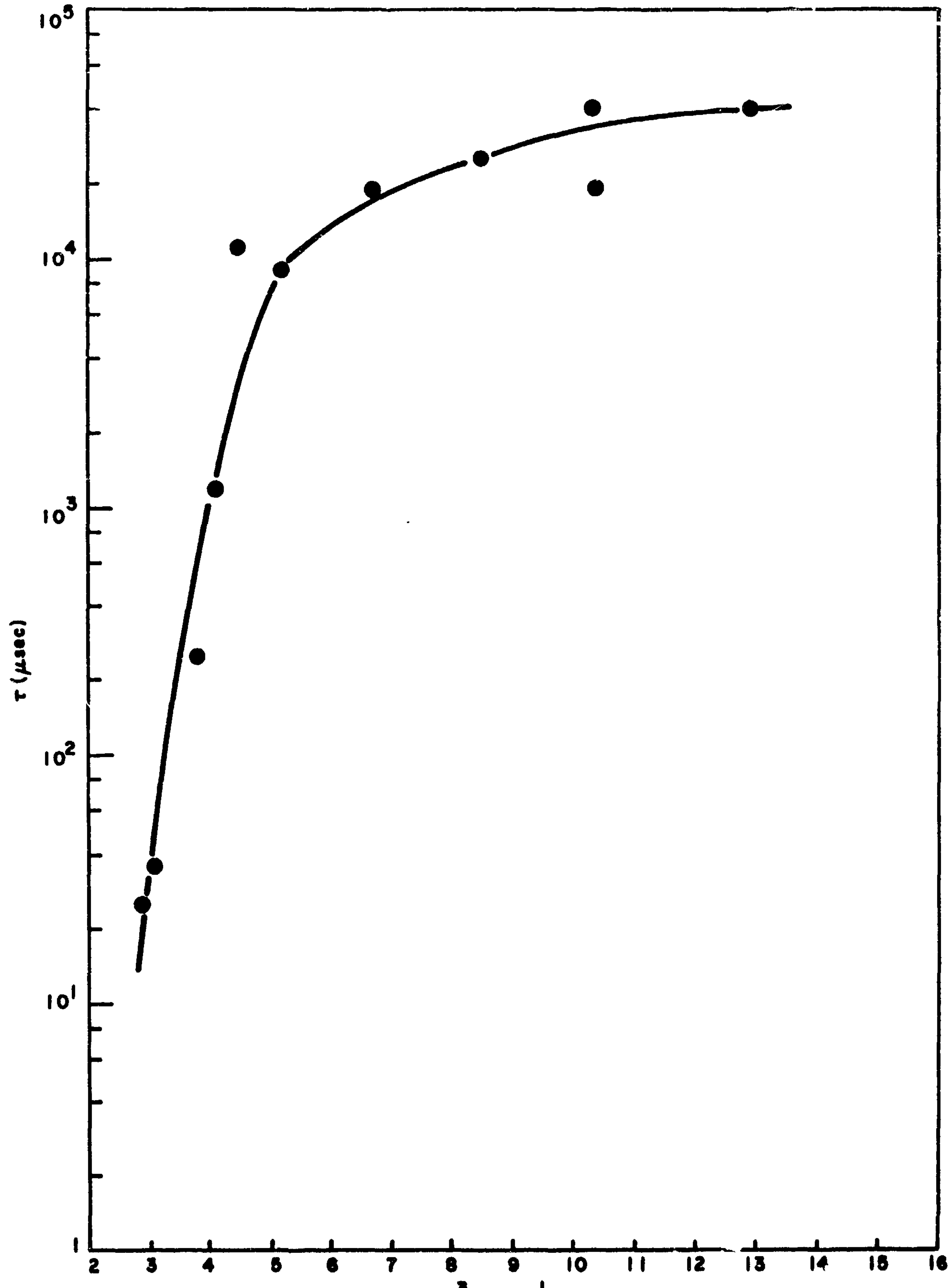

Fig. 2--Excess carrier lifetime after annealing n-type silicon to 310°K

heating and forming new electrically active centers. The temperature dependence of the excess-carrier lifetime, after bombardment and annealing to 310°K, shows that the defect introduced into the sample by the 4.2°K bombardment is a trapping center. The lack of a shorter time constant indicates that the decay of excess carriers is predominantly through a trapping center.

The isochronal anneal of the electrical conductivity starts to take place around 140°K; the excess-carrier lifetime also starts to anneal or change about this temperature. This indicates that the electrical conductivity and excess-carrier lifetime possibly anneal simultaneously. The large temperature range of anneal as seen on Fig. 3 indicates that the annealing defects are of a complicated nature or a rearrangement and not of a simple annealing process. This is to be expected for high-energy electrons at these temperatures. The slope of Fig. 2 indicates that the trapping center is located between 0.2 to 0.4 eV from a band edge.

At the present time this is only a preliminary analysis. A more complete analysis will be presented in the final report.

2.4 CONTRIBUTION OF ELECTRONS TO THE DIELECTRIC CONSTANT

In analyzing the dependence of the amplitude of the microwave signal reflected from a semiconductor sample, it has been assumed that the semiconductor has a dielectric constant (κ) independent of conductivity. (For silicon, $\kappa = 11.7$.) It must be recognized that free carriers can contribute to the value of the dielectric constant in a semiconductor. The change in dielectric constant due to the charge carrier contribution is given by[4]

$$\Delta\kappa = -4\pi\sigma \frac{m^*}{e} \mu_H$$

where m^* is the effective mass of the carriers, σ is the electrical conductivity, and μ_H is the Hall mobility. To obtain an estimate of the maximum change in κ due to free carriers excited during the electron pulse, a Hall mobility of 10^6 cm^2/volt-sec at 5°K is used. If a 10-rad pulse is used, the number of excited carriers is about 4×10^{14} electrons/cm^3. This corresponds to a change in dielectric constant of -0.7. This change is appreciable enough that the assumption of a dielectric constant independent of electrical conductivity is no longer valid. However, at low injection levels of 0.5 rad or less the change in dielectric constant due to free

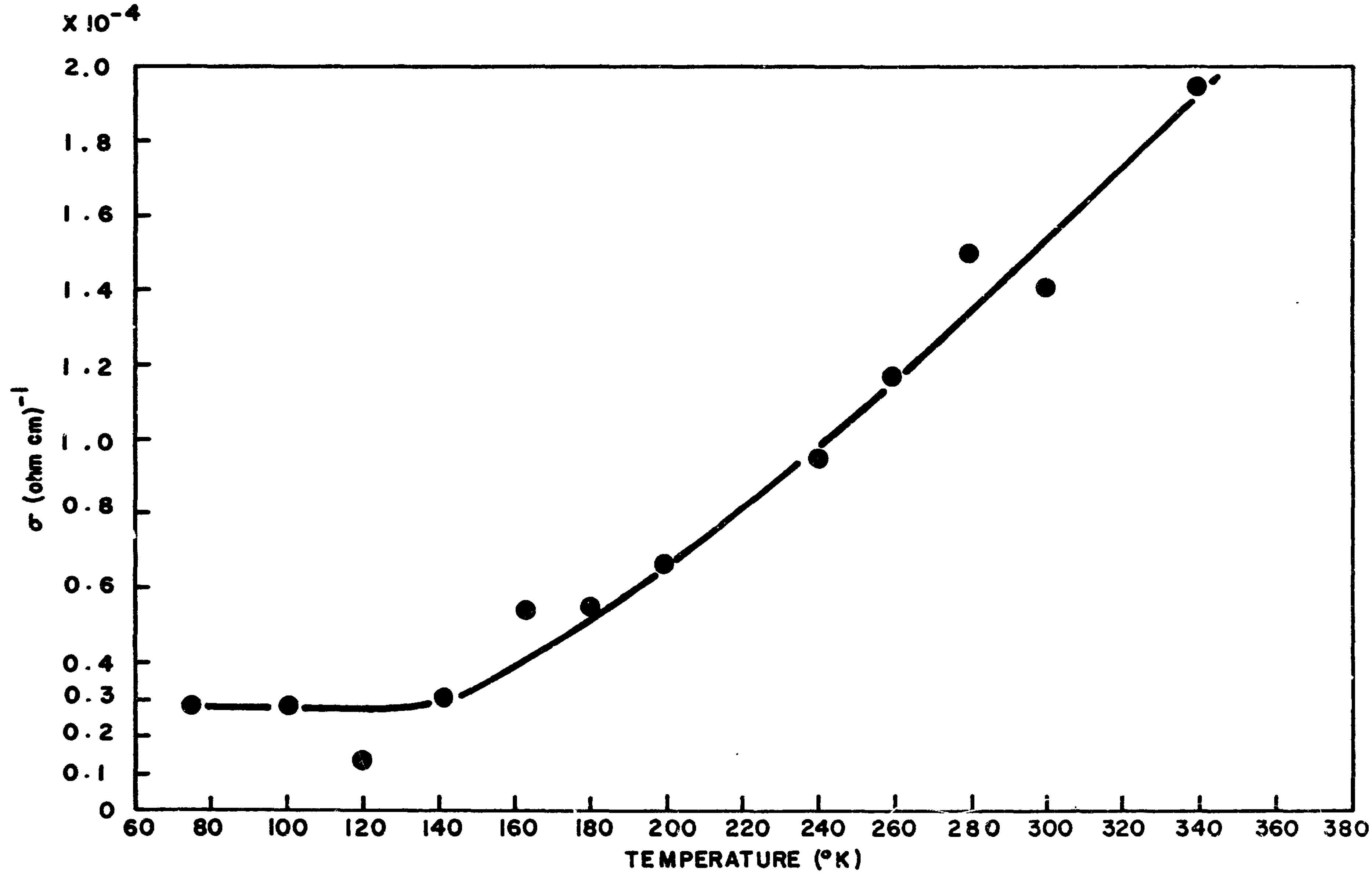

Fig. 3--Isochronal annealing of high-resistivity n-type silicon irradiated at $4.2^{\circ}K$

carriers can be neglected. The above estimates are made for an n-type silicon sample at $4.2^{O}K$. As the temperature of the sample is increased, the Hall mobility decreases so that at liquid nitrogen temperature the effect of free carriers on κ due to injection is negligible for a 10-rad pulse. At $4.2^{O}K$ the computer program used to calculate the electrical conductivity from the reflected signal needs to be modified to handle large carrier-injection levels.

2.5 FUTURE PLANS

The effect of electron damage, thermal annealing and injection-level dependence on the excess-carrier lifetime will be investigated for a high-resistivity n-type silicon sample bombarded at room temperature. The characteristics of the defect introduced by room temperature irradiation will be determined. The defects produced by the room temperature and $4.2^{O}K$ bombardment will be compared.

3. ELECTRON SPIN RESONANCE EXPERIMENTS

Additional experiments have been performed to verify some of the results and conclusions drawn in the last quarterly report on the annealing characteristics of the E center.

In n-type, 0.1 ohm-cm, P-doped silicon, annealing experiments were performed, and it has been observed that after an $80^{\circ}K$ irradiation and subsequent annealing to a temperature of $150^{\circ}K$, only a small change in the number of E centers was observed. Further annealing to $300^{\circ}K$ reduced the E-center resonance intensity to the order of 10% of the original value. After an anneal temperature of about $275^{\circ}K$, the resonance associated with the divacancy appeared. It had been postulated that these observations were due to a change in Fermi level caused by annealing of deeper levels not associated with either the E center or the divacancy defect. Samples which were run at different electron flux levels substantiated such a model. At high flux levels ($> 6 \times 10^{17}$ electrons/cm^2), the divacancy resonance immediately after the $80^{\circ}K$ irradiation was not seen, as in the above mentioned case. At lower fluxes, the divacancy resonance was seen after the $80^{\circ}K$ irradiation, with a smaller E-center resonance than in samples irradiated to higher flux levels. Annealing to $300^{\circ}K$ produced no significant change in the intensity of the divacancy resonance and a decrease of the order of a factor of 1.5 to 2 in the number of E centers. The change in the number of E centers was due to a shift in the Fermi level and not an annealing involving the E center, as substantiated by experiments using light. A sample which had been annealed to $400^{\circ}K$ and which had both divacancy and E-center resonances was illuminated at $20^{\circ}K$ with a microscope lamp. The E-center resonance intensity increased, while the divacancy resonance decreased. The total number of centers remained approximately the same. This signifies that a large number of phosphorus-vacancy defects (E centers) were still present after the $400^{\circ}K$ anneal, and the decrease in resonance was actually due to a changing electron population.

A number of 10 ohm-cm P-doped samples were irradiated between 5 and 12×10^{17} electrons/cm^2 at 30 MeV. The spectrum observed was similar to that of the large samples mentioned in the previous quarterly report. The sample with the lowest flux seemed to have a less complicated spectrum than the others. However, the small number of centers makes an orientation dependence study difficult. Further experimentation on this resistivity material will be made in the attempt to correlate the lifetime and resonance results.

REFERENCES

1. E. H. Putley, The Hall Effect and Related Phenomena, Butterworths, London, 1960, p. 140.

2. L. L. Sivo, Bulletin of A.P.S. 10, BH8, 1094 (1965).

3. E. G. Wikner, J. A. Naber and H. Horiye, "Radiation Effects on Silicon," Fifth Quarterly Progress Report on Contract NAS7-289, General Atomic Report GACD-6249 (3/31/66).

4. H. Y. Fan, Solid State Physics Vol. I, ed. by F. Seitz and D. Turnbull, Academic Press, Inc., New York, 1955, p. 52.