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FAST NEUTRON DAMAGE IN SILICON DETECTORS*

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Radiation effects of fast neutrons have been measured in silicon detectors of varying resistivity irradiated to ≈ 10^{11} n/cm^2 over periods of weeks. The principal damage effect is increased leakage current due to generation of carriers from defect levels in the depletion region. Damage and leakage current constants have been established for detector resistivities between 10 and 27,000 ohm-cm and lie in the range of 0.7 - 2 x 10E7 sec/cm^2 (K) for PuBe neutrons. A slight increase in K was observed for higher resistivities which translates into somewhat improved radiation hardness. A fit of this data was attempted to a two-level recombination formulation of the damage constant.

1. Introduction

Semiconductor detectors have found an increasing role as position and energy sensing detectors in high energy physics applications. At high luminosity machines, such as the Superconducting Super Collider (SSC) and the LHC, significantly higher radiation environments are expected than those of previous applications [1]. Calculations indicate that fast neutrons will

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constitute a substantial component of the expected fluences. This work attempts to quantify the early and most detrimental effects of fast neutrons on silicon radiation detectors.

The estimations of the radiation environment at the SSC, for example, assume a generic detector configuration in which the central tracking detectors of low mass occupy an open spherical region of 2 m radius which is enclosed by a calorimeter of various stopping and sensing materials such as uranium/silicon, uranium/scintillator, and others. The charged particle component produces a dose mainly in the beam directions and becomes tolerable at tens of cm radii from the beam pipe. Fast neutrons are generated by spallation and evaporation processes in the calorimeter and fill the cavity more or less uniformly with albedo neutrons at the $2 \times 10^{12}/\mathrm{cm}^2$-yr level. The fast neutron fluence in the calorimeter is about $10^{12}/\mathrm{cm}^2$-yr. Both of these estimates are qualitatively in the range where some radiation effect on silicon detectors might be expected [2]. The estimate of the fast neutron energy spectrum is remarkable in that a very distinct distribution about an average energy of 1 MeV is predicted [1], which is the result of some moderation of boil-off neutrons of several MeV and their final absorption and capture at much lower energy.

Fast neutrons interact primarily by elastic scattering with silicon atoms, imparting at most 1/29 of their kinetic energy, which causes atomic displacements in the silicon lattice. Within the very short range of the silicon recoils, many such displacements are present in "clusters" which may produce somewhat different electrical defect levels in the silicon bandgap from those of isolated, single displacement defects. Details of damage effects and mechanisms may be found in several texts [3,4]. The first effect that may be expected for silicon detectors having low leakage currents at room temperature is an increase of leakage current from a generation of carriers through defect levels in the band gap. This effect will be described in detail. Other effects that have been observed in semiconductor detectors include carrier trapping by defects which removes carriers from the energy signal for periods longer than the electronic processing time and even longer term trapping which results in an effective increase in material resistivity by removing majority carriers. Carrier trapping affects spectrometers (Ge) and is not of interest here; ccrrier removal leading to resistivity variations has been observed in strip detectors at rather high charged particle doses and will also not be considered [5].

The generation current in a detector, a depleted diode, is often described by a simple relationship where the generation process and recombination process dictating the minority carrier lifetime are assumed to be the same. Thus, the generation current density J(A/cm^2) is traditionally written:

$$J = \frac{qn_i w}{2\tau} \tag{1}$$

where q is the electronic charge, n the intrinsic carrier density (taken to be 1.5 × 10^{10}/cm^3 at 300°K, 1 × 10^{10}/cm^3 at 22°C), w the depletion width and t the minority carrier lifetime. Semiconductor device effects focus on the minority carrier lifetime and measurements are made as a function of radiation (neutron) fluence, ϕ, which define a lifetime degradation through a linear rate constant, the damage constant K (recombination damage constant Kr) defined in this instance by

$$\frac{1}{\tau} = \frac{1}{\tau_o} + \frac{\phi}{K} \tag{2}$$

The increase in generation current density ΔH varies linearly with fluence

$$\Delta J = \frac{qn_i w \emptyset}{2K} \quad . \tag{3}$$

Previous estimates of the damage constant [2,6] suggested values of about 10^6 sec/cm^2 which would yield a leakage current density in a 300 μm thick (typical) detector of 40 μa/cm^2 for the annual SSC dose of 10^{12} n/cm^2. Clearly this is a highly deleterious effect considering both noise and biasing and is the motivation for this study.

A model for the recombination damage constant as a function of material resistivity has been developed by Messenger [7] and described succinctly in Messenger and Ash [4]. Using Hall Schockley Read statistics to describe the complicated interactions of two defect levels, a fit to the damage constant for low energy neutrons at several low resistivities was obtained. Extrapolating this model to detector resistivities in the several kohm range, suggested that the damage constant might improve (harden) by more than an order of magnitude, bringing expected leakage currents into a more manageable range that could be further reduced by detector geometries that effectively reduce the depletion volume. Therefore, several detectors of resistivities spanning a range of available detector materials should be used to determine if a dependency exists and if a multi-level model is appropriate to describe the results.

It is useful to separate the concepts of recombination and generation lifetimes which pertain here for different reasons [8,9]. The recombination lifetime has considerable historic interest [2] and its associated damage constant can be used to describe an increase in leakage current through the above equations. It is especially pertinent to the device literature and serves to relate device experience to detectors. The generation lifetime is applicable to the increase in leakage current in depletion regions; it may be defined as a probability giving the rate of introduction of excess carriers R in a depletion region:

$$R = n_i \cdot (1/\tau_g) \quad (/\mathrm{cm}^3\text{-sec}) \quad . \tag{4}$$

Thus the leakage current per cm^3 is just R x volume:

$$I = \frac{q\ n_i w\ A}{\tau_g} \tag{5}$$

and the increase in current ΔI due to a fluence ϕ defines a damage constant K_g:

$$\Delta I = \frac{q\ n_i w\ A\ \phi}{K_g} \tag{6}$$

It is perhaps less confusing at this point to simply define a leakage current constant α in terms of the volume effect:

$$I = \alpha\ \phi\ W\ A \quad \text{where } \alpha \equiv q\ n_i/K_g = q\ n_i/2K \quad . \tag{7}$$

Results will be reported in terms of K and α.

2. Experimental Arrangement

The neutron source used is a ^{16}Ci PuBe source that is certified to yield 3.68×10^7 (± 3%) n/sec of ^{9}Be (a,n) neutrons which have an average energy of about 4.5 MeV. At 10 cm this source produces 1.06×10^8 n/cm^2-hr, which is similar to the annual flux of interest, 10^{12} n/cm^2-2400 hr. Rate effects, such as room temperature annealing during irradiation, are therefore incorporated into these exposures. The flux at 10 cm is taken as the geometrical flux using the NBS traceable certification of the source and was not measured.

The energy spectrum of (α,n) sources, as measured by several workers and calculated by Vijaya and Kumar for ^{241}AmBe neutrons is shown in Figure 1 [10]. Although it is not centered about 1 MeV, it is clearly defined above 1 MeV without an unknown low energy component. Geiger and van der Zwan [11] have calculated neutron spectra for several (α,n) sources, including ^{241}AmBe and ^{239}PuBe which are quite similar. The general features of the spectrum are governed by the reactions in the ^{12}C+n system and not by the particular alpha source in contact with the Be. Figure 2, taken from van Lint et al [3], shows the relative displacement damage as a function of neutron energy, conveniently normalized to unity at 1 MeV. If the generation current is proportional to the number of single defects, these curves may be used to relate various spectra to a 1 MeV standard effect. Weighting the relative damage curve by the calculated ^{239}PuBe spectrum yields a factor of 1.7:1.0 for relative damage of PuBe neutrons to 1 MeV. From this curve, the relative damage of 14 MeV neutrons to 1 MeV neutrons is 2.75:1.

The silicon detectors used ranged from devices from commercial suppliers wth typical high detector resistivities, > 2 Kohm-cm to custom devices from material with resistivities down to 10 ohm-cm. The material is float zone-refined, n-type, having primarily 1,1,1 orientation and was obtained from several suppliers. Various area and configurations of diodes were used: from small .09 cm^2 diodes from wafer periferies to 9 cm^2 large area devices. In order to observe some increase in generation currents, a minimum volume must be exposed; therefore for the cases of low resistivity material in which only 10 μm depletion can be achieved, larger diode areas were used. Except for the cases with higher resistivity where full depletion of the 300 μm wafer could be achieved, the depletion depth at a particular bias is derived from the donor concentration found directly from a plot of 1/C2 for the actual device. The error (fractional standard deviation) of this determinatin is estimated at 10%.

Initial leakage current measurements were made with Keithley picoameters and the capacitance versus bias was measured with a Hewlett Packard 4192A bridge at 100 kHz.

3. **Results**

Figures 3 and 4 are typical results of the increase in leakage current in nA with exposure time of the PuBe source, which gives 1.06×10^{8} n/cm^2-hr. Leakage current measurements were made a room temperature, 22 ± 1 °C. The total exposure in Figure 3 is 8.5×10^{10} n/cm^2 and in Figure 4, 2.2×10^{10} n/cm^2. The three diodes shown in Figure 4 are 9 cm^2 devices from a given production run of a commercial supplier and show remarkably similar behavior. Figure 6 shows the results with a pair of 3.4 cm^2 diodes, side by side, on the same wafer (again, commercially supplied) in which one diode was biased during the irradiation with PuBe neutrons and the other not. Uniform and identical increases in leakage current are observed for these devices with no effect of bias to be seen. The lines drawn on Figures 3, 4, and 5 are least square fits to the data, from which the linear rate constant K is derived.

At the relatively low doses of PuBe neutrons used in this experiment (10^{11} n/cm^2, for the most part) no change in donor concentration as measured by capacitance measurements were observed or really expected.

Table I summarizes the results of the measurements on the devices in order of increasing resistivity. For comparison of the damage constant K to a 1 MeV standard, the values of K (fourth column) would be multiplied by 1.7.

Figure 6 presents the data of Table I as a function of material resistivity in some analogy to the calculations in [4].

The resistivity dependence of K as formulated in Messenger and Ash [4] and Messenger [7] is given by Eq. 5.30 of [4] for n-type material at low injection levels (small δ_n and p_o),

$$K_{\ell n}^{-1} = \frac{C_{p1}R_1}{1+n_1/n_o} + \frac{C_{p2}R_2}{1+C_p p_2/C_{n2}n_o} \quad (\frac{cm^2}{sec}) \tag{8}$$

where $C_{p,n}$ are the hole and electron capture probabilities with 1 and 2 denoting each of the two levels; R_1 and R_2 are the introduction probabilities for each level per neutron and p_2, n_1, and n_o are excess carrier concentrations. The solid line in Figure 6 is a least squares fit to the data which yields the following parameters:

$C_{p1}\ R_1 \approx 0$

$C_{p2}\ R_2 = 0.9\ cm^2/sec$

$\frac{C_{p2}p_2}{C_{n2}} = 1.65 \times 10^{22}/cm^3$, $\frac{C_{p2}}{C_{n2}} >> 1$

$n_1 = 2.37 \times 10^{11}/cm^3$

Table I summarizes the results of the measurements on the devices in order of increasing resistivity. For comparison of the damage constant K to a 1 MeV standard, the values of K (fourth column) would be multiplied by 1.7.

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For PuBe irradiations lasting up to 800 hours, some room temperature annealing is probably included in the leakage currnt measurements (for a general consideration of annealing c.f. [13]). An annealing effect and its functional time dependence could be incorporated into the damage data, however, the data as colleced do empirically represent net generation current increases over the specified irradiation periods between 400 and 800 hours.

4. Conclusions

Increased leakage currents have been measured in silicon detectors irradiated with fast neutrons at fluences up to ≈ 10^{11} n/cm^2; this is believed to be the dominant problem to application of silicon detectors in applications at future high luminosity accelerators. Measurements at this dose rate emulates the SSC environment, thus including room temperature annealing effects.

Values of the conventionally-defined damage constant K have been measured in the 0.5 - 1.5 × 10^7 sec/cm^2 range with PuBe neutrons that translates to 0.8 - 2.5 × 10^7 sec/cm^2 for 1 MeV neutrons. These values are assigned an error, fractional standard deviation, of 25% which includes the systematic errors of dosimetry and current measurement and the estimation of depletion depth responsible for the generation current. Using 2 × 10^7 sec/cm^2 for K, 10^{12} n/cm^2 --the expected annual fluence in SSC environments-- an increase in leakage current in a 300 μm thick detector of 1.5 μA is expected, which is probably manageable for many applications. It has been suggested [9] that since the generation current in depletion regions is the current source, which is dependent on n_i (Eq. 4), then cooling devices is a viable means of reducing the damage induced leakage current through the temperature dependence of n_i.

Some variation of K with material resistivity was observed primarily at very high resistivities. The fit of this data to the Messenger two level formulation directly implicates only a single level. It would certainly be reasonable to describe a generation current (as opposed to a recombination process) in terms of a single or more concentrated group of levels associated with cluster damage; a multi-level formulation may not be required to describe a generation current.

The values of K, and the leakage current coefficient, α, are in agreement with recent measurements [12], some of which have used fission neutrons where a certain latitude is required to accomodate the unknown character of the energy spectrum. No change in capacitance versus bias revealing a decrease in donor concentration was observed or expected. Similarly, no difference in damage constant (hardness) was observed between devices on the same wafer that were irradiated with and without bias. Bias effects are associated with surface and oxide conditions; the neutron damage observed here is mainly a bulk effect of the depletion region. Some room temperature annealing has been observed, but has not been studied in detail.

It is a pleasure to thank the staff of the Brookhaven Calibration Facility for their cooperation in the use of the ^{238}PuBe neutron source. We are indebted to Professor James Brau of the University of Tennessee (and Oregon, presently) for several large area, high resistivity detectors used in this study. Several very educational discussions with Dr. J. R. Srour have helped to clarify damage constant concepts and we are grateful for his help. Mr. M. Momayezi of the University of Hamburg contributed several thoughtful, important comments and suggestions which are much appreciated.

TABLE I

Sample	Area (cm^2)	Resistivity (ohm cm)	Damage Constant* $K(sec/cm^2)$(PuBe) x 10^7	Leakage Current Coefficient† α(A/cm) x 10^{-16}
H	1.00	9.6	0.72	1.11
600	3.39	10.6	0.52	1.54
615	1.50	179.	0.38	2.11
611	1.50	467.	0.61	1.32
604	1.00	2.36 K	0.51	1.58
M	0.50	2.6 K	0.95	0.84
171	0.09	4.2 K	0.69	1.15
124	0.09	5.1 K	0.65	1.24
199	9.00	10.2 K	1.23	0.65
200	9.00	10.2 K	1.0	0.80
223	9.00	10.2 K	1.08	0.74
124U5	3.40	14.4 K	1.44	0.56
124U6	3.40	14.4 K	1.41	0.57
117U5	3.40	28.7 K	1.43	0.56
117U6	3.40	28.7 K	1.27	0.63

*To compare to 1 MeV neutron damage coefficients, multiply by 1.7.

Estimated errors are ± 25%.

†To compare to 1 MeV neutron leakage current coefficients, divide by 1.7.

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Figure Captions

Fig. 1. The comparison of measurements of the ^{241}AmBe Neutron energy spectrum with calculated spectra. From A. D. Vijaya and A. Kumar, Nucl. Insrum. & Meth. 111 (1973) 435.

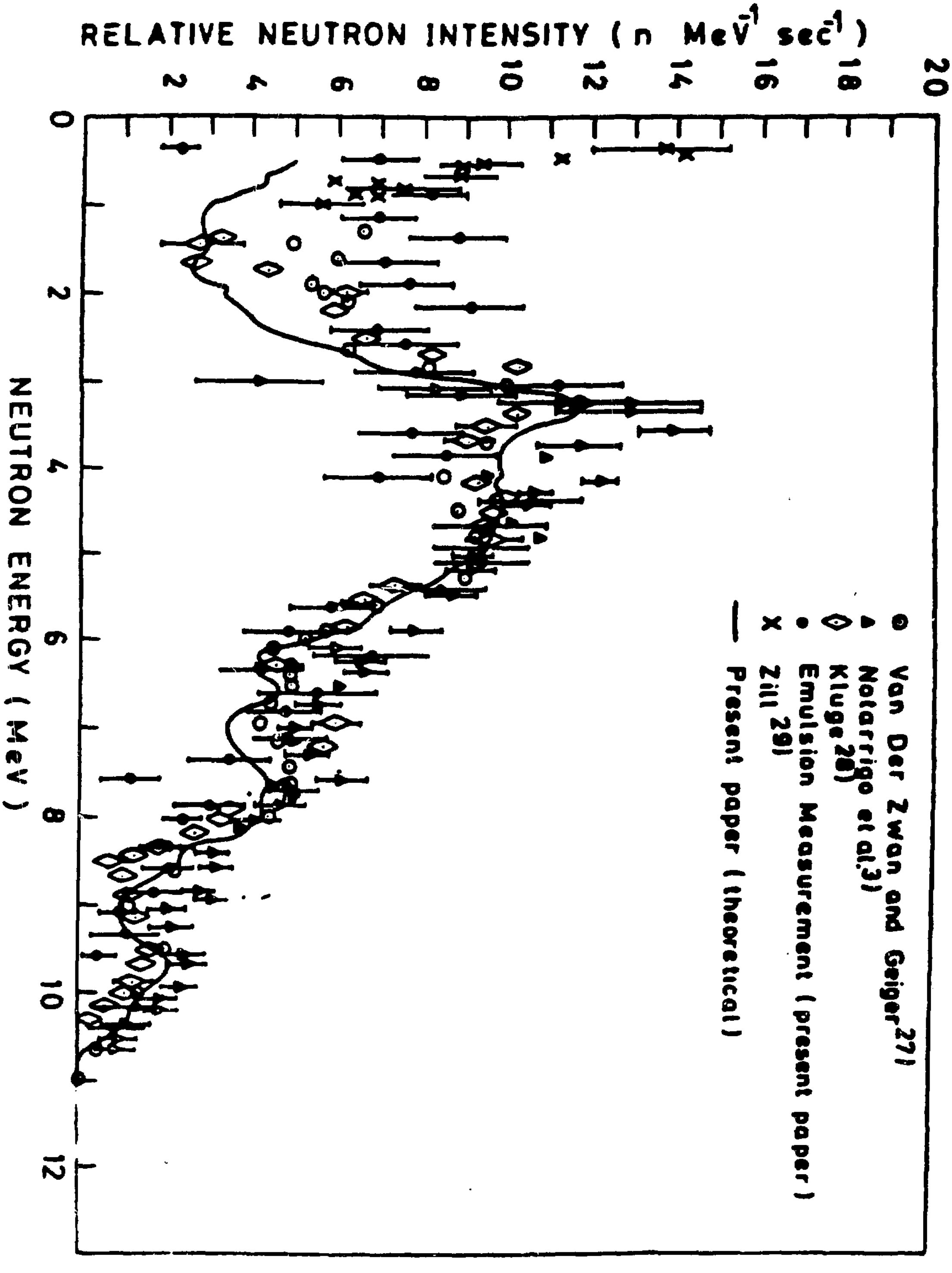
Fig. 2. The relative displacement damage in silicon by fast neutrons as a function of neutron energy. From [3], van Lint et al., Mechanisms of Radiation Effects in Electronic Materials I, John Wiley Co., NY, (1980).

Fig. 3. The increase in leakage current with fast neutron exposure up to 8.5 x 10^{10} n/cm^2 for a 4.2 K ohm-cm detector.

Fig. 4. The increase in leakage current of three 9 cm^2 10 K ohm-cm detectors exposed to 2.2 x 10^{10} n/cm^2 PuBe fast neutrons.

Fig. 5. The increase in leakage current for two adjacent detectors of 14.4 K ohm-cm on the same wafer exposed to 6.9 x 10^{10} n/cm^2 PuBe fast neutrons. One detector (◇) was biased during the exposure and one was not (□).

Fig. 6. The damage constant K (sec/cm^2) as a function of the material resistivity. The solid line is a fit of a two level recombination formulation to the data (4).


RELATIVE NEUTRON INTENSITY (n MeV^{-1} sec^{-1})
2
4
6
8
10
12
14
16
18
20
NEUTRON ENERGY (MeV)
0
2
4
6
8
10
12
⊙ Van Der Zwan and Geiger 27)
▲ Notarrigo et al.3)
◇ Kluge 28)
● Emulsion Measurement (present paper)
× Zill 29)
— Present paper (theoretical)

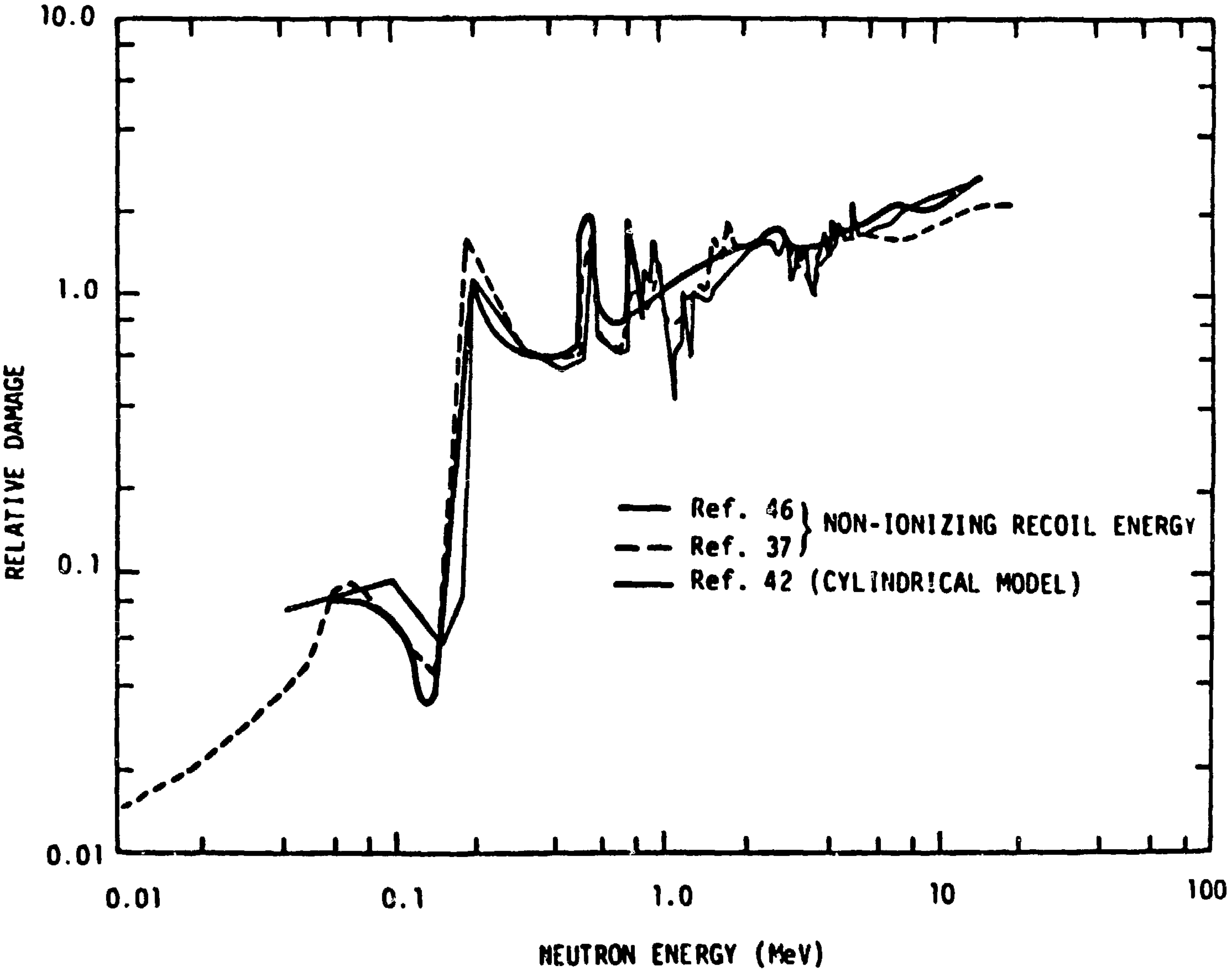

10.0
1.0
0.1
0.01
RELATIVE DAMAGE
0.01
0.1
1.0
10
100
NEUTRON ENERGY (MeV)
Ref. 46
Ref. 37
NON-IONIZING RECOIL ENERGY
Ref. 42 (CYLINDRICAL MODEL)

FIGURE 2

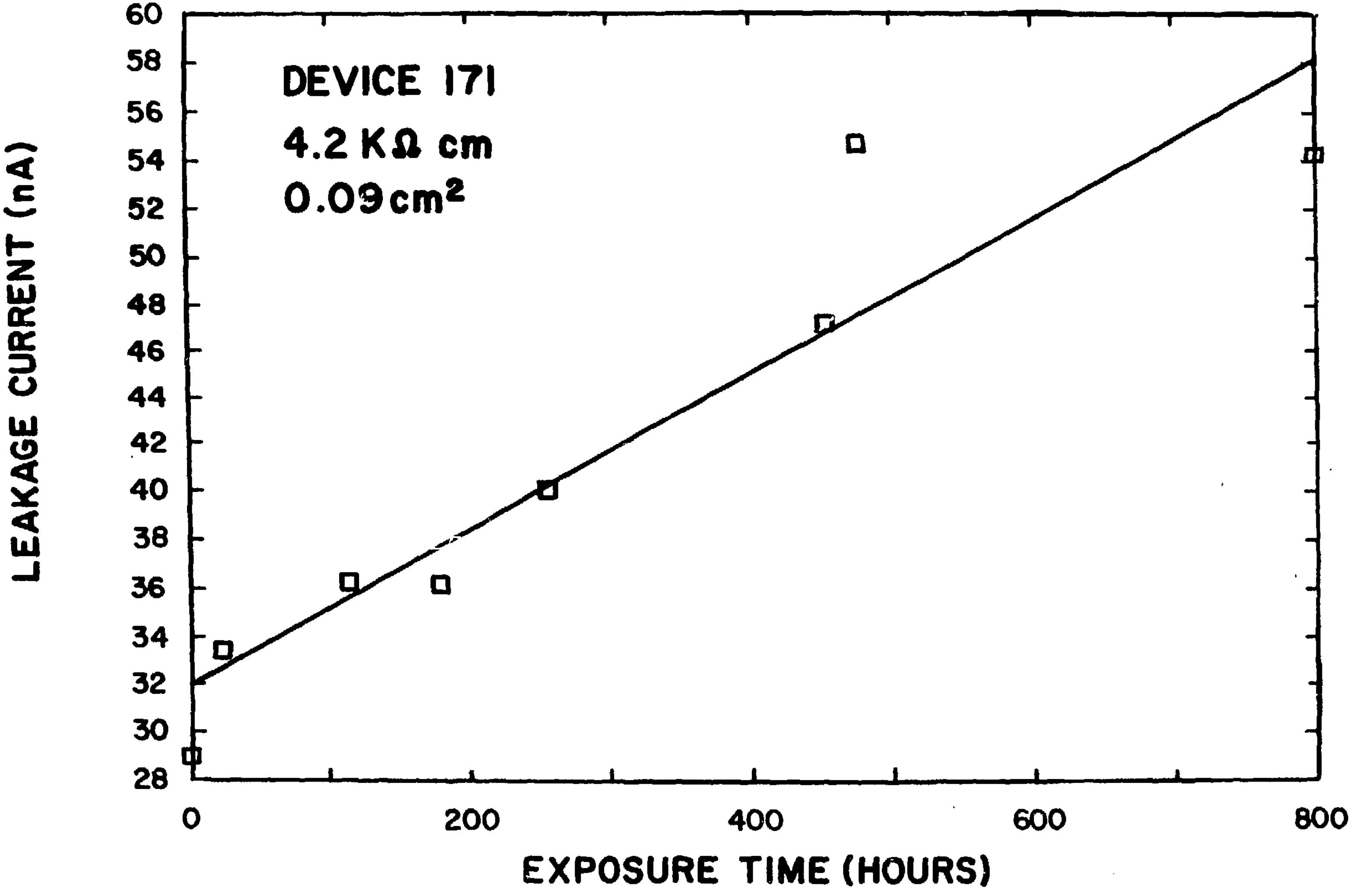
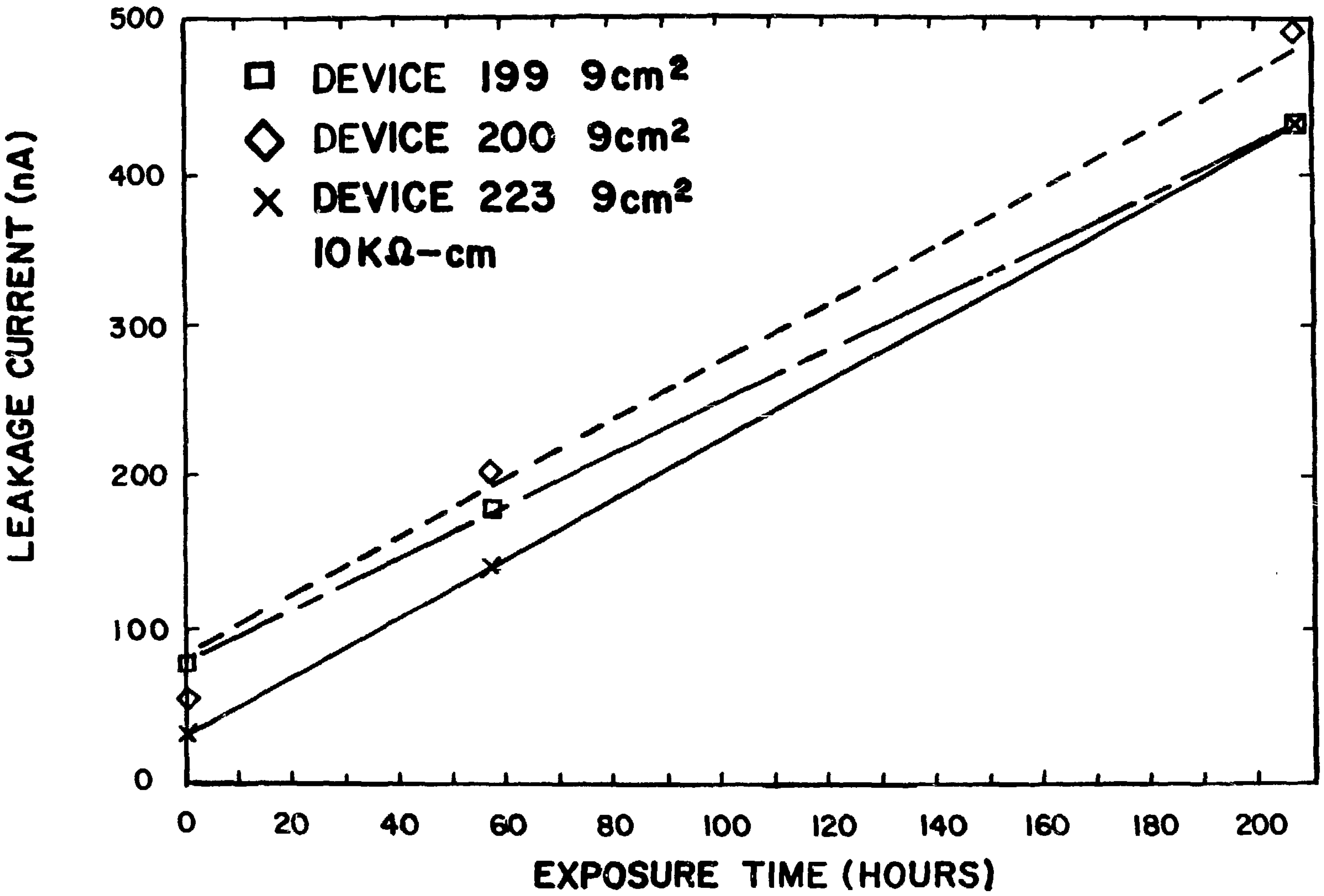

DEVICE 171
4.2 KΩ cm
0.09 cm²
LEAKAGE CURRENT (nA)
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
28
0
200
400
600
800
EXPOSURE TIME (HOURS)

FIGURE 3



500
400
300
200
100
0
LEAKAGE CURRENT (nA)
0
20
40
60
80
100
120
140
160
180
200
EXPOSURE TIME (HOURS)
□ DEVICE 199 9cm²
◇ DEVICE 200 9cm²
× DEVICE 223 9cm²
10KΩ-cm

FIGURE 4

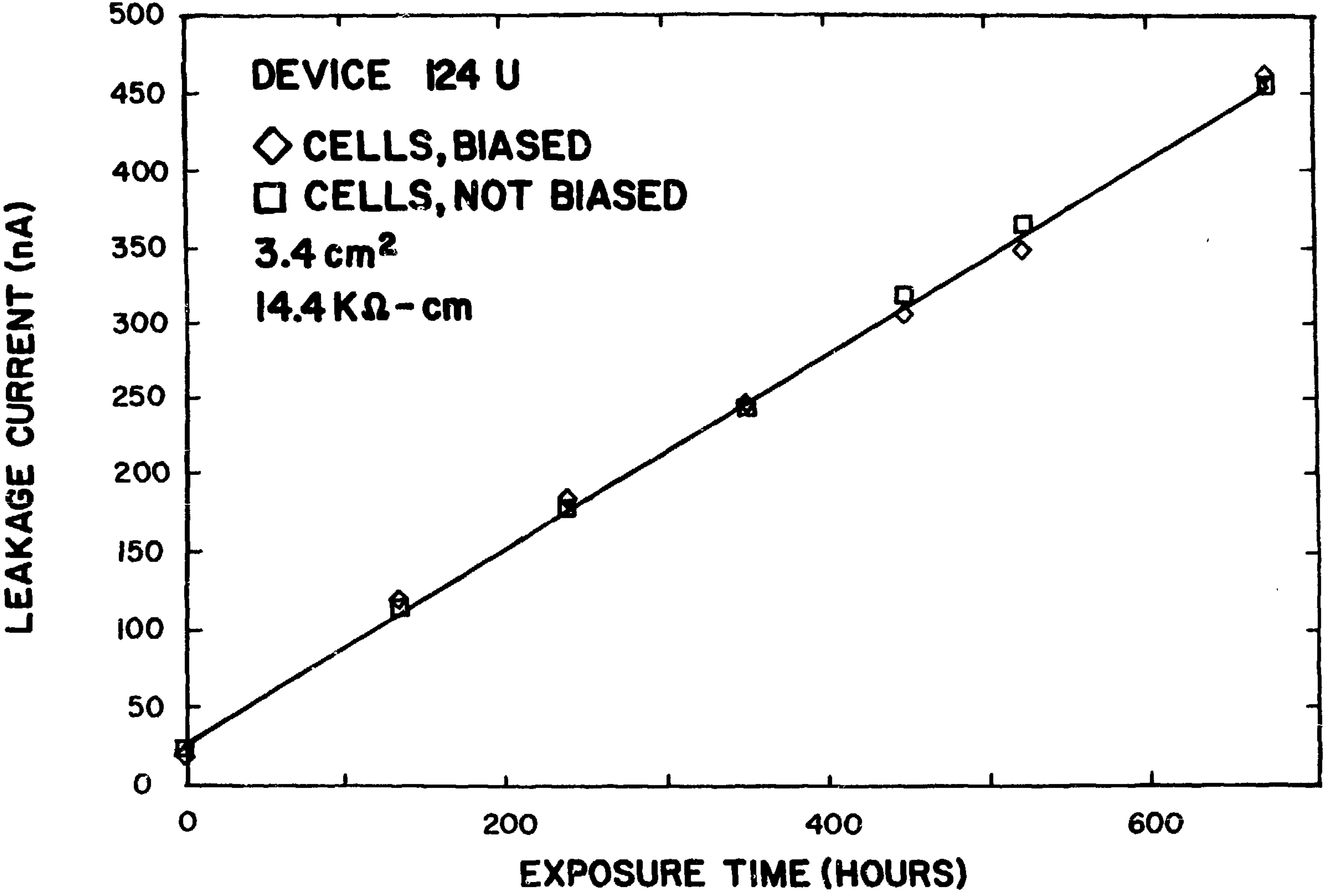

DEVICE 124 U
◇ CELLS, BIASED
□ CELLS, NOT BIASED
3.4 cm²
14.4 KΩ - cm
LEAKAGE CURRENT (nA)
500
450
400
350
300
250
200
150
100
50
0
EXPOSURE TIME (HOURS)
0
200
400
600

FIGURE 5

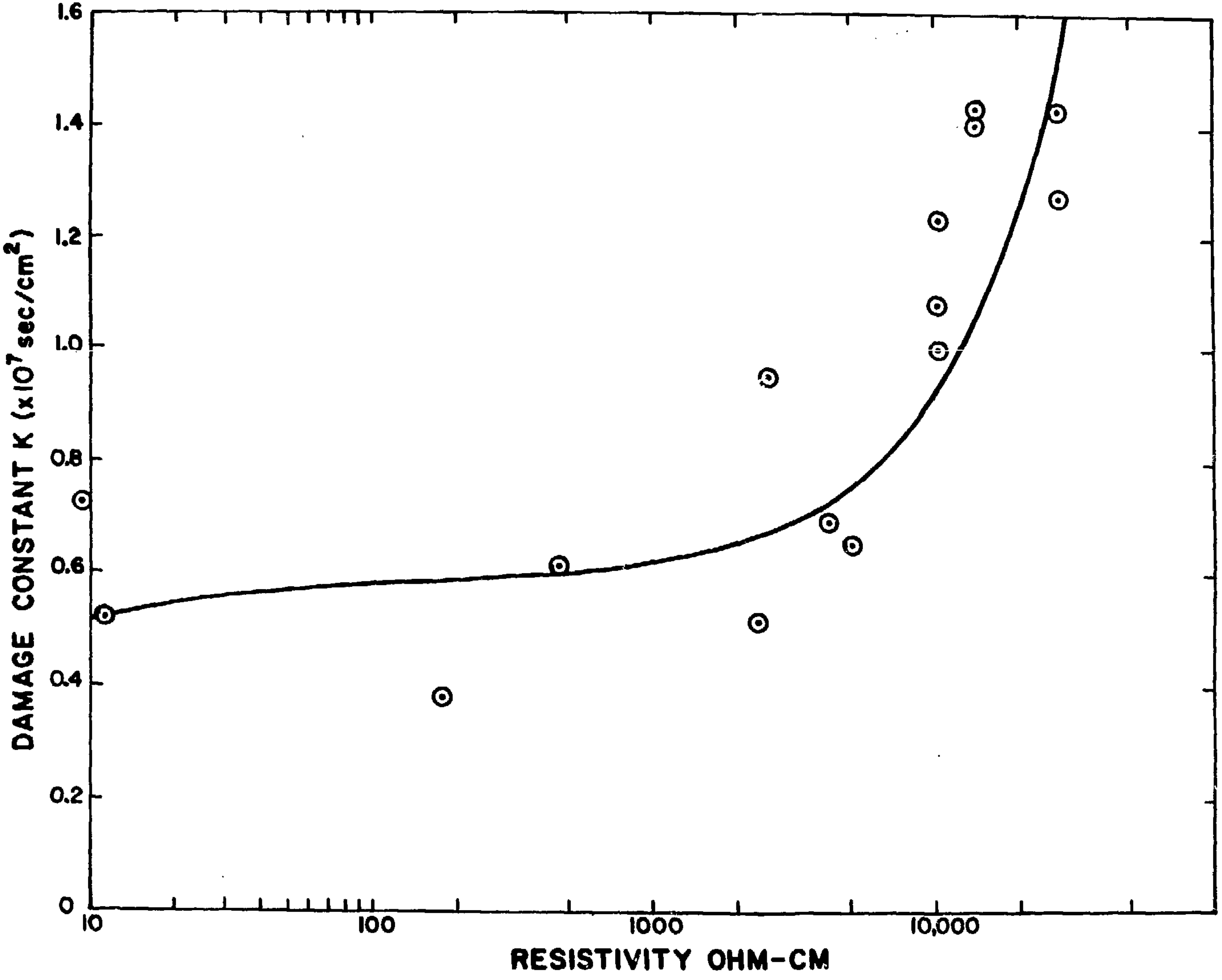

DAMAGE CONSTANT K ($\times 10^7$ sec/cm^2)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
10
100
1000
10,000
RESISTIVITY OHM-CM

FIGURE 6