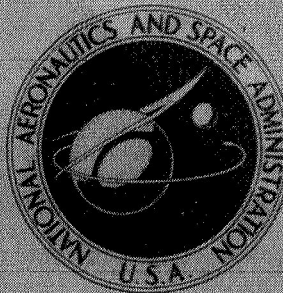# NASA TECHNICAL MEMORANDUM

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EFFECTS OF REACTOR RADIATION ON 4.7-VOLT SILICON VOLTAGE-REGULATOR DIODES

by Suzanne T. Weinstein, Edward A. Maslowski,
and Erich W. Kroeger
Lewis Research Center
Cleveland, Ohio

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16. Abstract

Twenty-five silicon voltage-regulator (Zener) diodes (1N3995A) were exposed to reactor radiation to a fast neutron fluence of 8.2×10^{13} neutrons/cm^2 and a gamma dose of 6.3×10^7 rads-carbon. The diodes were electrically energized in three different operating modes during irradiation. The Zener voltage remained constant, and the breakdown knee was somewhat softened. The forward- and reverse-leakage currents increased. The junction capacitance remained unchanged. Electrical operating mode did not affect the radiation damage in these diodes.

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SUMMARY

Twenty-five silicon voltage-regulator (Zener) diodes (1N3995A) were exposed to reactor radiation at the NASA Plum Brook Reactor Facility. This 10-watt, 4.7-volt Zener diode was selected for radiation testing on the basis of its applicability to nuclear space power generation systems. This test is part of a series designed to provide design data for a variety of semiconductor components for such systems and to correlate radiation damage to the devices tested with present theories of damage mechanisms.

The diodes were exposed to a fast neutron fluence of approximately 8.2×10^{13} neutrons per square centimeter and a gamma dose of approximately $^{\cap}.3 \times 10^7$ rads-carbon. The diodes were divided into three groups that were irradiated under different electrical operating conditions. The current-voltage characteristics of all diodes were measured before, periodically during, and after irradiation. In addition, junction capacitance at zero bias was determined for each diode before and after irradiation. The variation of capacitance with applied bias was measured on a few selected diodes before and after irradiation.

These Zener diodes displayed a resistance to radiation damage that is considerably greater than that of most other types of semiconductor devices. The electrical operating mode did not affect the amount of radiation damage. The Zener voltage remained constant, and the breakdown knee was somewhat softened. The increase in forward- and reverse-leakage currents was probably caused by the introduction of additional deep levels within the band gap. Junction capacitance remained unchanged. This behavior is in agreement with theoretical damage predictions and with results reported previously on other Zener diodes. The increase in leakage current and knee softening would not, in general, preclude the use of these devices in a nuclear environment at fast neutron doses up to 10^{14} neutrons per square centimeter.

INTRODUCTION

Nuclear electric systems are of interest for long-duration, large-power space missions. However, the use of nuclear electric power generating systems presents severe requirements for system reliability. Power conditioning and control are an integral part of such space power systems. Although semiconductor devices are desirable for power conversion and control because of their low weight, low power consumption, and high reliability, they are the most radiation sensitive electrical components. This radiation sensitivity may necessitate increased shield requirements over that needed for a nonsemiconductor power system. It is desirable, therefore, to know more exactly the radiation tolerance of presently available power devices for space power system applications.

A testing program was undertaken to investigate the effects of reactor radiation on semiconductor devices. This report describes the reactor testing of a 4.7-volt, 10-watt silicon voltage-regulator (Zener) diode (1N3995A). Work performed by others (see ref. 1) indicates that Zener diodes are among the least radiation sensitive semiconductor components. Reported damage threshold doses are of the order of 10^{15} fast neutrons per square centimeter.

This diode (1N3995A) was selected on the basis of the mechanism by which the Zener voltage is maintained and because of its large junction area, as well as its applicability to space systems. Since the Zener voltage is maintained by a combination of tunneling and avalanche breakdown, this diode type should theoretically be quite insensitive to radiation. Therefore, this diode was selected to be irradiated simultaneously with another diode type in which the Zener voltage is maintained solely by bulk avalanche. Reference 2 presents the results of the irradiation of the avalanche diode. In addition, in some semiconductor devices, the larger the junction area, the greater the radiation sensitivity. Therefore, this particular diode was chosen because it has a junction area larger than that of Zeners previously tested.

Twenty-five Zener diodes (1N3995A) were irradiated in the NASA Plum Brook Reactor to a fast neutron fluence of approximately 8.2×10^{13} neutrons per square centimeter and a gamma dose of approximately 6.3×10^7 rads-carbon. These dose levels are larger by at least a factor of 10 than estimated dose levels for a 1-year space system mission. The diodes were divided into three groups that were irradiated under different electrical operating modes. The current-voltage characteristics and junction capacitance at zero bias were measured on all diodes before and after irradiation. Capacitance as a function of voltage was measured on a few diodes before and after irradiation. In addition, the current-voltage characteristics for each diode were monitored periodically during irradiation.

EXPERIMENT DESIGN AND PROCEDURES

The silicon voltage-regulator diode selected for this test is the 1N3995A. The 1N3995A is a 4.7-volt, ±5-percent, 10-watt Zener diode, which maintains voltage regulation by internal field emission. The nominal electrical characteristics of 1N3995A are presented in table I. The diode is a square silicon chip approximately 2 millimeters on a side, and it contains an alloyed P^+N junction. The diodes are mounted in hermetically sealed metal and glass cases with the stud being the cathode.

TABLE I. - ELECTRICAL CHARACTERISTICS OF 1N3995A AT 30° C

Zener test current, I_{zt}, mA	530
Nominal Zener voltage at I_{zt}, V	4.7
Zener impedance at I_{zt}, ohms.	1.2
Zener impedance at 1.0 mA	500
Maximum Zener dc current, A	1.94
Maximum reverse current at 1.0 V, μA	50

Twenty-five 1N3995A diodes, selected at random, were irradiated in the HB-6 beam port of the NASA Plum Brook Reactor Facility (see ref. 3 for a detailed description of the HB-6 facility). The diodes were mounted on a circular, water-cooled, aluminum plate 38.1 centimeters in diameter and 0.635 centimeter thick, which was positioned perpendicular to the reactor beam. The stud temperature of each diode was monitored by a Chromel-Alumel thermocouple. The installation of a diode on the test plate and the arrangement of the diodes on the plate are shown in figure 1. Diode code numbers correspond to plate position. The remainder of the plate was occupied by the diodes discussed in reference 2.

The diodes were irradiated for four reactor cycles, each consisting nominally of 10 days at a reactor power of 60 megawatts. The fast neutron (above 0.1 MeV) fluence for the four cycles was 8.2×10^{13} neutrons per square centimeter, and the gamma dose was 6.3×10^7 rads-carbon. The foregoing neutron fluence and gamma dose are defined for the center of the HB-6 beam port (see fig. 1). References 4 and 5 discuss the neutron and gamma ray flux mapping of the HB-6 facility.

The diodes were electrically energized during irradiation. The irradiation facility and equipment location are shown in figure 2. The effects of electrical operation on radiation damage were determined by dividing the devices into three different operating modes, as shown in table II. During irradiation, the stud temperature of the diodes in groups A and C was approximately 65° C and that in group B was approximately 50° C. The dc biases of 50 percent of maximum Zener current and 50 percent of maximum

(a) Diode mounting.

(b) Diode positions on test plate, looking along reactor beam.
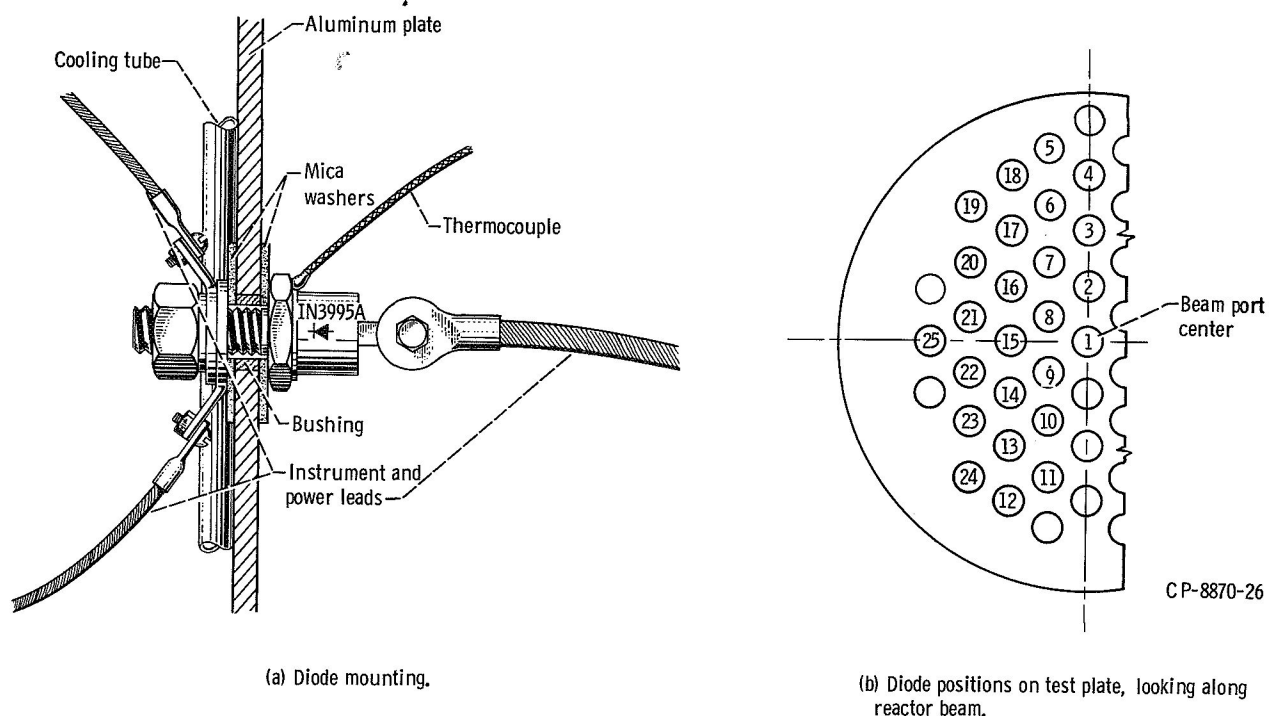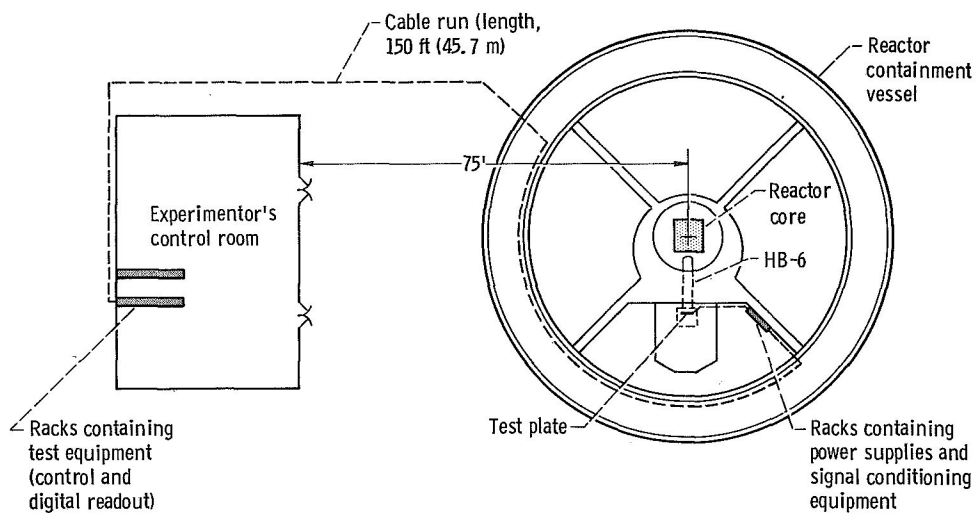
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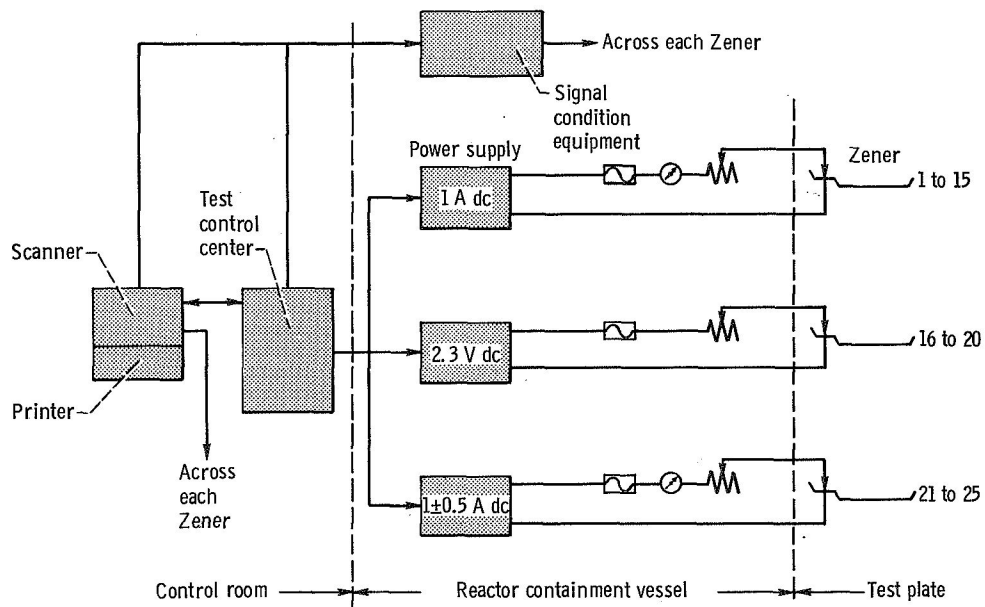
Figure 1. - Irradiation assembly.

Zener voltage were obtained from conventional current-regulated and voltage-regulated power supplies, respectively. Modulated dc bias was obtained from 60-hertz ac and RC filters adjusted to a maximum voltage and ripple output to give the required bias.

Periodically during the course of irradiation, the system was manually switched from powered (normal) operation, and the electrical characteristics listed in table III were automatically printed out for each of the Zeners. The power supplies and signal conditioning equipment were located in the reactor containment vessel. The control system and the digital readout were located outside the containment vessel.

The current-voltage characteristics and the junction capacitance at zero bias were measured on each diode before and after irradiation. In addition, the variation of junction capacitance with applied bias was determined for a few diodes. All pre- and post-irradiation measurements were made at room temperature (27° C). Repeatability of these measurements was generally better than 1 percent, except in the case of leakage current measurements below 10^{-6} ampere, where variations of 5 to 10 percent were typical depending on the current range. The reverse-leakage current was measured at 14 preselected voltage points from 5.0 millivolts to 2.5 volts. The Zener voltage was measured at 19 current points from 0.1 milliampere to 1.5 amperes. The forward current was measured at 14 voltage points from 5.0 to 550 millivolts. The forward voltage drop was measured at 23 current points from 0.1 milliampere to 5.0 amperes. Junction

4

(a) General layout.

(b) Zener test.

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Figure 2. - Facility and instrumentation locations.

TABLE II. - DIODE OPERATING CONDITIONS

DURING IRRADIATION

Diode number	Group	Operating condition
1 to 15	A	1.0-Ampere dc bias at 50 percent maximum Zener current
16 to 20	B	2.3-Volt dc bias at 50 percent nominal Zener voltage
21 to 25	C	1.0±0.5-Ampere modulated dc bias at 50±25 percent maximum Zener current

TABLE III. - ELECTRICAL CHARACTERISTICS

MONITORED DURING IRRADIATION

Monitored characteristic	Test condition
Reverse-leakage current	0.5 V 2.0 V
Zener voltage	0.4 A 1.0 A 2.0 A
Forward current	0.4 V
Forward voltage	1.0 A 2.0 A

capacitance was measured by using a variable-frequency capacitance bridge at an ac signal of 20 millivolts peak to peak at 10 kilohertz. The variation of capacitance with applied dc bias was measured at 19 reverse-voltage points from 50 millivolts to 3.0 volts.

RESULTS AND DISCUSSION

Both neutrons and gamma rays produce permanent damage in semiconductor devices. However, the amount of gamma ray-induced damage was not considered significant in this test. The large junction area did not appear to increase radiation sensitivity, and electrical operating mode during irradiation did not affect the amount of damage.

Two basic mechanisms of radiation damage are (1) the introduction of electrically active defects that reduce the net carrier concentrations and (2) the introduction of re-

combination centers that decrease the minority carrier lifetimes and also affect tunnel current.

Carrier Removal

Neutron irradiation introduces electrically active defects in silicon that cause a decrease in the net carrier concentrations. This carrier removal will eventually produce heavily compensated intrinsic material at high neutron doses. Stein (ref. 6) has determined carrier removal rates in silicon under fission spectrum neutron irradiation. The removal rates vary from 3 to 10 carriers per neutron per centimeter. The removal rate remains nearly constant for low initial carrier concentrations but rises sharply for concentrations above 10^{15} carriers per cubic centimeter. There is also a slight dependence of the removal rate on the crystal growth process and the dopant type.

The reference, or Zener, voltage is generally the most important characteristic for these devices. A plot of the Zener voltage as a function of current for the median and the extremes is presented in figure 3. The pre- and postirradiation curves are not distinguishable above about 10 milliamperes. The Zener voltage is maintained in these diodes by a combination of tunneling and avalanche multiplication. Both these processes are very weak functions of the doping level (ref. 7) and should be unaffected by radiation damage as long as the total carrier removal remains small compared with the doping level. The slight softening of the breakdown knee is the result of increased reverse-leakage current, which will be considered later in the following section.

The junction capacitance is somewhat more sensitive to changes in the doping level and was measured on all diodes before and after irradiation. The variation of capacitance
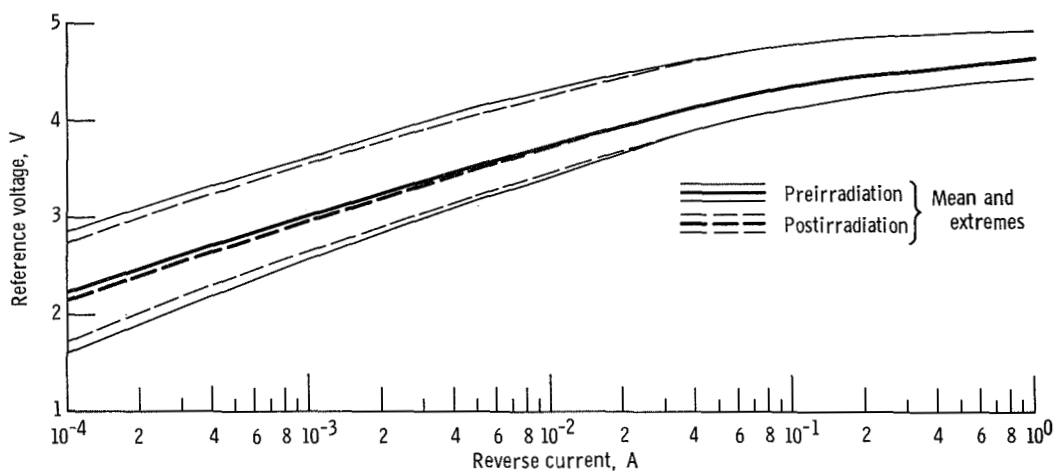

Figure 3. - Reference voltage as function of current for median and extremes (25 diodes) before and after irradiation.
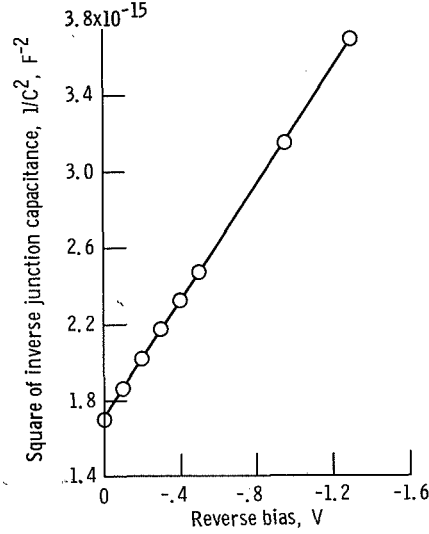
Figure 4. – Square of inverse junction capacitance as function of voltage for typical diode. (Pre- and postirradiation values coincide.)

with applied bias on four diodes was used to identify the junction profile and to estimate the doping levels. Figure 4 is a plot of 1 over the capacitance squared as a function of applied bias for a typical diode; the resulting straight line indicates that the junction is probably abrupt, as would be expected for an alloyed diode. The capacitance of an abrupt junction is given in reference 7 as

$$C = A\left[\frac{-q\epsilon N_D N_A}{2(V_A + V_B)(N_D + N_A)}\right]^{1/2} \tag{1}$$

where A is the junction area, q is the electron charge, ϵ is the permittivity, N_D and N_A are the doping levels in the n and p regions, respectively, V_A is the applied voltage, and V_B is the built-in voltage. The doping level in the n-type base region can be estimated provided that a highly asymmetrical junction is assumed. That is,

$$N_D \ll N_A$$

and

$$\frac{N_D N_A}{N_D + N_A} \approx N_D = \frac{2}{-q\epsilon A^2}(V_A + V_B)C^2 \tag{2}$$

8

The calculated base doping level is $N_D = 5 \times 10^{17}$ cm^{-3}.

The junction capacitance of these diodes (fig. 4) was not affected by radiation damage at the fast neutron fluence of 8.2×10^{13} neutrons per square centimeter. Assuming a conservative carrier removal rate of 10 carriers per neutron per centimeter gives a removed carrier density for this irradiation of 8×10^{14} carriers per cubic centimeter, which is insignificant compared with the doping level just calculated. Therefore, those characteristics that are doping-level dependent, the Zener voltage and junction capacitance, will not affect diode usability in typical nuclear space power applications.

Introduction of Deep Levels

Neutron irradiation introduces recombination centers that result in an increase in the density of levels within the forbidden band gap and a decrease in the carrier lifetimes. An analysis of the reverse-leakage and forward currents was made to identify the sources of these currents and to assess the effects of recombination center introduction on these sources.

Slope calculations indicated that the forward current above about 0.5 volt is dominated by diffusion current, which is a function of the base minority carrier lifetime (see ref. 7). Shown in figure 5 is the medium and high forward current as a function of applied bias for the median and the extremes before and after irradiation. The average increase in diffusion current was by a factor of 2.5, which implies a decrease by a factor of 6 in the base minority carrier (hole) lifetime. Above about 0.8 volt, the pre- and postirradiation characteristics converge and for some diodes cross, as can be seen in figure 5. After irradiation, the current was not dominated by diffusion, but the current sources could not be identified.

The reverse-leakage and low forward bias currents are shown in figures 6 and 7, respectively, for the median and the extremes before and after irradiation. The average change in the currents was an increase by a factor of 7 in the reverse current and an increase by a factor of 9 in the low forward current. These currents do not exhibit the voltage dependence typical of a pure recombination-generation current. Theoretical calculations indicated that these curves could result from a combination of a recombination-generation current and tunneling currents, but analytically separating these current sources was not possible. The radiation-induced increases in total current presumably reflect increases in both current sources. The introduction of additional deep levels by neutron irradiation decreases the carrier lifetimes and produces a proportional increase in recombination-generation current. Two possible sources of tunnel current are (1) transitions between the band edges and (2) transitions between a band edge and a level within the band gap (see refs. 8 and 9). The current contribution from band-to-band tunneling should be quite small for these diodes and would be insensitive to radiation
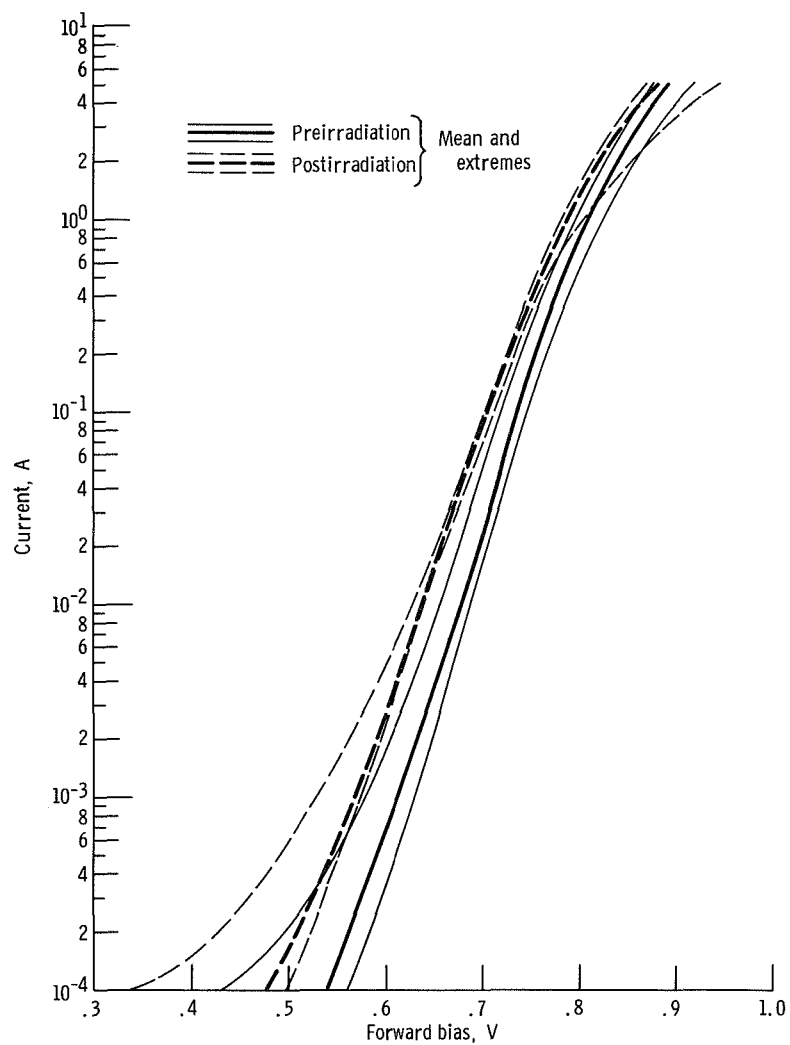
Figure 5. - Medium and high forward current as function of voltage before and after irradiation for median and extremes (25 diodes).
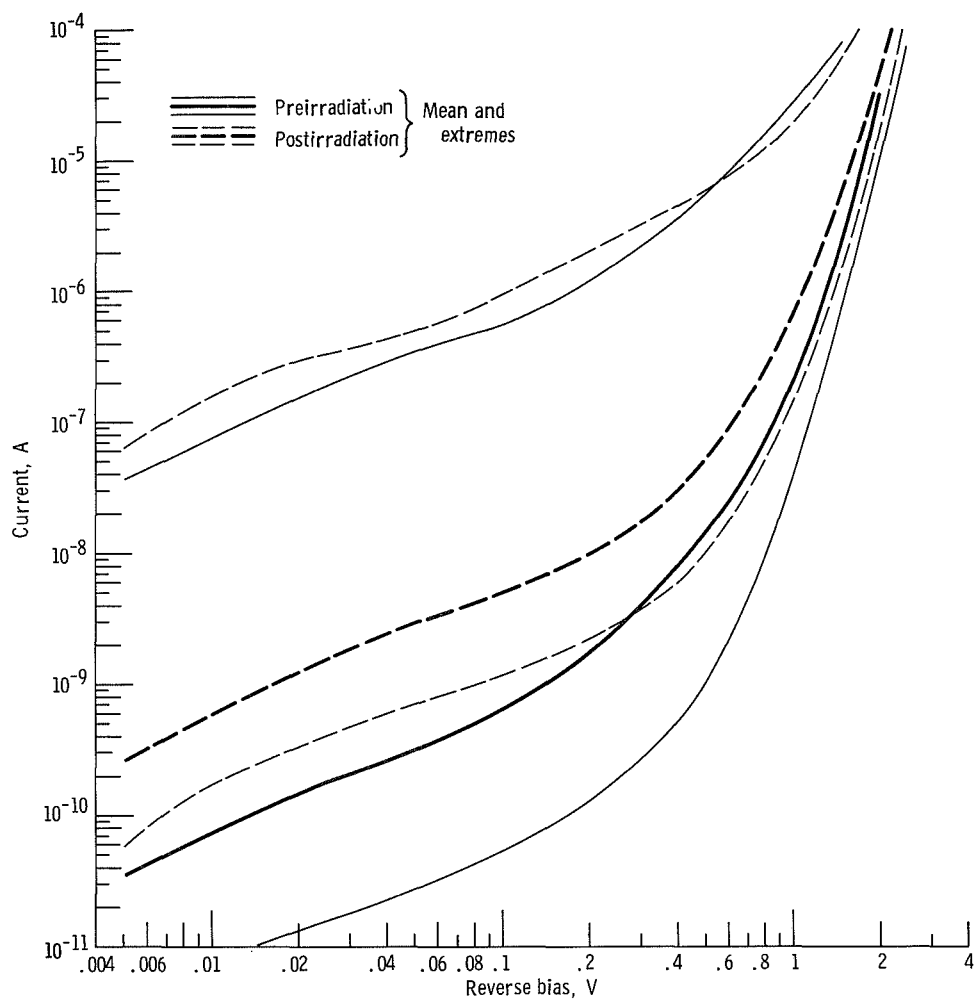
Figure 6. - Reverse current as function of voltage before and after irradiation for median and extremes (25 diodes).
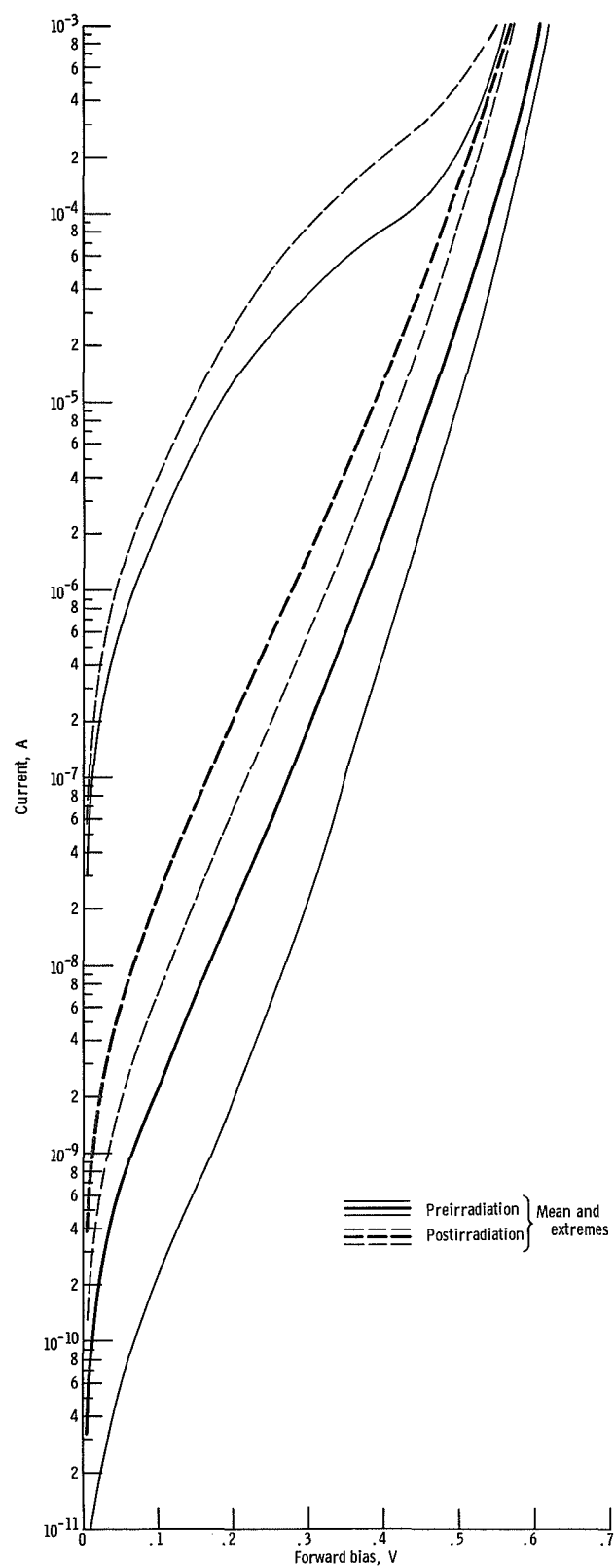
Figure 7. – Low forward current as function of voltage before and after irradiation for median and extremes (25 diodes).

damage at this dose level. However, the level-to-band tunneling is quite sensitive to the introduction of additional band gap levels.

SUMMARY OF RESULTS

Twenty-five voltage regulator (Zener) diodes (IN3995A) were exposed to reactor radiation to a fast neutron fluence of 8.2×10^{13} neutrons per square centimeter and a gamma dose of 6.3×10^{7} rads-carbon. The following results were obtained:

1. The amount of radiation damage was not affected by electrical operating mode during irradiation.

2. The effects of neutron-induced carrier removal were negligible at this dose level; that is, those electrical characteristics that depend only on carrier concentration (Zener voltage and junction capacitance) were not affected.

3. The increase in the density of energy levels within the forbidden band gap due to radiation damage was the source of all observed changes in electrical characteristics.

    a. The low forward bias and reverse-leakage current showed increases by a factor of 9 and 7, respectively. These increases result from decreases in the carrier lifetimes and increases in band-to-level tunneling.

    b. The high forward current at biases above about 0.5 volt showed an increase by an average factor of 2.5 as a result of a six-fold decrease in the base minority carrier lifetime.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, September 19, 1969,
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