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EFFECTS OF 22-MeV PROTONS ON SINGLE JUNCTION AND SILICON CONTROLLED RECTIFIERS

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16. Abstract

The effects of 22-MeV protons on various types of silicon single junction and silicon controlled rectifiers were investigated. The results show that low-leakage devices and silicon controlled rectifiers are the most susceptible to radiation damage. There are also differences noted between single junction rectifiers of the same type made by different manufacturers, which emphasizes the need for better selection of devices used in spacecraft.

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EFFECTS OF 22-MeV PROTONS ON SINGLE JUNCTION AND SILICON CONTROLLED RECTIFIERS

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SUMMARY

The effects of 22-MeV protons on various types of single junction and silicon controlled rectifiers useful for space applications are presented. The reverse leakage current was the device parameter chosen for determining the damage induced in the single junction silicon rectifiers by the protons. In addition to the reverse leakage increase, silicon controlled rectifiers (p-n-p-n) were tested for changes in forward leakage, breakover voltage, gate voltage, gate current, and holding current.

The devices found to be the most susceptible to proton irradiation were the low-leakage rectifier and silicon controlled rectifier. The low-leakage devices exhibited increases in reverse leakage current of up to 10 000 percent for a 22-MeV proton fluence of 5×10^{11} protons/cm^2. The silicon controlled rectifier exhibited somewhat less increase in reverse leakage current (up to 2000 percent), but it is a much more complicated device and showed large changes in several other critical parameters, notably the forward leakage current and breakover voltage.

It was noted that in several types of single junction rectifiers, similar devices fabricated by different manufacturers reacted quite differently under irradiation. These differences were not quite so noticeable in silicon controlled rectifiers.

INTRODUCTION

Silicon single junction (p-n) and silicon controlled rectifiers (p-n-p-n) will be used in future space missions which will require that these devices operate for years without failure. Since the operation time in space will be lengthy, the particulate radiation that these devices will receive from the Van Allen belt and solar flares could be extensive. Much attention has been given in the past several years to the effects of particulate radiation on integrated circuits, transistors, and solar cells (refs. 1 to 4). As a result of this effort, large increases in radiation tolerance have been achieved either through device improvement, recommended trade-offs of less sensitive devices for more sensitive ones, or proper shielding. Some of the devices that were considered less critical, such as rectifiers, could now possibly become sensitive parts of an electronic system in a radiation environment (especially for very long missions). Also, more sophisticated and critical rectifiers have been developed (e.g., low-leakage, power, and silicon controlled rectifiers) which could be very sensitive to a space radiation environment. Silicon controlled rectifiers are especially useful in high current switching circuits, and their response to ionizing radiation could be critical.

The small number of radiation-damage studies that have been carried out for rectifiers have involved the use of neutrons as the bombarding particle (refs. 5, 6, and 7), and the types of devices tested have been limited. Since it is also desirable to know the effects that high-energy protons have on single junction and silicon controlled rectifiers, tests were performed by using the 22-MeV cyclotron at the Oak Ridge National Laboratory, Oak Ridge, Tennessee.

The test parameter for the p-n rectifiers was the increase in reverse leakage current. For the silicon controlled rectifiers the parameters tested included the reverse leakage current, forward leakage current, gate current, gate voltage, holding current, and breakover voltage. The results of changes in these parameters due to irradiation with the 22-MeV protons are presented in this report.

SYMBOLS

I rectifier current, A

I_A anode current, A

I_B base current, $I_{B,1} + I_{B,2}$, A

I_c collector current, $I_{c,1} + I_{c,2}$, A

I_{co} collector-base reverse saturation current, $I_{co,1} + I_{co,2}$, A

I_F forward current, A

I_{gf} gate current, A

I_h holding current, A

I_k cathode current, A

I_R reverse leakage current, A

I_S	saturation or forward leakage current, A
$I_{S,o}$	initial saturation current, A
k	Boltzmann's constant
q	electronic charge
T	temperature, ^{o}C
V	voltage, volts
V_{BO}	breakover voltage, volts
V_F	forward voltage, volts
V_{gf}	gate voltage, volts
V_R	reverse voltage, volts
α	common base transistor current gain, $\alpha_1 + \alpha_2$
τ	minority-carrier lifetime, sec
ϕ	proton influence, protons/cm^2

THEORY

Single Junction Rectifiers

Most rectifiers in use today have an abrupt single p-n junction. (See ref. 8.) Various fabrication techniques (including variances in the amount and type of impurities) are employed for rectifiers, depending on the particular applications of the devices. The various device applications classify the rectifiers, for example, low leakage, power, regulator, computer, stabistor, and zener.

Ideally, all abrupt single junction rectifiers exhibit the characteristics shown in figure 1 and obey the equation

$$I = I_S\left(e^{qV_j/kT} - 1\right) \tag{1}$$

where

V_j rectifier junction voltage

I_s magnitude of saturation current when rectifier is reverse biased

The saturation current I_s for a p-n junction can be represented by the equation

$$I_s = qA\left[P_n \frac{D_p^{1/2}}{\tau_p} + N_p \frac{D_n}{\tau_n}\right]^{1/2} \tag{2}$$

where

A junction area

D_n diffusion constant of electrons in p-type semiconductor

D_p diffusion constant of holes in n-type semiconductor

N_p minority-carrier density (electrons)

P_n minority-carrier density (holes)

τ_n minority-carrier lifetime of electrons in p-type material

τ_p minority-carrier lifetime of holes in n-type material

The junction voltage is represented by

$$V_j = V_a - V_{b,n} - V_{b,p} \tag{3}$$

or

$$V_j = V_a - \frac{IW_n}{A\sigma_n} - \frac{IW_p}{A\sigma_p} \tag{4}$$

where

V_a voltage applied

$V_{b,n}$ potential drop across n-region

$V_{b,p}$ potential drop across p-region

W_n width of n-region

W_p width of p-region

σ_n conductivity of n-region

σ_p conductivity of p-region

The forward current I_F depends exponentially on forward voltage V_F. For very large I_F, the single junction rectifier behaves like a small resistor connected in series with a battery. Most rectifiers are used for blocking a current (e.g., in power or switching applications) or for converting ac to dc. In these applications, it is desirable to keep the reverse leakage current I_R to a minimum. Even small increases in I_R from radiation effects can be critical to the successful operation of a space-vehicle electronic system.

According to p-n junction theory, when a reverse bias is applied, it is required that minority-carrier densities be depressed below the equilibrium values in the neutral region. Holes will diffuse from the neutral n-type material to the junction. This diffusion will cause an increase in the hole density at the junction edge. This total concentration will be greater than the holes required by the junction bias and a hole flow from right to left through the transition region is generated which gives rise to I_R.

Radiation Effects on Single Junction Rectifiers

Particulate radiation can affect single junction rectifiers in the following manner (ref. 5):

1. Radiation can produce recombination centers which reduce minority-carrier lifetime τ (ref. 9). The reduction in τ can be represented empirically by

$$\frac{1}{\tau} = \frac{1}{\tau_o} + K\phi \tag{5}$$

where

τ_o minority-carrier lifetime before irradiation

τ minority-carrier lifetime after irradiation

ϕ radiation particle fluence

K damage constant

The damage constant K depends on the type of material, temperature, radiation particle fluence, and particle energy.

2. Radiation can produce defects which act as trapping centers that remove carriers from the conduction process.

3. Radiation can produce defects which act as additional scattering centers and decrease carrier mobility.

At fluences less than 10^{13} protons/cm^2, most of the radiation damage in rectifiers is in the form of a reduction in τ (ref. 9). Sah, Noyce, and Shockley (ref. 10) have shown that the generation rate of carriers in the space charge region of the junction and, therefore, the leakage current are inversely proportional to τ. The saturation current I_S varies approximately as τ^{-n} $\left(\text{where } \frac{1}{2} \leqq n \leqq 1\right)$. As τ decreases, I_S increases (see eq. (2)) and results in a corresponding increase in I_R (from eq. (1)).

At $\phi > 10^{13}$ protons/cm^2 the removal of carriers from the conduction process becomes the dominant factor and the conductivity σ of equation (4) decreases, with a resulting increase in V_b. This results in a reduction of V_j of equation (3).

During the operating life of most space vehicles, the radiation fluence experienced will be $\phi < 10^{13}$ protons/cm^2; therefore, the change in I_R was chosen as the damage parameter for the single-junction-rectifier experiments since it reflects changes in the minority-carrier lifetime τ.

Silicon Controlled Rectifiers

The silicon controlled rectifier (SCR) is a four-layer switching device (p-n-p-n arrangement of doped layers) with three terminals shown in figure 2(a). (See ref. 11.) There are three p-n junctions, J_1, J_2, and J_3, in series. Figure 2(b) shows the accepted standard symbol for a silicon controlled rectifier. Figure 2(c) gives the basic current-voltage characteristics for a typical SCR. From region 0 to 1 the SCR is in the "off" state and has a very high impedance. From region 2 to 3 the SCR is in the "on" state where the maximum forward blocking voltage is exceeded. This voltage is the breakover voltage V_{BO} measured with the gate circuit open. The SCR will remain "on" as long as the anode-to-cathode current exceeds a value known as the holding current I_h. Region 1 to 2 is known as the negative resistance region, 0 to 4 is the reverse blocking state, and 4 to 5 is the reverse breakdown or avalanche region which occurs when the maximum reverse voltage V_R is exceeded.

The operation of the silicon controlled rectifier depends on minority-carrier injection, efficient transport of carriers across the base, and collection of carriers at a collector junction. Unlike a transistor, the SCR has both a hole emitter and an electron emitter at the ends of the device. This means that the SCR collector or J_2 (fig. 2(a)) collects both electrons and holes. The SCR, then, is essentially a p-n-p and an n-p-n transistor with a common collector junction (fig. 3). The p-n-p section has a gain of α_1 whereas the n-p-n has a corresponding gain of α_2. When combined, the total current flow is essentially a sum of the individual transistor currents. The junction current will consist of a hole current from the p-type end material, an electron current from the n-type end region, and leakage current.

The equation for the SCR current is obtained as follows:

According to standard transistor terminology the collector current of the p-n-p transistor is

$$I_{c,1} = \alpha_1 I_A + I_{co,1} \tag{6}$$

since

$$I_{B,1} = I_A - I_{c,1} \tag{7}$$

$$I_{B,1} = (1 - \alpha_1)I_A - I_{co,1}$$

The collector current of the n-p-n transistor is

$$I_{c,2} = \alpha_2 I_k + I_{co,2} \tag{8}$$

$$I_{B,1} = I_{c,2}$$

Therefore,

$$(1 - \alpha_1)I_A - I_{co,1} = \alpha_2 I_k + I_{co,2} \tag{9}$$

$$I_k = I_A + I_{gf}$$

Therefore,

$$I_A = \frac{\alpha_2 I_{gf} + I_{co,1} + I_{co,2}}{1 - (\alpha_1 + \alpha_2)} \tag{10}$$

$$= \frac{\alpha_2 I_{gf} + I_{co}}{1 - (\alpha_1 + \alpha_2)} \tag{11}$$

When $(\alpha_1 + \alpha_2)$ is kept small, I_A is also small and the SCR is in the "off" condition. When $(\alpha_1 + \alpha_2)$ approaches unity, a small increase in I_{gf} will cause I_A to become very large and the SCR switches from the low-conduction state to the high-conduction state. The SCR is then said to be in the "on" state. When the SCR fires or switches on, it behaves as an ordinary rectifier. Controlled rectifiers may be used in series or parallel and are bistable, making them readily applicable to signal and power switching.

Radiation Effects on Silicon Controlled Rectifiers

Silicon controlled rectifiers were expected to be more sensitive to radiation-produced defects than single junction rectifiers, since their operation depends on the efficient transport and collection of minority carriers across base regions analogous to transistors. Again, the important effect to consider is reduction of τ (ref. 3) which will cause an increase in the SCR's triggering level and reverse leakage current. This will lead to larger breakover voltages and changes in gate characteristics. After firing, the device behaves as an ordinary rectifier; hence the radiation-damage effects discussed for the single junction rectifier also apply for the SCR.

APPARATUS AND PROCEDURE

The devices tested are listed in table I and were chosen from the electronic parts lists of various satellites. At least five of each type were tested and the results were averaged. Several of the devices tested included samples from more than one manufacturer in order to determine variations due to differences in quality control and manufacturing techniques. The devices are grouped into two classes – single junction rectifiers and silicon controlled rectifiers (three junction) – for the discussion of test procedure and results.

Single Junction Rectifiers

The single junction rectifiers tested included medium-power, high-power, low-leakage, computer, zener, forward regulator, and stabistor types. The reverse leakage current was the parameter chosen to observe the effects of proton radiation in these devices.

In order to obtain a range of operating conditions, the reverse leakage current was measured on a Dynatron diode tester at various bias voltages depending on the device under investigation. Since a junction rectifier will break down if V_R becomes too large, care was taken to keep the bias-voltage range below the maximum rating established by the manufacturers. A thermocouple system was used to ensure that the temperature of the rectifiers was maintained at $28^{\circ} \pm 2^{\circ}$ C throughout the tests.

The irradiation experiments were performed by using the 22-MeV cyclotron at the Oak Ridge National Laboratory. Since most of the rectifiers were protected by their cases with the equivalent of at least 254 μm (10 mils) of copper shielding, calculations from proton range-energy curves for copper showed that 22-MeV protons were the lowest proton energy readily available that could penetrate the case and produce significant damage in the semiconductor material. For these experiments a test chamber was used which holds 12 samples (fig. 4). The samples, which were mounted on connectors and extended to the center of the beam window, were connected through a rotary commutator to remote electronic instrumentation. The wheel is provided with heat sinks, a sample locator, and a Faraday cup. Figure 5 shows the test chamber connected to the proton beam pipe.

The proton fluence striking the rectifier was monitored with an ion chamber using air as the gas. The output of the ion chamber was calibrated by the results of several iron-foil activation analysis measurements. The desired flux of 10^9 protons/sec was determined by measuring the current from a metal gate which could completely stop the proton beam. The current induced in the gate was proportional to the proton flux. By using the gate, measurements of electrical properties before, after, and at selected points during irradiation could be made. When the charge collected in the ion chamber indicated that the sample had been exposed to the desired fluence, the gate was closed. After sufficient time had elapsed for any transient effects to disappear, the electrical properties were measured at the various bias voltages. The gate was then opened and proton irradiation continued. This cycle was repeated until the measurements had been made at all the desired fluence levels. The fluence levels for each type of device were established by irradiating a monitor sample and observing the changes in I_R.

Silicon Controlled Rectifiers

Silicon controlled rectifier types 2N685 and 2N1874 were on the Lunar Orbiter satellite parts list, and important electrical parameters were measured after irradiation with fluences of 1×10^{12} to 5×10^{12} protons/cm^2. These parameters were measured on an Owen Laboratories controlled-rectifier test set and included gate voltage, gate current, forward leakage current, holding current, and breakover voltage. The parameters which were most affected by the radiation were then determined for all the SCR types listed in table I at lower fluence levels. Emphasis was placed on changes in breakover voltage, since a large increase in V_{BO} for neutron irradiation was observed by Leith and Blair (ref. 6). The breakover voltage is the anode-to-cathode voltage at which the SCR fires with the gate open. The same general radiation testing procedure was used in determining proton effects on SCR's as was previously described for single junction rectifiers. The two SCR types (2N1874 and 2N685) are similar in fabrication except for the protective cases. The 2N1874 is a low-current device $(I_F < 10\ A)$ which is shielded by a thin TO-5 case common to many transistors and other devices. The 2N685 is a medium-current device ($I_F < 100$ A) shielded by a heavy 1.4-cm (9/16-inch) cover which is used in devices required to handle high currents. (See fig. 6 .) The 1.4-cm (9/16-inch) case affords greater protection to the silicon than the thinner TO-5 case as can be seen by comparing the results for these two SCR types.

EXPERIMENTAL RESULTS

Single Junction Rectifiers

The increase in reverse leakage current for several proton fluences is given in table II for the single junction rectifiers which were appreciably damaged. The discussion of radiation effects on each major type of rectifier begins with the more sensitive devices and ends with the least sensitive.

Low-leakage rectifier.- Several 1N645 low-leakage rectifiers were tested. Those chosen for the tests had an initial reverse leakage current of 0.10 nA at 50 V. The initial conditions varied greatly in 1N645 rectifiers fabricated by different manufacturers. Therefore, a large number of devices were tested in order to obtain samples with similar initial conditions.

The importance of manufacturer selection is seen from the results of the radiation tests plotted in figure 7. This figure shows a plot of the percent increase in I_R as a function of proton fluence for the average reaction of a 1N645 rectifier to 22-MeV proton irradiation for selected bias voltages. In the figure, results are also compared for devices from two manufacturers. It is easily seen that manufacturer A's devices are much more severely affected by radiation than manufacturer B's. In fact, the increase in I_R is about twice as much for manufacturer A as it is for manufacturer B at lower bias voltages. Another interesting manufacturer difference which concerns I_R response to changes in bias voltage is shown in this figure. As the bias voltage increases, I_R also increases for the manufacturer B devices at a proportional rate which is analogous to radiation response of many other types of silicon devices (transistors, etc.). However, as the bias voltage increases in manufacturer A's devices, the I_R does not increase proportionally; in fact, it decreases. The explanation for this effect and the overall differences between the two manufacturers must lie in manufacturing techniques. It is well known that charged particle radiation alters the electronic properties of silicon surfaces by charge buildup in the silicon dioxide (SiO_2) passivation layer and by change in the energy distribution of surface states at the silicon-SiO_2 interface (ref. 12). The result of these processes is the formation of inversion layers (e.g., an n-type surface layer on p-type bulk material) which may account for the anomalous behavior at reverse biases.

Figure 7 shows that a very small fluence of protons can result in large changes in the reverse leakage current of the low-leakage rectifiers. At the relatively small fluence of 5×10^9 protons/cm^2, the reverse leakage increase varied from 40 percent to 200 percent, depending on manufacturer and applied bias voltage.

Radiation effects in low-leakage devices are extremely important, since it is possible to have leakage current increases in the thousands of percent for fluence levels less than 10^{12} protons/cm^2. It would be desirable to exclude low-leakage rectifiers from circuits which will be subjected to a radiation environment.

Stabistor rectifier.- Radiation effects in these devices can be characterized by results with the 1N4156 rectifier. The 1N4156 is a special zener type used in temperature-control circuits and so forth. Since there was very little voltage dependence of I_R for the stabistor, the test results are simply listed in table II as average percent increases for three fluence levels. As can be seen, up to 5×10^{10} protons/cm^2 produces an average increase in I_R of 100 percent or less. However, at 5×10^{11} protons/cm^2 the I_R increase is about 450 percent. This is a fairly large increase and could cause malfunctions in temperature-control circuits on long space missions.

Medium-power rectifiers.- The effects of radiation on medium-power rectifiers can be characterized by results obtained with the 1N540 rectifier. These devices have much thicker cases than low-leakage and stabistor rectifiers and are expected to be less affected by radiation due to shielding provided by the metal cases. The results of the radiation-damage tests on the 1N540 are shown in table II and figure 8. The increases in I_R are not nearly so large as they are in low-leakage devices (approximately $1\frac{1}{2}$ orders of magnitude less), but they are still quite significant. Again, the differences between manufacturers is pointed out. Manufacturer B's devices are about a factor of 10 more sensitive to radiation than manufacturer C's devices. Quality control for space use of this rectifier type is also a necessity. In addition, there is a dependence on bias voltage for radiation-induced increases in I_R, but it is small for voltages between 200 V and 400 V.

High-power rectifiers.- High-power rectifiers can be typified by the 1N1204 and 1N2158 devices. Results of tests on these devices are given in table II. The I_R increases are not extremely large in these devices, with the largest increase being 100 percent at $\phi = 5 \times 10^{11}$ protons/cm^2 for the 1N1204 rectifier (at fluences greater than 5×10^9 protons/cm^2 the I_R produced by the radiation in the 1N1204 device is larger by a factor of about 1.5 than the I_R produced in the 1N2158 device). This difference is explained by the fact that the 1N2158 is designed to handle high currents (up to 30 A) and, as a result, has a very thick (S-2 type) case. The 1N2104 is designed for lower currents (15 A maximum) and has a thinner (S-1 type) case. The S-2 case affords about twice the shielding that the S-1 case does, and the radiation-effects characteristics demonstrate the value of the increased shielding. Here again, there would be little concern for these devices except for very critical operations or very large radiation exposures. Bias dependence of I_R increases was negligible.

Zener, forward regulator, and computer rectifiers.- These types of rectifiers are represented by the 1N1770, 1N746, 1N816, 1N754A, FCT 1135, and 1N916 devices and are listed in table I. No I_R increases of more than 10 to 15 percent were observed for any of these devices for fluences up to $\phi = 10^{12}$. It is assumed, therefore, that these devices will be of no concern when designing "radiation hard" circuits for space use and, in fact, their use instead of more sensitive types of rectifiers is advisable where possible.

Silicon Controlled Rectifiers

The results of irradiation of the two monitor SCR types are shown in table III for fluences of 1×10^{12} and 5×10^{12} protons/cm^2. Compared with the 2N685 SCR, the 2N1874 SCR experienced increases in I_S, I_R, and V_{BO} which were higher by factors of approximately 3, 6, and 3, respectively, at $\phi = 5 \times 10^{12}$ protons/cm^2.

From the results in table III, I_S, I_R, and V_{BO} were selected as the parameters to observe for the rest of the SCR types to be tested in a radiation environment. The holding current increased by only 10 percent in both types listed in table III at the fluence of 5×10^{12} protons/cm^2 and thus can be neglected. The I_{gf} and V_{gf} appear to have sizable increases that might affect the firing of the device in circuit operation, but this increase occurs mainly between $\phi = 1 \times 10^{12}$ and 5×10^{12} protons/cm^2. A quick test at $\phi = 5 \times 10^{11}$ protons/cm^2 indicated less than 10 percent increase in I_{gf} and V_{gf} in these devices; therefore, measurements of this parameter in the tests were eliminated.

The irradiation test results for the SCR's listed on table I are discussed in terms of the changes in I_R, I_S, and V_{BO}.

Reverse leakage current I_R.- The reverse leakage current is an important parameter for all rectifiers, including SCR's. Large increases in I_R were noted for the SCR's tested; however, the responses to various fluence levels were as much as an order of magnitude apart, as can be seen in figure 9. The actual values of I_R are plotted here because the initial I_R of all the SCR's was zero as far as the test apparatus was concerned. In all the types tested, the I_R was less than 50 μA after irradiation with $\phi = 10^{11}$ protons/cm^2. From this point, however, I_R increased rapidly for the 2N2323 and C6A devices (to over 300 μA at $\phi = 6 \times 10^{11}$ protons/cm^2). For the TI 145A0, 2N1874, and 2N1881, I_R did not approach 300 μA until they had been irradiated with $\phi = 1 \times 10^{12}$ to 2×10^{12} protons/cm^2. The 2N685 and 2N3005 SCR's did not approach this value until a fluence of about 10^{13} protons/cm^2 was reached. As is shown later, the increase in V_{BO} follows the same trend in terms of device response to irradiation. This is to be expected since decreases in τ are controlling both parameters. (See ref. 3.)

The I_R increase is quite large for all the SCR's, with the 2N2323 and C6A having the largest increase and 2N3005 and 2N685 being about an order of magnitude less susceptible. Of course, the critical increase in I_R for a particular SCR depends on its function in a particular circuit and its tolerance levels.

Forward leakage current I_S.- Another important parameter of SCR's is the dc forward saturation or leakage current I_S which is measured before device firing with the gate open. The results of 22-MeV proton irradiation on I_S are shown in figure 10. Again the actual values are plotted since the $I_{S,o}$ was for all practical purposes zero. This figure is a plot of forward leakage current as a function of proton fluence for a constant forward bias of 200 V. Although I_S is not as important to device operation and can be larger than I_R without critical effects, there were still excessive increases in I_S for increasing proton fluences in all the SCR's except possibly the TI 145A0. However, these increases did not begin to occur until $\phi \approx 10^{12}$ protons/cm^2. At this point, I_S varied from about 60 μA for TI 145A0 to about 200 μA for 2N1874. At a higher fluence, I_S increases fairly rapidly until a fluence of about 3×10^{12} to 5×10^{12} protons/cm^2 where the I_S increases level off. However, the actual effect the I_S increase will have depends on the circuit using the SCR. As shown in figure 10, there is quite a difference in I_S increases, depending on device type. For example, 2N685 ranks about fourth in terms of I_S increases due to irradiation, but it is the "best" in terms of I_R increases. Conversely, TI 145A0 is the "best" in terms of I_S increases but one of the "worst" in terms of I_R increases.

Breakover voltage V_{BO}.- One of the most critical parameters sensitive to proton irradiation was the breakover voltage V_{BO}. Since most uses of SCR's on a satellite will involve fluences of 10^{12} protons/cm^2 or less, the devices were checked for V_{BO} changes for fluences between 10^{11} and 10^{12} protons/cm^2. Most of the SCR's fall in the same general range, V_{BO} = 300 to 500 V, with 2N2323 and C6A being in the 700 to 900 V range. A plot depicting the results of proton irradiation on V_{BO} is shown in figure 11. As can be seen from the figure, V_{BO} increased as the proton fluence increased. Leith and Blair (ref. 6) also noticed an increase in V_{BO} for several SCR's irradiated with neutrons. They explained the increase as the result of a decrease in α. From figure 11, at $\phi = 10^{11}$ protons/cm^2 the 2N3005 and 2N685 SCR's show only a negligible increase in V_{BO}. The increase in V_{BO} for 2N2323, C6A, and 2N1874 is about 20, 40, and 50 percent, respectively. At $\phi = 10^{12}$ protons/cm^2 the TI 145A0, 2N2323, and 2N685 show V_{BO} increases of approximately 20, 25, and 30 percent, respectively, whereas the 2N1874, 2N3005, C6A, and 2N1881 are fairly close together in the range from 60 to 80 percent. For fluences above 10^{12} protons/cm^2 refer to table III for typical SCR response shown for 2N1874 and 2N685.

As the fluence increases, there is a point where $(\alpha_1 + \alpha_2)$ becomes very small, and the device fails completely. Since the 2N1874 showed the most damage, it was tested at higher fluences to see where this breakdown would occur. The test showed that it occurred somewhere between 1.5×10^{12} and 5×10^{12} protons/cm^2. This breakdown seemed to occur shortly after a 100-percent increase in V_{BO} was experienced. At the other extreme, one of the SCR's least sensitive to radiation, TI 145A0, did not display any breakdown until $\phi \approx 10^{13}$ protons/cm^2. This was an order of magnitude less sensitive than the 2N1874 device. Of course, these fluences are extremely large and the devices have no shielding other than their encapsulating case. Both of these SCR types had TO-5 cases; this case is one of the least protective from a radiation-damage point of view as was pointed out in the description of the rectifiers.

The radiation sensitivity of SCR's and single junction rectifiers is shown in table IV, in which the average percent increase in the reverse leakage current for a fluence of 5×10^{11} protons/cm^2 is listed.

CONCLUDING REMARKS

Results of an investigation to determine the effects of 22-MeV protons on single junction and silicon controlled rectifiers have been presented. The following remarks and general conclusions are based on these results.

Single Junction Rectifiers

By using the reverse-leakage increase as the criterion for radiation damage from 22-MeV protons, the tests showed that the low-leakage, stabistor, and power rectifiers are damaged, possibly to a serious degree, by proton irradiation below fluences of 10^{12} protons/cm^2. The zener, forward regulator, and computer rectifiers show no appreciable damage. Of the types critically affected the low-leakage rectifier is most seriously damaged by irradiation and should be excluded from satellite electronic circuits where possible.

If low-leakage devices must be used, one way of insuring predictable radiation response is to irradiate large batches of devices from several manufacturers and record their leakage characteristics. The best devices are selected from those tested and annealed at a high temperature (300° C) until the reverse leakage current returns to normal or near normal. The annealing will not greatly affect the radiation response previously observed and will result in devices with a predictable radiation response (RCA Review, June 1967, pp. 208-240).

For space missions of 1 year or less, there would probably be no significant effects of radiation on medium-power rectifiers. For missions which will stay in the Van Allen belt or are multiyear missions significant effects in electronic operation could occur and shielding would be advisable. For example, a fluence of 10^{12} protons/cm^2 is easily obtainable in multiyear missions and could produce increases in reverse leakage current of 500 percent or more in the most sensitive 1N540 types.

It was noted also that there was a wide variation in the parameters of the same type of device fabricated by different manufacturers. This was true not only initially but also during irradiation and points out the need for better quality control and selection of critical semiconductor rectifiers.

If the use of a more susceptible device is required, or if it is suspected that large fluence levels will be encountered, shielding should be incorporated and ground tests on the device to be used should be performed that will approximate actual space conditions.

Silicon Controlled Rectifiers

From the types of silicon controlled rectifiers (SCR's) which were used to survey the effects of large doses of radiation, it was determined that for a fluence of below 10^{12} protons/cm^2 the critical parameters of SCR's for proton irradiation were the reverse and forward leakage currents and the breakover voltage. Also, large increases were noted in the gate current and voltage, but they were for fluences of 10^{12} protons/cm^2 and greater. The holding current was affected very little by irradiation. At a fluence of 10^{12} protons/cm^2, there were large increases in the reverse leakage current for all the devices tested. The increase in breakover voltage followed the same pattern as the reverse leakage with increases of up to 75 percent for several types and 20 percent for TI 145A0 at a fluence of 10^{12} protons/cm^2. The survey SCR's showed breakover voltage increases in the hundreds of percent for fluences above 10^{12} protons/cm^2.

The forward leakage current increased by large amounts for the SCR's, but the type that showed the largest reverse-leakage-current increase showed the smallest forward-leakage-current increase. Considering all the parameter responses of SCR's to proton irradiation, it is believed that use of this type of device may be very sensitive to circuit operation for fluences greater than 10^{11} protons/cm^2.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 21, 1972.

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TABLE I.- GENERAL DESCRIPTION OF RECTIFIERS USED IN RADIATION EXPERIMENTS WITH 22-MeV PROTONS

Single junction rectifiers:

Type	Purpose
[a] 1N540	Medium power
[b] 1N645	Low leakage
1N746	Zener
1N754A	Zener
1N816	Forward regulator
1N916	Computer
1N1204A	High power
1N1770	Zener
1N2158	High power
1N4156	Stabistor
1N4157	Stabistor
FCT 1135	Zener

Silicon controlled rectifiers:

Type
[b] 2N685
2N1874
2N1881
2N2323
2N3005
TI 145A0
C6A

[a] Manufacturer B and manufacturer C.
[b] Manufacturer A and manufacturer B.

TABLE II.- AVERAGE PERCENT INCREASE IN I_R AT HALF-MAX REVERSE VOLTAGE FOR VARIOUS PROTON FLUENCES FOR RECTIFIERS DISPLAYING SIGNIFICANT RADIATION DAMAGE

Type	V_R, volts (a)	Average percent increase in I_R for ϕ, protons/cm^2, of –		
		5×10^9	5×10^{10}	5×10^{11}
[b] 1N645	150	85	900	10 000
[c] 1N645	150	52	560	830
1N4156	50	10	75	450
[c] 1N540	200	25	75	450
[d] 1N540	200	0	0	25
1N1204	100	25	50	100
1N2158	200	20	35	60

[a] Half-max reverse voltage.
[b] Manufacturer A.
[c] Manufacturer B.
[d] Manufacturer C.

TABLE III.- AVERAGE PERCENT INCREASE IN SCR CHARACTERISTICS FOR VARIOUS PROTON FLUENCES FOR SURVEY SCR's

Type	V, volts	Average percent increase in –						
		ϕ	V_{gf}	I_{gf}	I_s	I_R	I_h	V_{BO}
2N685	400	10^{12}	5	25	≈400	≈250	5	30
(1.4-cm (9/16-in.) case)	400	5×10^{12}	40	70	≈1400	≈1200	10	50
2N1874	100	10^{12}	15	30	≈900	≈400	5	80
(TO-5 case)	100	5×10^{12}	60	300	≈4000	≈7000	10	150

TABLE IV.- RECTIFIERS LISTED IN ORDER OF INCREASING RADIATION RESISTANCE

$[\phi = 5 \times 10^{11}]$

Silicon controlled rectifiers

Type	Average percent increase in I_R	Comments
2N2323	2000	Damage also large due to increase in I_S and V_{BO}. At $\phi > 10^{12}$ protons/cm^2 changes in I_{gf} and V_{gf} become critical. (applies to 2N2323, C6A, TI 145A0)
C6A	2000	
TI 145A0	800	
2N685	400	Thicker case than other types tested.
2N1874	150	
2N1881	150	

Single junction rectifiers

Type	Purpose	Average percent increase in I_R	Comments
1N645	Low leakage	5000 to 10 000	Wide variance between devices from different manufacturers
1N4156	Stabistor	700	
1N4157	Stabistor	700	
1N1204	Power	600	High-voltage devices have larger damage than low-voltage devices with same type of case (see 1N540)
1N2158	Power	600	Damage similar to that for 1N1204
1N540	Medium power	300	
1N1770	Zener	<100	Zener diodes will not be affected by moderate space fluences (10^{12} protons/cm^2 or less) (applies to 1N1770, 1N746, 1N754)
1N746	Zener	<100	
1N754	Zener	<100	
FCT 1135	Zener	0	No noticeable change in I_R (applies to FCT 1135, 1N816, 1N916)
1N816	Forward regulator	0	
1N916	Computer	0	

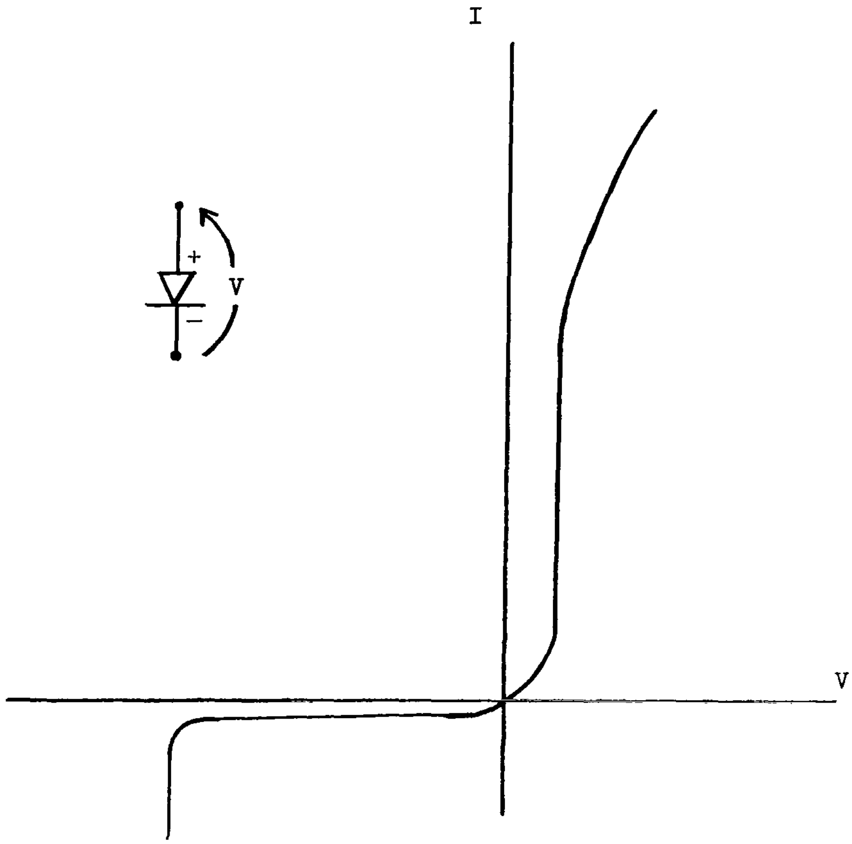
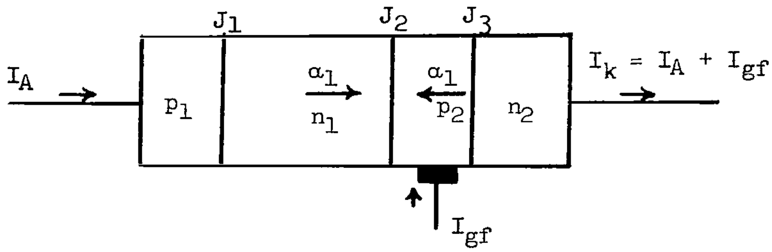
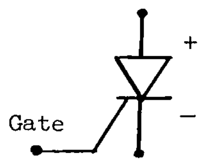


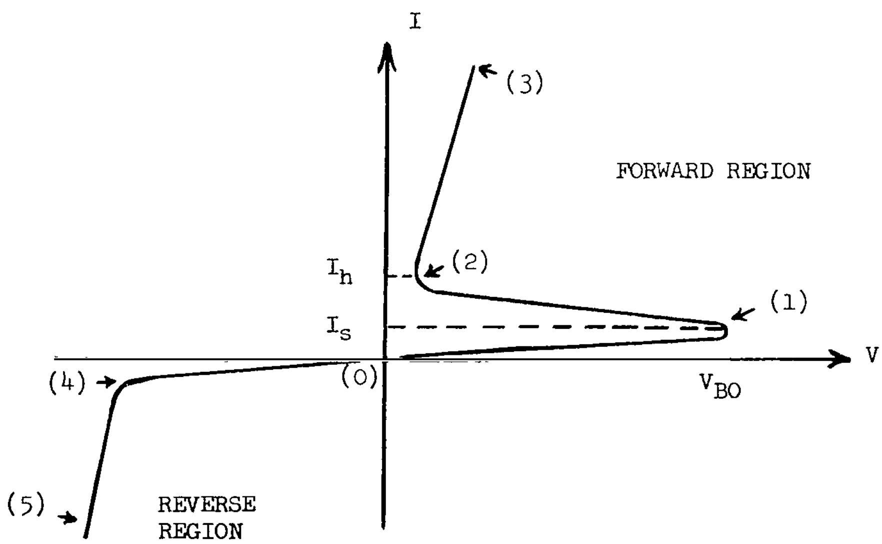
Figure 1.- Current-voltage characteristics of an abrupt single junction rectifier.



(a) Silicon controlled rectifier (SCR).

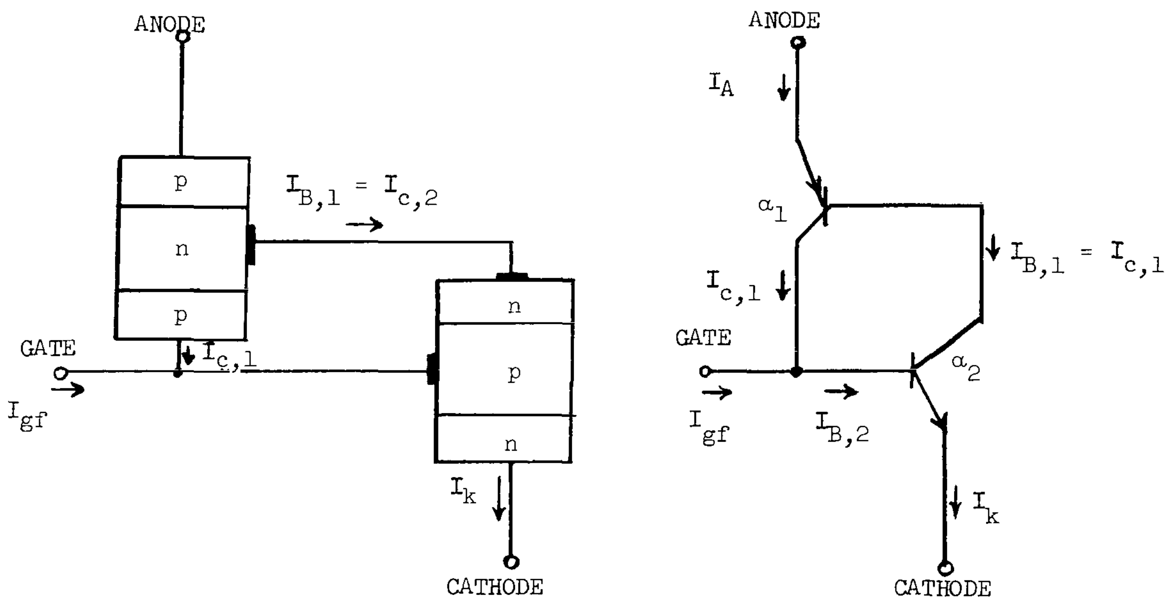


(b) Standard symbol.



(c) Current-voltage characteristics.

Figure 2.- Features of silicon controlled rectifier.



(a) Two-transistor approximation of a three-terminal p-n-p-n device.

(b) Same as (a) with transistor notation.

Figure 3.- Schematic diagrams of p-n-p-n devices.

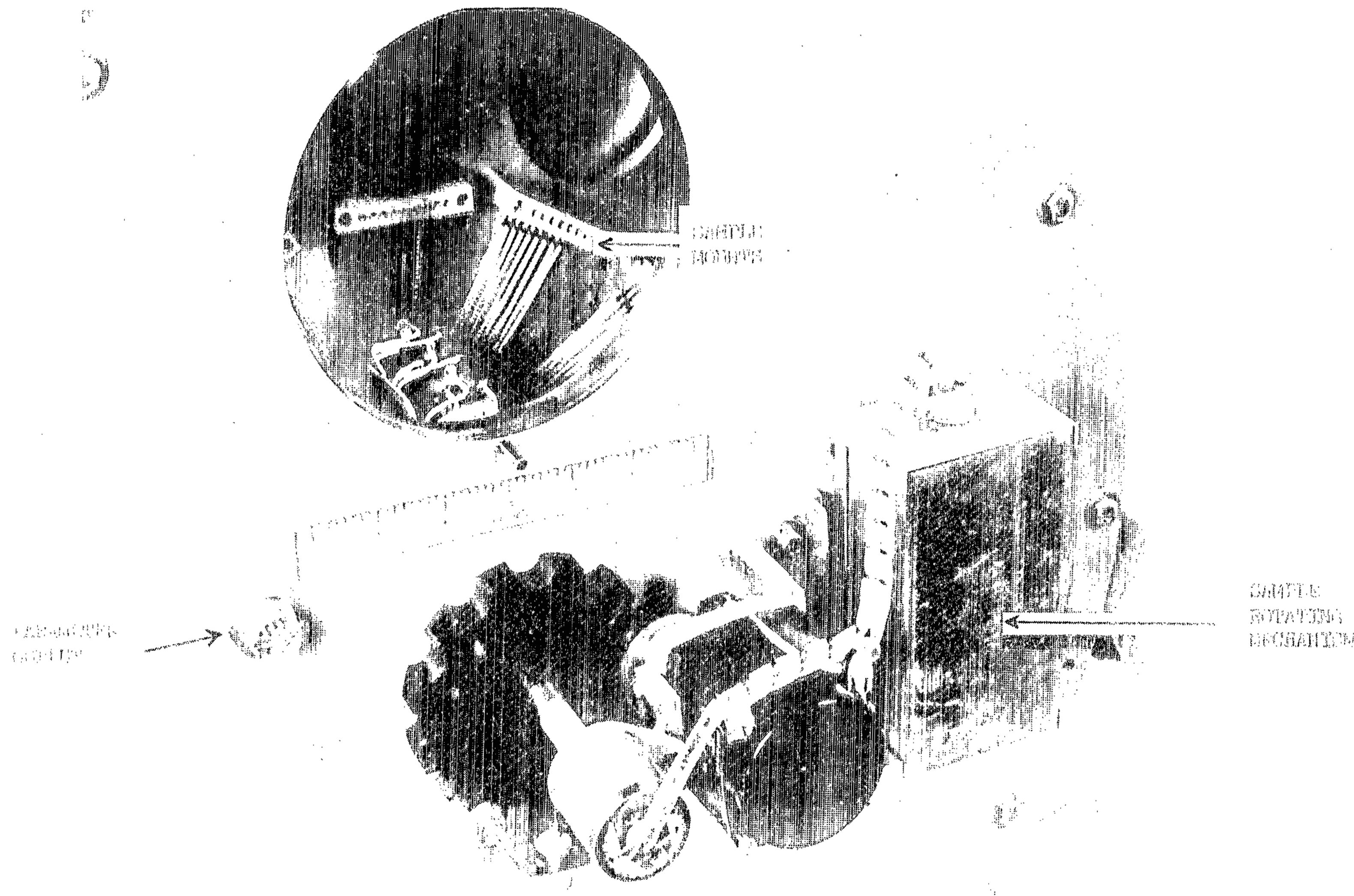


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Figure 4.- Irradiation chamber used for 22-MeV proton tests.

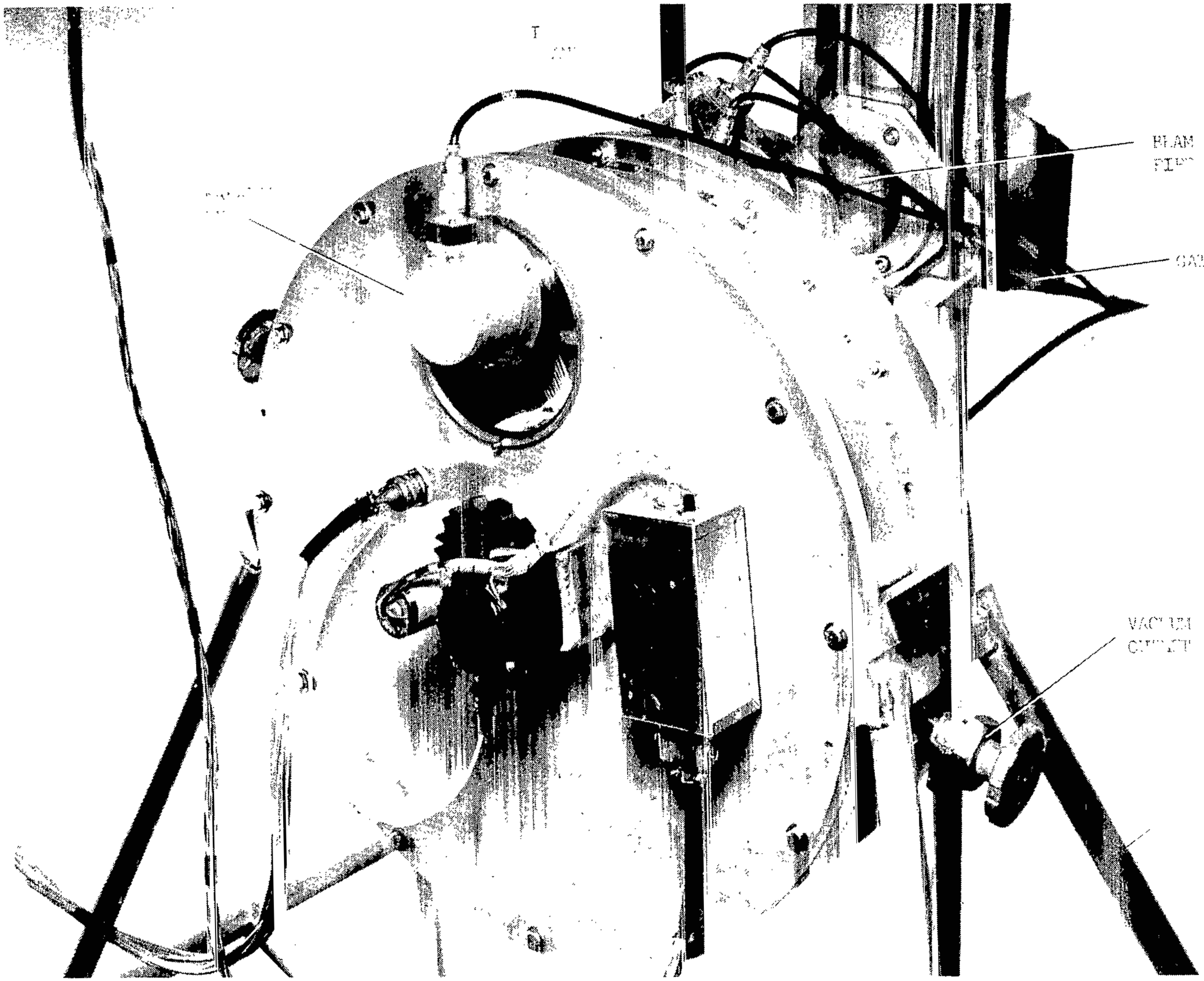

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Figure 5.- Irradiation chamber connected to 22-MeV proton beam pipe.

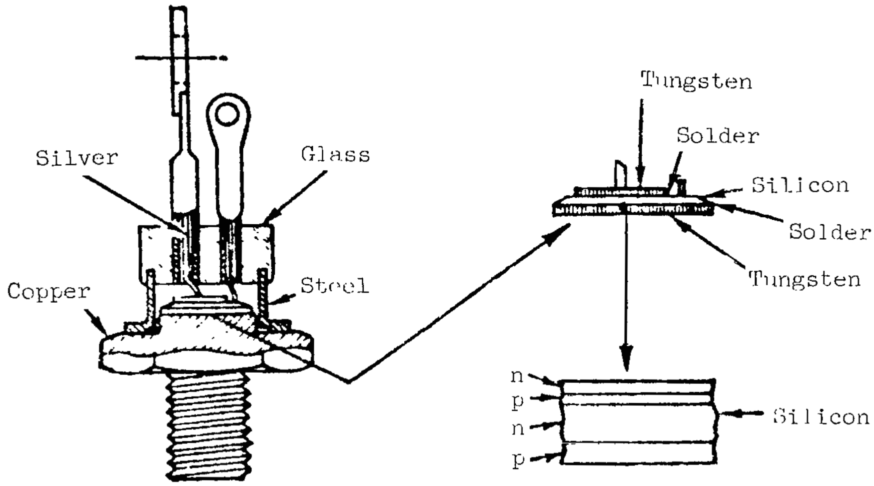

Figure 6.- Cross-sectional view of medium-current SCR.

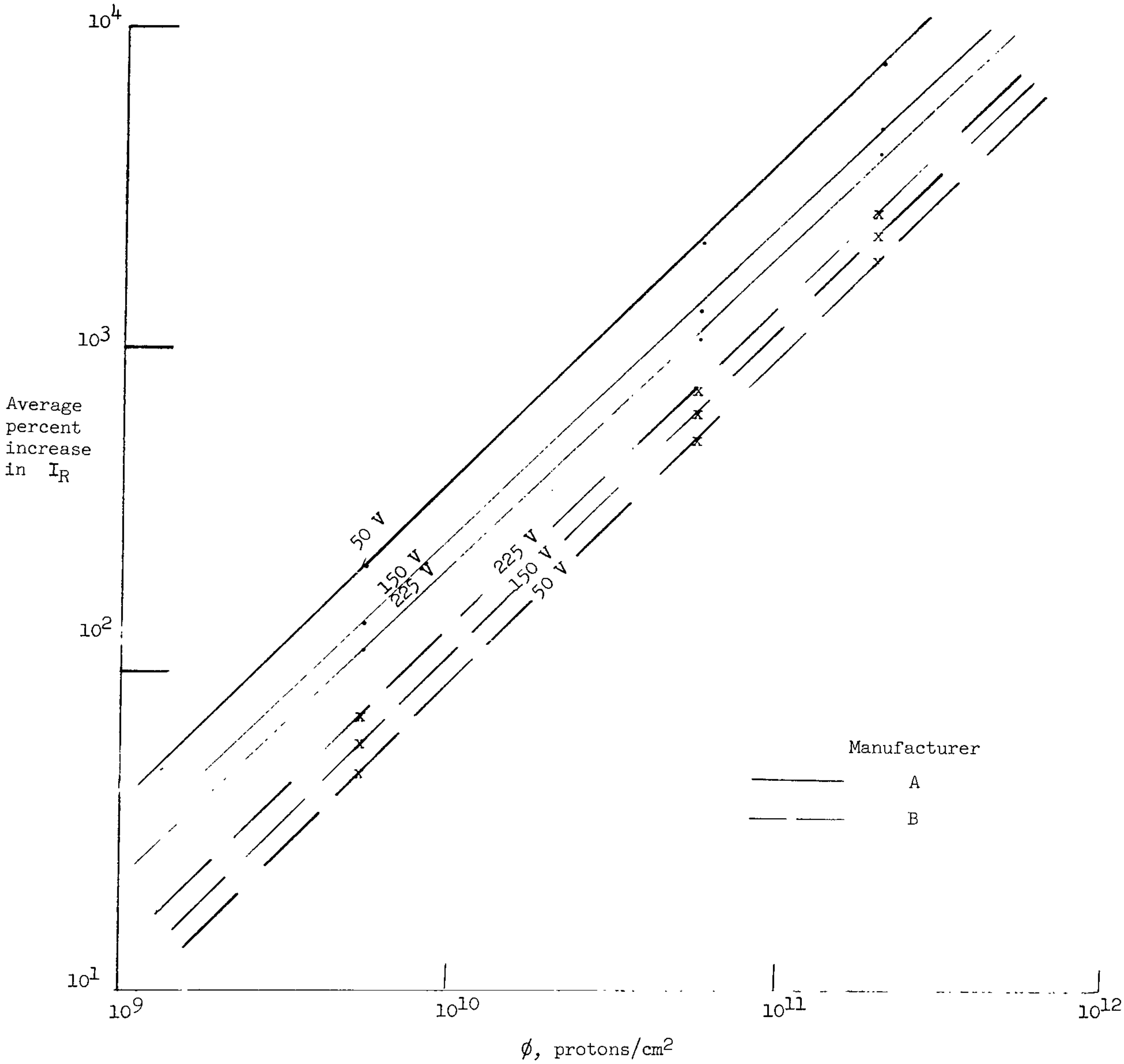

Figure 7.- Effects of 22-MeV protons on I_R of low-leakage rectifier 1N645 for selected bias voltages.

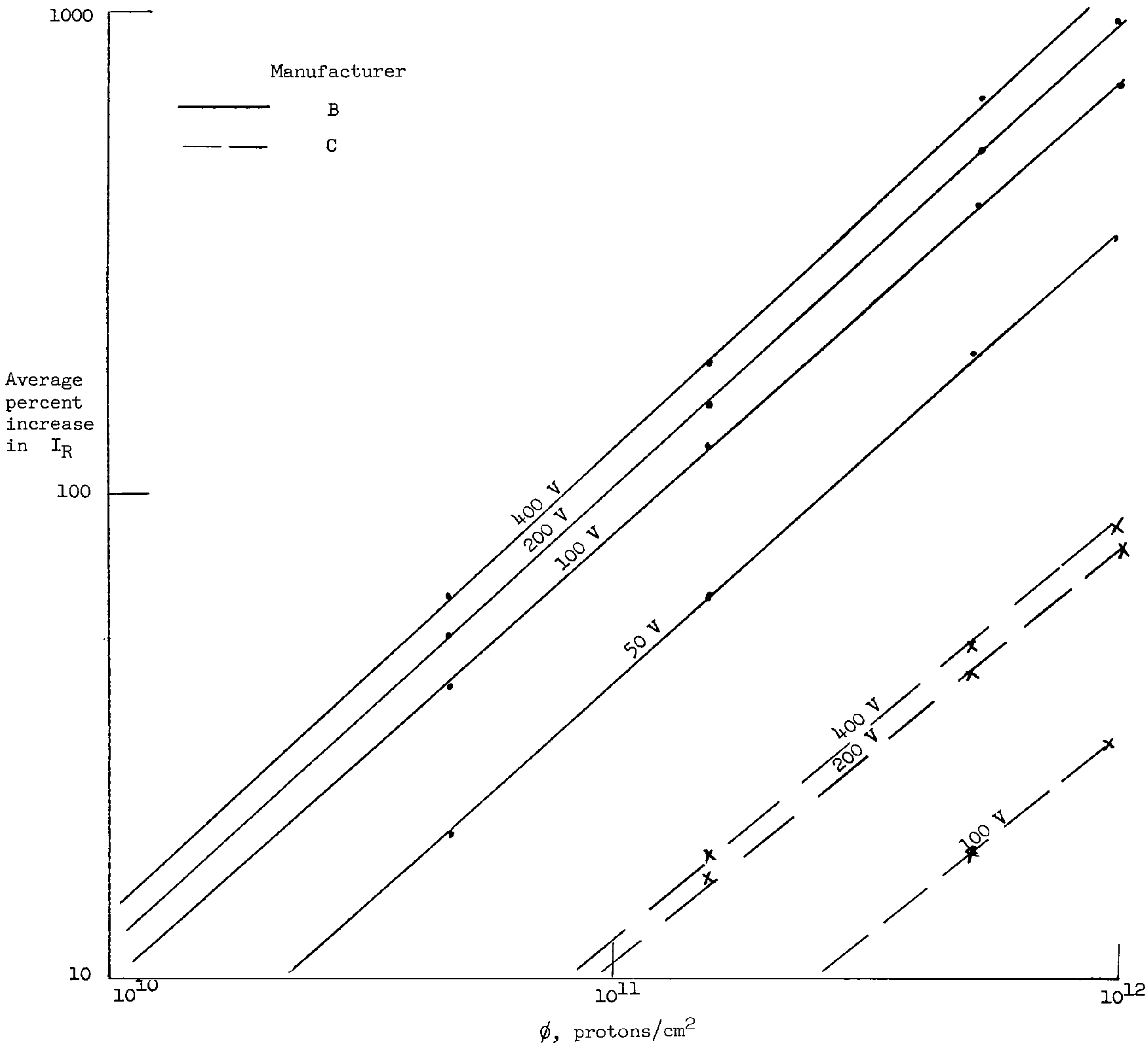

Figure 8.- Effects of 22-MeV protons on I_R for medium-power rectifier 1N540 for selected bias voltages.

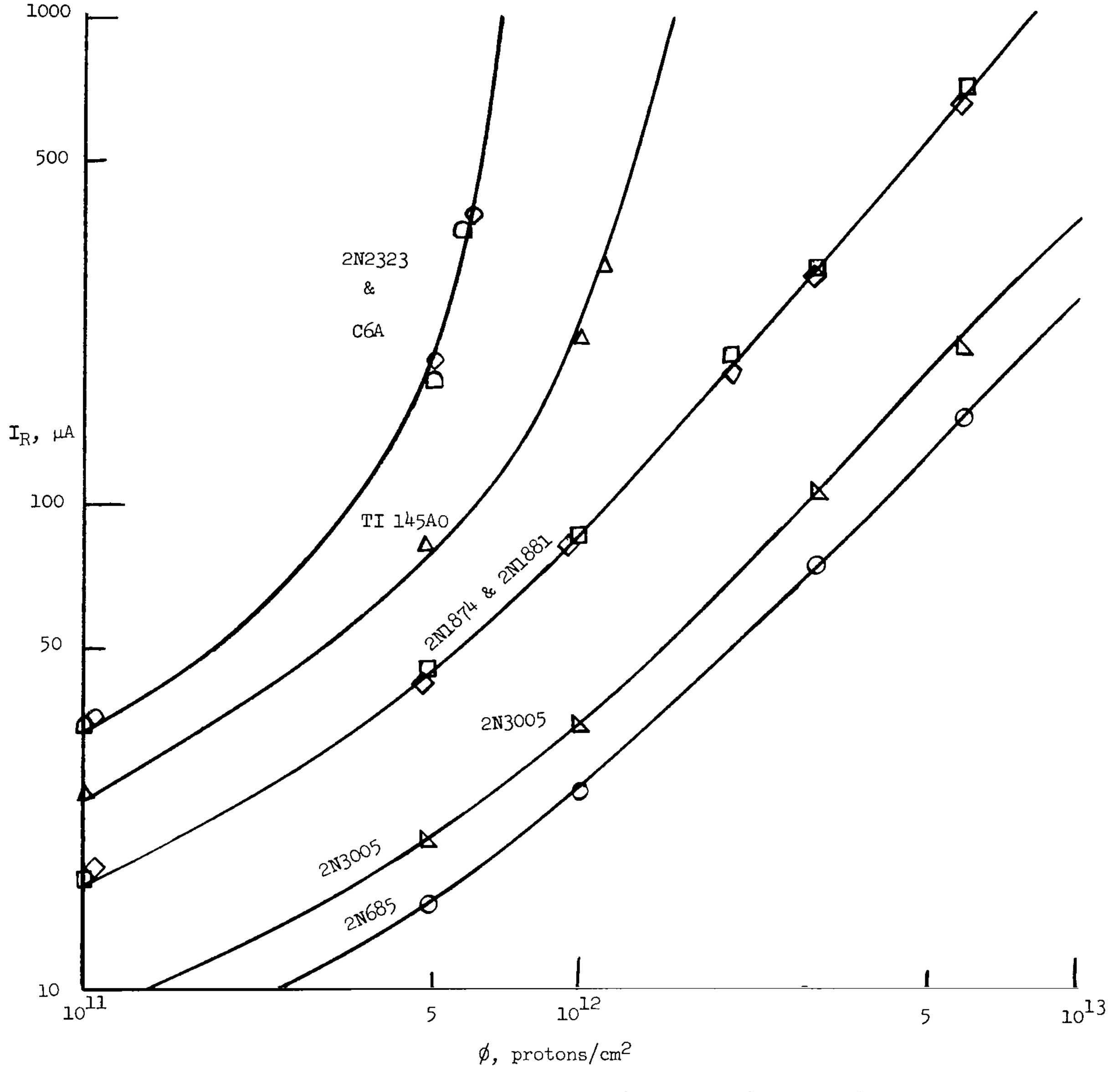

Figure 9.- Reverse leakage current I_R as a function of proton fluence for SCR's. Test voltage, 50 volts.

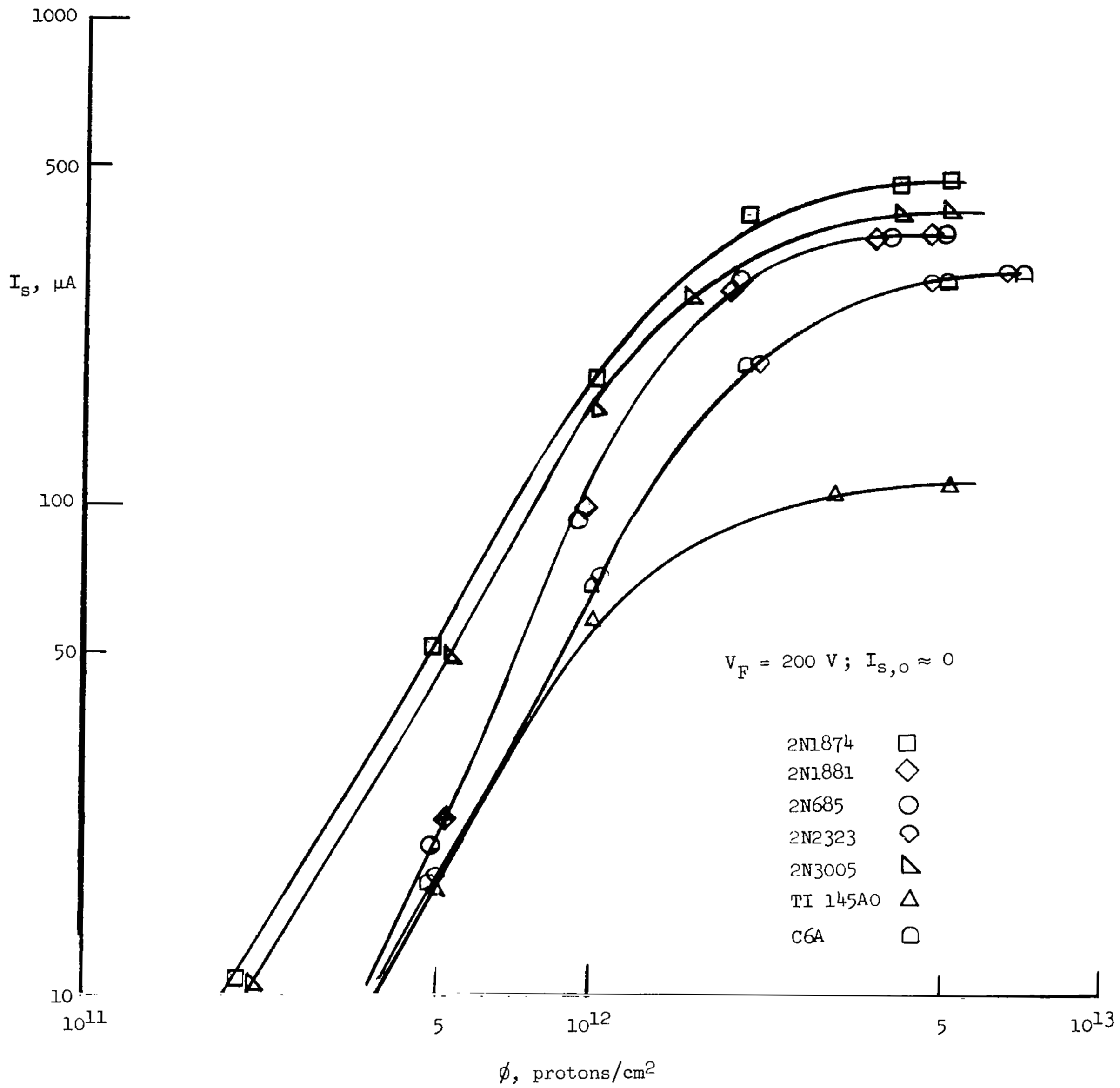

Figure 10.- Forward leakage current I_S as a function of proton fluence.

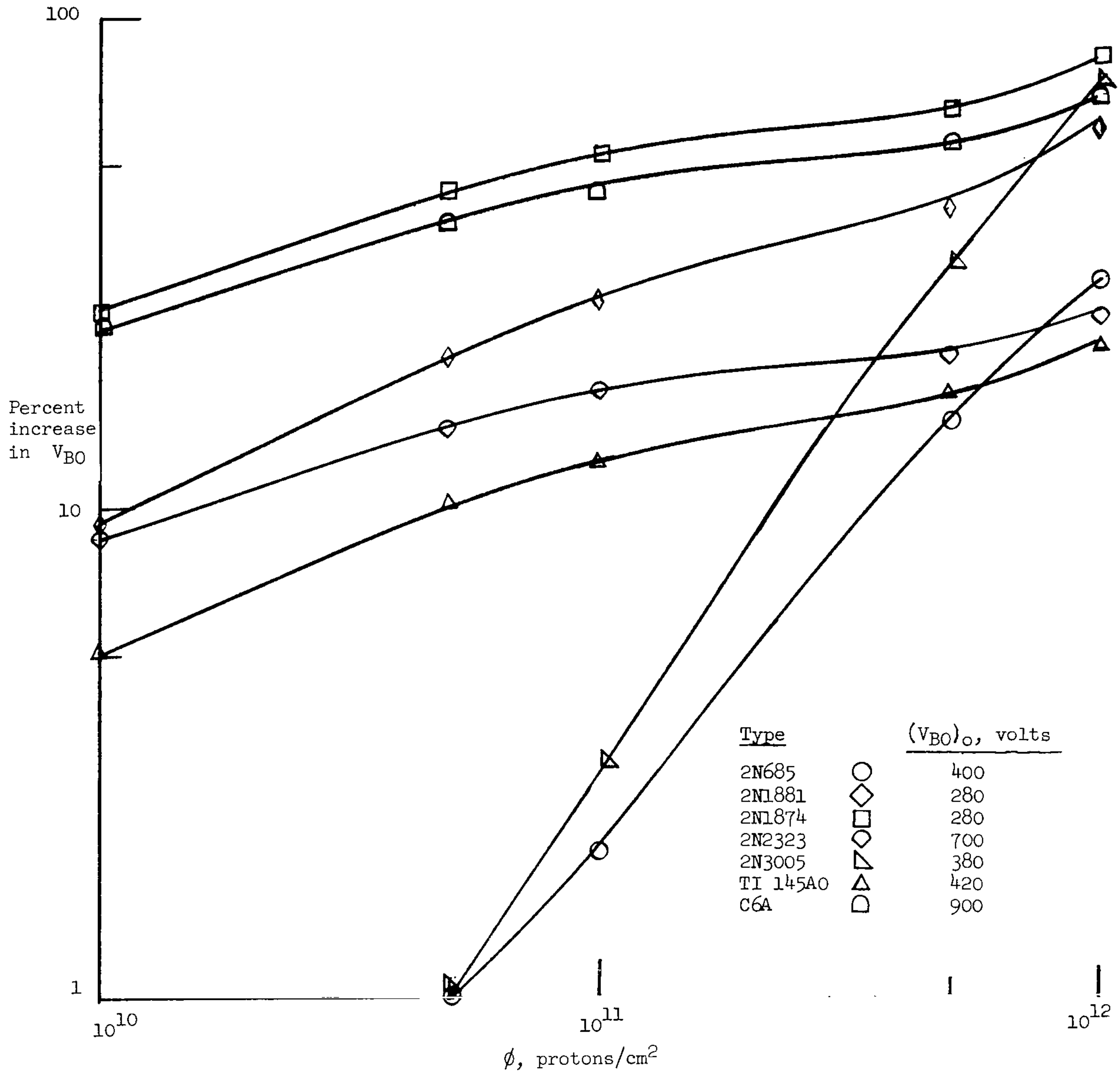

Figure 11.- Percent increase in V_{BO} as a function of 22-MeV proton fluence.

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