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Technical Memorandum

THE EFFECTS OF IONIZING RADIATION ON TRANSISTORS

by D. P. PELETIER

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

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ABSTRACT

An experiment, in which 15 npn bipolar silicon transistors were exposed to Co^{60} gamma radiation, is described. The known theory concerning the radiation damage of transistors is presented. In addition, the distinguishing characteristics of ionizing radiation damage are discussed, and a method of estimating bulk damage is developed.

During the experiment, the following transistor parameters were measured: AC and DC common emitter current gain, collector-to-base leakage current, gain-bandwidth product, and base spreading resistance. The damage curves for leakage current and AC and DC common emitter current gain are plotted and discussed The relation between transistor parameter degradation and bias current is investigated by dividing the transistor into three equal groups and biasing them at three different collector levels during irradiation. The recovery of leakage current is plotted and an exponential curve fitted to the data. Recovery time of current gain is qualitatively observed.

Data indicate that in some transistors damage to leakage current peaks near an accumulated radiation dose of 10^6 rad. The value of this peak is as large as 300 times the final damage value. The recovery time constant of leakage current damage is less than 15 minutes for the transistors tested.

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SECTION I

INTRODUCTION

In addition to the natural radiation belts, seven artificial radiation belts have been created by the explosion of high altitude nuclear bombs since 1958.[1] These belts, both natural and artificial, are large populations of charged particles trapped by the earth's magnetic field. The natural belts consist mostly of energetic electrons and protons, plus small numbers of deuterons, tritons, and possibly some alpha particles and positrons.[1] The artificial belts are composed of electrons, protons, and possibly some of the other particles.[1] An extended exposure in the stronger belts, even with moderate shielding would be lethal to both man and electronics. Consequently, the nature of these belts and the damage they cause is of interest to the experimental and operational satellite programs, as well as to the manned space program.

On July 9, 1962 the United States exploded the high altitude experimental nuclear explosion called Starfish. This explosion plus subsequent similar experiments performed by the U.S.S.R. greatly increased the number of energetic particles in the artificial radiation belts. Telstar I, launched on July 10, 1962, was the fourth orbiting satellite to carry electron detector experiments. One of these satellites operated for only a week after Starfish. Two others produced fruitful data for about one month after Starfish. Telstar operated for three months before it finally died. These satellites all showed excessive solar cell degradation attributable to the increased intensity of trapped radiation. Solar cell degradation was expected but damage began at a much lower accumulated radiation dose than had been predicted by existing theory.

Thus occurred the rather costly discovery of the damage to semiconductors by exposure to ionizing radiation. Prior knowledge of radiation damage was restricted to bulk or lattice damage caused by massive or energetic particles interacting with atomic nuclei. Bulk damage theory had not predicted the large leakage current increases experienced by the solar cells and transistors on the ill-fated satellites.. Dr. E. S. Peck et al[2] proposed a model for ionizing radiation damage based upon their experience with Telstar I. This early model stated that radiation ionized the gas enclosed in the transistor and fringing electric fields drew the ions to the surface near the reverse-biased junction. These ions would act on contaminants at the surface and create an inversion layer causing large leakage currents. Early experiments[3,4,5] endorsed the original ionized gas model. As experiments continued, however, the model seemed incomplete. It was thought that passivation (surface protection) of silicon transistors with an oxide layer would protect them from the harmful ionized gas. Under the influence of ionizing radiation, however, ions now formed at the $Si-SiO_2$ interface and migrated to the junction again causing excessive leakage currents. The understanding of the exact mechanisms of increased leakage current is still incomplete.

Ionizing damage is not a surface phenomenon alone. Radiation-induced trapping centers in the bulk base region and in the transition region, as well as at the surface, contribute independently to increase the base current and thus lower the dc current gain of the transistor.

These mechanisms are also undergoing careful examination.[6,7,8] The base current component from each region is isolated and its radiation sensitivity is evaluated.

Aside from any damage incurred in radiation, there is a photocurrent caused by ionizing radiation which is exactly analogous to that caused by light. Although this current exists only while the transistor is in the radiation field, the errors caused are just as real as if the transistors were damaged permanently.

This report describes the performance of fifteen 2N2222 high frequency silicon npn bipolar transistors which are exposed to gamma radiation. This particular transistor type was chosen as a typical modern, general purpose, high-frequency transistor. The manufacturing procedures employ up-to-date passivation techniques which are reported to reduce susceptibility to radiation damage. The ac and dc current gains and the collector-to-base leakage current are examined closely because of their obvious importance and known susceptibility to ionizing radiation damage. The bulk base resistivity (r_{bb}') and alpha cutoff frequency are also monitored.

SECTION II

BULK DAMAGE

Bulk or lattice damage results primarily from collisions of high energy particles with atomic nuclei of the semiconductor. In these collisions, sufficient energy is transferred to create defects in the bulk of the solid. As a result, certain atoms are displaced from their normal positions in the lattice to form a vacancy and a nearby interstitial as shown in Figure 1. The resulting defect is called a Frenkel pair.

These defects are often highly mobile in the crystal and may recombine to restore the local crystal perfection. Otherwise the defects may become associated with one another or with other chemical or structural imperfections in the crystal. This type of combined center is in general stable at room temperature and constitutes bulk radiation damage. The damage is generally permanent although raising the temperature of the material may partially repair the crystal.[9,10]

Similar effects are produced in all solids. Semiconductor devices, however, require a high degree of lattice perfection and therefore, radiation damage is usually more important than in other solids. Bulk damage causes a decrease in minority carrier lifetime which is significant in determining the current-voltage characteristics of p-n junctions and the current gain of transistors. The relation which describes the effect of radiation on carrier lifetime is:[11,12]

$$\frac{1}{T} = \frac{1}{T_o} + \frac{\phi}{C_1} \qquad \text{(II.1)}$$

where: T = minority carrier lifetime

T_o = initial minority carrier lifetime

C_1 = radiation damage constant of the material

Φ = the integrated radiation flux

For efficient emitter-to-collector transfer, the minority carrier lifetime must be greater than the transit time across the base region. Equation II.1 indicates how minority lifetime, T, decreases with increasing accumulated radiation flux. As T decreases, the base current must increase to make up for the loss of minority carriers. Thus emitter efficiency decreases.

By neglecting emitter efficiency and considering only the degradation of minority carrier lifetime, the approximate relation for the change in common emitter current gain is:[13,14]

$$\frac{1}{h_{FE}} = \frac{1}{h_{FEO}} + \frac{w^2\Phi}{2DC_1} \qquad \text{(II.2)}$$

where: h_{FE} = dc common emitter current gain

h_{FEO} = initial dc common emitter current gain

w = effective base width

D = diffusion constant of minority carriers in the base

Φ and C_1 are defined above

It is significant that w is the "effective" base width and is a function of the quiescent operating conditions of the transistor. Data on effective base width and its voltage and current dependence are not generally available. Effective base width is related to the alpha cutoff frequency, f_α, of a transistor by:[15]

$$f_\alpha = \frac{1.22\ D}{\pi\ W^2} \qquad \text{(II.3)}$$

One may now rewrite Equation II.2 in a more convenient fashion as:

$$\frac{1}{h_{FE}} = \frac{1}{h_{FEO}} + \frac{\Phi K_B}{f_\alpha} \qquad \text{(II.4)}$$

where K_B is the damage constant for a particular transistor. Specifications of transistor alpha cutoff frequency are generally available, and even in cases where this information is not available, it is easily measured at the desired quiescent operating conditions. Thus, one can predict which of a number of transistor types is most radiation resistant (as far as bulk damage is concerned) by knowing K_B and f_α. In this experiment it is desired to estimate how much bulk damage is caused in the transistors. The remaining damage is then attributable to ionizing damage. The discussion which follows is devoted to estimating the bulk damage incurred by the transistors under investigation in this experiment.

Bulk damage is highly dependent upon the type of particle involved. Ionizing damage, on the other hand, requires only a knowledge of the absorbed energy and perhaps the rate of absorption of energy. The problem is to correctly relate absorbed energy to bulk damage. The considerations which follow resolve this problem.

The radiation source in this experiment is Co^{60}. As it decays, the source produces one photon of 1.17 Mev energy and one photon of 1.33 Mev energy over 99% of the time.[16] Knowing the atomic number of silicon (14) and the energy of the gamma radiation, one may assume that the majority of absorbed gamma energy produces Compton electrons[17] (see Figure 2). If one makes the final assumption that the Compton electrons are all approximately 1 Mev, then 100 ergs per gram of absorbed energy produces about 10^7 1 Mev electroms per cm^2. The unit of absorbed energy commonly employed is the Rad (100 ergs/gm). Experimental results[11,18] indicate equivalences of 1.7 x 10^7 1 Mev electrons/cm^2/Rad and 3.2 x 10^7 1 Mev electrons/cm^2/Rad. For the purposes of estimation in this experiment the equivalence,

$$1 \text{ Rad} \cong 2 \times 10^7 \text{ 1 Mev electrons/cm}^2, \qquad \text{(II.5)}$$

is used under the assumptions described above. Table 1 shows an equivalence of damage caused by various energetic particles obtained in a solar cell experiment.[11] The equivalences are applicable to transistors as well.[18]

The damage constant, K_B, is now estimated using known values for similar transistors[19,20,21] and employing Equations II.4 and II.5 and Table 1. Figure 3 shows the bulk damage estimated for the transistors under test.

SECTION III

TRANSIENT DAMAGE

Any charged particle passing through a solid produces ionization through collisions with bound electrons. These collisions excite electrons to the conduction band and leave holes in the valence band producing electron-hole pairs in exact analogy to the production of pairs by light. The excited electrons and holes move through the material in response to electric fields and according to laws of diffusion. The current thus established is called primary photocurrent. The pairs recombine within microseconds and, for all practical purposes, the photocurrent exists only while the transistors are in the radiation environment.

Measurements have shown that the average energy required for electron-hole pair production is 3.6 ev in silicon and 3.0 ev in germanium.[22,23] Thus, the intensity of the ionizing radiation does not have to be large to cause photocurrent. The magnitude of induced photocurrent is directly related to the dose rate. At high intensities transient currents may be equal to or greater than the normal operating currents of the device.

Primary photocurrents occur in both forward and reverse biased junctions. The reverse biased case is now considered for illustrative purposes. If one assumes that a reversed biased junction is irradiated by a short pulse of ionizing radiation which creates electron-hole pairs uniformly throughout the volume, then those carriers located in the junction transition region will be swept across the junction by the existing electric fields and collected within a few nanoseconds. These carriers produce a current which to a good approximation is instantaneous. Carriers produced outside the transition region cause a transient current increase at a slower rate because the minority carriers have to diffuse to the junction before they are swept across by the electric field.

A typical response[24] for a back-biased junction is shown in Figure 4. The ordinate in Figure 4 is highly rate dependent and the abscissa is on the order of microseconds. It should be noted that there is an immediate dropoff after the pulse is completed because of the removal of pairs from the transition region. A decay then occurs which results from the finite time required for the carriers to diffuse to the junction. The current ceases when the last of the induced pairs recombine.

Data was taken at 10^7 Rads to establish the magnitude of the transient current produced by the 5000 Curie (nominal) source used in the latter part of the experiment. The results of these data are shown in Figure 5. The primary photocurrent essentially doubled the transistor leakage current. The gradual decrease of leakage current after $t = 0$ indicates partial recovery from permanent ionizing radiation damage (see Section IV).

SECTION IV

IONIZING DAMAGE

A. Surface Leakage Models

As mentioned in Section I the failure of the four orbiting experimental satellites in 1962 directly after the high intensity nuclear explosion, Starfish, brought the surface effect problem to increased attention. The first significant paper in this area, published by Peck et al,[2] noted that reverse biased devices showed leakage current degradation at much lower accumulated radiation doses than unbiased devices or bulk semiconductor material. They postulated a model to explain the leakage current increase as follows: The gas surrounding the transistor is ionized by radiation. The fringing electric field of the reverse biased junction of an npn transistor separates the electron-ion pairs and causes electron accumulations on the collector side of the junction and positive ion accumulations on the surface of the base (Figure 6). Figure 7 shows an enlarged view of an npn transistor. Accumulated ions induce an electron-rich inversion layer or "channel" on the surface and, in effect, extend the collector region out over the base. The model is the same for pnp transistors if one exchanges the roles of electrons and holes.

Even in such an early investigation, the authors realized that a lack of reproducibility of data among devices of the same type with the same gas filling indicated that an extension of the model was necessary.

It was postulated that the gas ions themselves did not cause the damage but probably exchanged their charge with residual contaminants on the surface. In fact, it was noted that in some cases the chemical surface condition was more important than the magnitude of the fringe field.

This model was checked experimentally[3,25] by bombarding a junction with electrons and ions. The surface damage which resulted confirmed the original gas model. Various techniques which isolated the surface from the surrounding atmosphere appeared to increase the transistor's radiation resistance.

If the above model were complete, SiO_2 passivation would eliminate the leakage problem. Surface passivation does eliminate much of the gas-induced damage. A second damage mechanism, however, partially offsets the protection gained by passivation. Ions form at the SiO_2 surface. Ion accumulation produces an electric field across the passivation layer. The ions furthest from the surface are repelled and migrate thru the oxide. When the silicon surface is reached, the ions form channels as described in the gas model. Since migration must occur, the damage is not evident as quickly as it is with an exposed silicon junction. In addition, damage is relatively permanent and virtually independent of external electric fields.

B. Characteristics of Surface Damage

Irrespective of its origin or cause, surface damage very definitely exhibits certain characteristics. First, and most important, is the fact that surface damage occurs significantly earlier than bulk damage. The effect may become apparent at radiation doses as low as 10^3 Rads, depending upon the type of manufacturing process and the amount of contamination in the crystal. In contrast, the bulk damage for the 2N2222 transistors in this experiment becomes noticeable after 10^7 Rads.

Second, it is difficult to make surface conditions uniform from one semiconductor chip to another. Thus, surface damage varies from one transistor to the next. It has been shown that the damage in transistors of the same JEDEC number may be drastically different between manufacturers and in some cases even between different lots from the same manufacturer.

Third, the transistor bias conditions are important when the gas model is applicable or when the surface passivation is poor. When transistors are properly passivated, damage occurs after charge migration. As indicated previously, quiescent conditions are then relatively unimportant.

Fourth, devices that have suffered surface damage will recover upon removal from the ionizing radiation field. Recovery is accelerated when bias is removed because ions are no longer held by an electric field and can diffuse more freely. Recovery also occurs when devices are in the radiation field without bias.

Fifth, initial studies indicate that degradation of reverse collector current is primarily a function of total radiation dose. Devices, however, recover upon removal from the radiation field. Thus, the observed damage cannot be solely dependent upon total dose. In addition, devices irradiated at a high dose rate will recover when the rate is decreased. Therefore, although the damage is primarily a function of accumulated dose, there is evidence of some dose rate dependence.

Sixth, when the devices have been allowed to recover and then are placed in the radiation field they will degrade almost immediately to the condition that they were in before the radiation field was removed. This characteristic is commonly referred to as "memory".

Seventh, the memory effect discussed above can be erased by baking the device at elevated temperatures for a number of hours. In some cases, such annealing processes virtually restore the transistor to its original condition.

Finally, the leakage current degrades rapidly when exposed to ionizing radiation. After this early rapid increase, the leakage current approaches a constant value. Moreover, transistors from the same manufacturing lot approach very nearly the same constant leakage current.

C. Recombination-Generation Centers and h_{FE} Degradation

The model for I_{CBO} degradation implies that h_{FE} will degrade because of the increased collector-to-base current. Certainly part of the dc gain degradation results from this, since any leakage current must be considered part of the base current. Hence, increased leakage current will degrade the collector-to-base current ratio. One would expect, however, that this effect is only significant at low current levels.

In 1957, Sah, Noyce, and Shockley[26] observed and reported that the measured current-voltage characteristics of certain p-n junctions deviated from the ideal case presented by the diffusion model. They proposed that current resulting from generation and recombination of carriers from traps in the transition region of the p-n junction accounted for the observed deviation. The relative importance of the diffusion current outside the transition region and the recombination current inside the transition region also explained, they claimed, the increase of emitter efficiency (h_{FE}) of silicon transistors as a function of emitter current. Shockley and Reed[27] showed that recombination and generation of electrons and holes in semiconductors may take place at some types of recombination-generation centers or traps. These sites may be crystal lattice dislocations, impurity atoms located interstitially or substitutionally in the crystal lattice, or surface defects. Recombination can also occur directly with emission of light. In 1962, Coppen and Matzen[28] used a dual base technique to distinguish between recombination current which is concentrated at or near the surface periphery of the junction space-charge region and recombination current distributed over the area of the junction (see Figure 8). It is stated that for oxide masked diffused structures, the space-charge region intersects a surface which has a very high impurity density and so may have many mechanical strains or some precipitation of impurities. These effects may give rise to a greater density of recombination centers near the surface periphery than elsewhere in the space-charge region. At least for the diffused types they tested, Coppen and Matzen claimed that the majority of recombination took place at the periphery and not in the space-charge region.

Presently, it would appear that there are four contributions to the base current of a transistor. The first is the normal diffusion current characterized by the equation:

$$I_b = I_{bo}\,[\exp(\frac{qV_{be}}{kt}) - 1] \qquad (IV.1)$$

where:

I_b = the base current

I_{bo} = a constant for a particular transistor

q = the charge of an electron

V_{be} = the base to emitter voltage

k = Boltzmann's constant

T = the absolute temperature

The second contribution is bulk recombination in the transition region. The third is surface recombination in the transition region. The fourth is surface channel current. The ideal diffusion current equation can be modified to accommodate each of these contributions by placing an "n" in the exponential as follows:

$$Ib = I_{bo} [\exp(\frac{qV_{be}}{nkt}) - 1] \qquad (IV.2)$$

Each of these currents may then be characterized by an "n" value. Obviously, n equals one for the ideal or diffusion case. N is approximately 2 and 1.5 for the second and third cases respectively, and n is between 2 and 4 for the surface channel current. All of these investigations used the technique developed by Coppen and Matzen.[28] In 1964 and 1965, Goben[29,30] showed that the neutron bombardment of silicon transistors induced a base current component which arose from the bulk space-charge region as opposed to the surface periphery region.

It is Goben's contention that, at least for neutron damage, the base current component in the bulk space-charge region is predominant. Very recent (December, 1966) investigations[6,7,8] show that ionizing radiation gives rise to independent increases in these current components. A different threshold for each component is observed and degradation contributed by each component is examined independently.

SECTION V

EXPERIMENTAL PROCEDURES

A. Experimental Approach

Fifteen 2N2222 npn silicon bipolar transistors are irradiated with a Cobalt 60 source. In order to complete the experiment in a reasonable time, and yet to obtain data resolution in the lower accumulated dose region, two dose rates are used. The less intense source is nominally 5.2×10^4 Rads per hour and the more intense source is nominally 4.3×10^5 Rads per hour. The assumption is made that ionizing radiation damage is primarily dependent upon dose accumulation as opposed to dose rate (Section IV.A).

The dosimetry is accomplished with the cobalt glass method.[31] The change of transmission of the glass is a direct indication of the accumulated radiation dose that the glass is exposed to. The change of transmission over a measured time period is then a measurement of dose rate. The glass used in this experiment is borosilicate and the transmission is measured at 400 mμ wave length. The absolute accuracy of the dosimetry is approximately ± 20% and the variance is approximately ± 5%. The dosimetry is performed at the transistor sockets. Therefore, any attenuation caused by the surrounding environment and transistor container is accounted for in the dosimetry.

The source consists of cobalt pencils placed in concentric circles within a pool of water. The water shields the user from the source. The canister containing the test specimens is placed directly in the middle of the source. Figure 9 shows the transistors as they would be irradiated from a nominal source. The radiation attenuation is a strong function of distance through the water. Therefore, the intense radiation is essentially perpendicular to the transistor as shown. The actual vertical variation of radiation intensity along the container is shown in Figure 10. Measurements taken around the axis of rotation of the container indicate negligible deviation from the nominal surface value (less than 3%). Nonetheless, as an added precaution, the container is oriented the same way after each data measurement. Also, the transistors are kept in known sockets at constant heights.

If bias power were inadvertently lost, the data would be in serious error. Instead of degrading, the transistors would actually recover while being irradiated (Section IV.A.). To eliminate this possibility, a safety is employed which shuts down the experiment if power is lost, even momentarily. Fortunately, power was never lost.

The fifteen transistors are divided equally into three groups and irradiated in the common emitter configuration with V_{CE} = 10 V. Bias collector currents are 0.1 ma for units 1-5, 1.0 ma for units 6-10, and 10 ma for units 11-15 (see Figure 11).

Measurements of base spreading resistance, alpha cutoff frequency,* dc current gain, ac current gain, and leakage current are made before and after the irradiation. In addition, measurements of leakage current and ac and dc current are made at various intervals during the irradiation.

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*The alpha cutoff frequency, f_α, and the gain-bandwidth product, f_T, are used interchangeably. Although they are not the same quantity, they have almost the identical numerical value.

In order to observe the recovery of leakage current, measurements of I_{CBO} are taken at one minute, two minutes, four minutes, eight minutes, 32 minutes, and 64 minutes after removal from the source. The transistors are not removed from the pool, but rather, I_{CBO} is measured at a distance far enough from the source such that the source intensity is virtually zero.

Between the 32 and 64 minute readings of leakage current, the transistors are removed from the pool and gain measurements are made. The assumption is made that the ac and dc current gains do not recover very much within the first half hour. This assumption is validated in the experimental results (Section V).

B. Test Procedure

1. $\underline{I_{CBO}}$. To obtain information about the I_{CBO} recovery time, measurements are made within the first minute after removal from irradiation. The only practical way to accomplish this is to leave the transistors in their sockets and switch each transistor from its bias circuit to the test circuit. Fifteen DPST switches are employed as shown in Figure 12.

The initial transistor leakage current is typically 100 pa. The length of cable required to place the transistors at the bottom of the pool is approximately 20 feet. Such remote high impedance measurements require extreme care. First, a wire insulation is chosen which has high insulation resistance and high radiation resistance. The insulation chosen to meet these needs is polyvinylchloride. Next, a guard voltage is used as illustrated in Figure 13. The signal ground return uses the power ground to establish essentially zero potential across the signal ground insulation. Thus, for all practical purposes, the signal ground current is truly the transistor leakage current. As insurance, an empty socket is used to calibrate the measurement. Also, the leakage current of each circuit is checked, after irradiation, with the transistors removed. This leakage is typically 0.1 pa and consequently introduces negligible error.

The final important source of error is the severe temperature dependence of I_{CBO}. To maintain a stable temperature during the vital early measurements, the container is left in the pool, which is isothermal within ± 2°C. Even with a ± 2°C constancy, the I_{CBO} error due to temperature is about ± 15%.

2. Base Spreading Resistance. Base spreading resistance or base sheet resistance is the ohmic resistance of the base region. The common emitter T-equivalent circuit of Figure 14 shows the parameter of interest.

The transistor input impedance is given by:

$$\frac{\Delta V_{bE}}{\Delta I_B} = r_{bb}' + (1 + \beta)\, r_e \qquad (V.1)$$

Ordinarily, $(1 + \beta)\, r_e$ is large compared to r_{bb}' which makes r_{bb}' difficult to measure. However, for emitter currents large compared with the base-emitter leakage current:

$$r_e \cong \frac{kT}{q} \frac{1}{I_e} \qquad (V.2)$$

where: I_e = the emitter current

k = Boltzmann's constant

q = charge of an electron

T = absolute temperature

At I_e equals 1 ampere, r_e is approximately .026 ohms.

Therefore, provided one operates at sufficiently large emitter currents, the effect of r_e on input impedance is negligible and r_{bb}' is measurable. Figure 15 shows the test circuit used to obtain the common emitter input impedance. Emitter currents of about 800 ma are used and a pulse technique employed. The pulse duty cycle is 0.1% and the collector-emitter voltage is 3 volts.

At such enormous current densities the simple model of Figure 14 may be in error. Nevertheless, it is assumed that at least a relative r_{bb}' measurement is achieved for comparisons of transistors. Actually, the spread of data showed $4 < r_{bb}' < 10$ ohms. This is in good agreement with the manufacturer's specifications which indicate that r_{bb}' is typically 15 ohms.

3. Other Considerations. The h_{FE} and f_T measurements are relatively standard and the circuits used are shown in Figures 16 and 17. The β measurement is made at 400 Hz on a Quan Tech Laboratories Transistor Noise Analyzer, Model No. 300.

SECTION VI

EXPERIMENTAL RESULTS

A. Leakage Current (I_{CBO})

1. Bias Dependence. The data show no correlation between transistor leakage current damage and the current at which the transistors are biased during irradiation. Neither the slope of the curve nor the extent of the damage can be related to bias current.

2. Characteristics of Damage Curve. Three regions of interest exist on an I_{CBO} damage curve. First, there is a region where relatively little damage is observed. Second, there is a region of rapid leakage current increase. Finally, the leakage current damage virtually ceases. Figure 18 shows the spread of data points taken at approximately two minutes after the units were removed from the pool. Below 10^4 Rads almost no damage occurs. Between 10^4 and 10^6 Rads, the rapid damage is evident. At 10^7 Rads, the damage is saturated. There has been little mention of anomalous peaking prior to damage saturation and its importance has not been given proper emphasis. Figure 19 shows the results for units 15, 3, and 10. Unit 15 exhibits relatively uniform degradation and a positive slope only. Unit three is typical of the transistors tested. It shows some peaking. Finally, unit 10 is plotted to show the extreme peaking observed. Unit 10 reached a peak damage value 300 times larger than its saturated value. This may seem extreme, but since the data points are taken sparsely on the abscissa, the probability is high that Unit 10 may have sustained even higher peak damage than observed.

Another interesting observation is that the leakage current values have a smaller spread in the saturation region then they did initially. When the experiment began there was a 6:1 spread between the maximum and minimum leakage units. In the saturation region there is only 2:1 spread between maximum and minimum leakage units. It would have been interesting to continue the experiment beyond 10^8 Rads; however, the time and money required to accumulate 10^8 Rads is prohibitive even when using a 5000 Curie source. Thus, one cannot state from the data obtained in this experiment that the surface damage to I_{CBO} saturates beyond 10^7 Rads. There is supporting evidence, however, that this is the case.[2,7]

3. <u>Recovery Time of Leakage Current</u>. This section is concerned with defining the time it takes for the leakage current to recover and whether this recovery time varies with bias current or accumulated dose. Since the nature of the recovery is unknown, one cannot describe it as a known function of time. In addition, the error in measurement is large and allows great freedom in fitting a curve to the data. One of the most natural types of decay or recovery is a simple exponential in which the rate of change of a substance is proportional to the amount of existing substance. If the first set of data taken at each dose level corresponds to zero recovery, then the exponential curve fits the data in a reasonable fashion. Figure 20 shows I_{CBO} as a function of time after 10^6 Rads for the three irradiation bias currents. The equation of this curve is given by:

$$I_{CBO}(t) = I_{CBO}(\infty) + (I_{CBO}(0) - I_{CBO}(\infty))e^{-\frac{t}{\tau}} \qquad \text{(VI.1)}$$

Percent recovery is defined as:

$$\text{Recovery} = R = \frac{I(0) - I(t)}{I(0) - I(\infty)} \times 100\% \qquad \text{(VI.2)}$$

But VI.1 yields,

$$I(0) - I(t) = (I(0) - I(\infty)) - (I(0) - I(\infty))e^{-t/\tau}$$

$$\therefore \quad R = (1 - e^{-t/\tau}) \times 100\% \qquad \text{(VI.3)}$$

Before proceeding, it should be emphasized that this definition is a reasonable but arbitrary fit to the data, which lends itself to ease of discussion, particularly for engineers who are familiar with this type function.

The recovery is consistently about 50% of the initial reading as illustrated by Figure 20. Since the accuracy of the initial data is only ± 10%, the accuracy of the plot of recovery is only ± 20%.

There is no correlation between recovery time constant and bias current (Figure 20) or dose rate. Although a substantial amount of degradation has taken place at 3×10^5 Rads, no recovery is apparent. The plots of recovery vs. time are shown for 10^6, 8.5×10^6, and 3.8×10^7 Rads in Figure 21. These plots indicate time constants of approximately ten minutes. No correlation of time constant and accumulated dose is evident. Figure 22 shows an extended time plot of the recovery after the last irradiation.

Although we have discussed the recovery in terms of a single-time constant, data indicate that this viewpoint may not be valid over a long period of time. Figure 22 shows that even beyond five time constants, recovery of 10% or more may be expected.

Irrespective of what curve is fitted to the data, clearly significant recovery occurs within the first few minutes after removal from the radiation field.

B. DC Current Gain Degradation

1. Base Spreading Resistance (r_{bb}'). Common emitter dc current gain is an important function of the conductivity of the base region[32] (base spreading resistance for a given geometry). Readings of base spreading resistance were taken in an attempt to correlate h_{FE} degradation with the initial values of base spreading resistance. The data show no correlation, and the reason is that the base spreading resistance also varies with accumulated radiation. In fact, it appears to saturate at some low resistance value. Initially,

$$4 < r_{bb}' < 11 \text{ ohms.}$$

After irradiation

$$2.2 < r_{bb}' < 3.7.$$

The damage to h_{FE} is commonly observed to saturate. Since h_{FE} depends strongly upon r_{bb}', it is not surprising that the r_{bb}' damage also saturates.

2. Bias Current. The transistors are biased in groups of 5 at collector currents of 0.1 ma, 1 ma, and 10 ma. The experimental results show that the damage is independent of bias current. This result is illustrated in Figure 23, which shows the dc current gain measured at I_c = 0.1 ma. This result is in direct contrast to early reports which state that damage is inversely related to bias current. The result is consistent with the concept that transistors which are passivated properly show little correlation between radiation damage and quiescent operating conditions.

3. Characteristics of h_{FE} Damage Curve. The h_{FE} data correlation is high. Since there is no bias dependence, the measured h_{FE} of the 15 units may be averaged. Figure 24 shows the average h_{FE} versus radiation for I_C values of 0.1 ma, 1 ma, and 10 ma. There is a noticeable difference in the way these parameters degrade. The 0.1 ma h_{FE} degradation has an early threshold (less than 10^4 Rads) and an early saturation (less than 10^6 Rads). As I_C increases the damage threshold and saturation occurs later. The 10 ma h_{FE} damage threshold is at 10^4 Rads and saturation is not reached even at 3.8×10^7 Rads. Thus, it appears that the higher current h_{FE} has degraded less proportionally than the lower current h_{FE}. This is another way of saying that the high current h_{FE} is more radiation resistant than the low current h_{FE}.

4. Recovery. Data taken after the final irradiation indicate that no recovery occurs within the first six hours. After two months, only 15% recovery is observed.

C. AC Common Emitter Current Gain (β)

The ac current gain data indicate no correlation of β degradation as a function of radiation bias current. Figure 25 shows the average β of the 15 units plotted against radiation dose. The pronounced damage threshold and saturation regions exhibited by h_{FE} damage do not exist for β damage. On a percent damage basis, β measured at 10 ma shows the greatest radiation resistance. In this respect h_{FE} and β degradation are very similar. Recovery after six hours is negligible and after two months is approximately 20%.

D. Gain Bandwidth Product (f_T)

The common emitter gain-bandwidth product (f_T) changed little during irradiation. Before irradiation:

$$560 < f_T < 780.$$

After irradiation:

$$510 < f_T < 650.$$

The average decrease is 8%.

SECTION VII

DISCUSSION

A. I_{CBO}

The I_{CBO} data yield the most important results of the experiment. In particular, the peaking seen near 10^6 Rads is very significant. It is not unusual for a satellite orbiting through the stronger belts to absorb 10^6 Rads. If transistors thought to be "radiation resistant" actually exhibit this anomalous peaking in orbit, the radiation damage estimate could be in error by nearly three orders of magnitude.

Until this peaking is fully explained, any "annealing" type of radiation hardening may be useless because one is not sure if this peaking will occur the next time the transistor is irradiated.

Indeed, if the ionizing damage saturates after peaking, it might be advantageous to irradiate transistors with low energy particles until the ionizing radiation damage reaches saturation. If the particle energy is low enough (nominally 150 kev), then no bulk damage will have occurred. Standard bulk damage equations may then be employed to predict further damage when the transistors are used in a known radiation environment.

The next significant result is the behavior of the recovery time of I_{CBO}. The import of this phenomenon must be weighed for each individual circumstance. The very existence of recovery indicates that the reaction is seeking an equilibrium state and thus it is dose rate dependent. Exactly how dependent is yet unknown. Consequently, one may argue that for low dose rates, recovery is insignificant. Nevertheless for accelerated life tests, such as in this experiment, the recovery time must be established. Without it, the data are questionable because the amount of recovery for each data point is unknown. The fact that the transistors in this experiment recovered over 50% in less than 10 minutes shows that this problem is not trivial.

B. DC Current Gain (h_{FE})

The fact that h_{FE} damage is independent of bias conditions is not unexpected. Present day planar techniques provide good passivation. Therefore, the contribution of channel current to the base current is due to ion migration and is virtually independent of bias conditions.

The greater radiation sensitivity of low current h_{FE} is consistent with the presently accepted theory which states that increased base current components cause h_{FE} degradation. This theory, however, does not explain why the higher current h_{FE} continues to degrade when the low current h_{FE} has saturated.

The decrease and saturation of r_{bb}' substantiates the known dependence between h_{FE} and r_{bb}'.

C. AC Current Gain

Since the dc current gain is an indication of how the transistor characteristic curves are changing, it is not surprising that the ac β results closely follow the h_{FE} results. On a percentage basis, the β and h_{FE} degradation are almost identical. The h_{FE} and β recovery also correspond on a percentage basis.

D. Gain-Bandwidth Product (f_T)

This parameter which, initially, was needed to predict bulk damage yielded an interesting and important result. The average gain-bandwidth decrease was only 8%. For high frequency linear amplifiers employing negative feedback, a factor of four decrease in β may be tolerable provided the gain-bandwidth product remains essentially constant.

Radiation	Radiation Damage Equivalent neutron/cm^2	proton/cm^2	electron/cm^2	Co^{60} γ (Rads)
neutrons/cm^2	1	0.3	1.2×10^3	8×10^{-5}
protons/cm^2	3	1	4×10^3	2.5×10^{-4}
electrons/cm^2	8×10^{-4}	2.5×10^{-4}	1	6×10^{-8}
Co^{60} γ (Rads)	1.2×10^4	4×10^3	1.7×10^7	1

TABLE 1: Radiation damage equivalents.* Average radiation required to produce equal lifetime changes in p on n and n on p solar cells.

* This table is redrawn from reference 11, p.98.

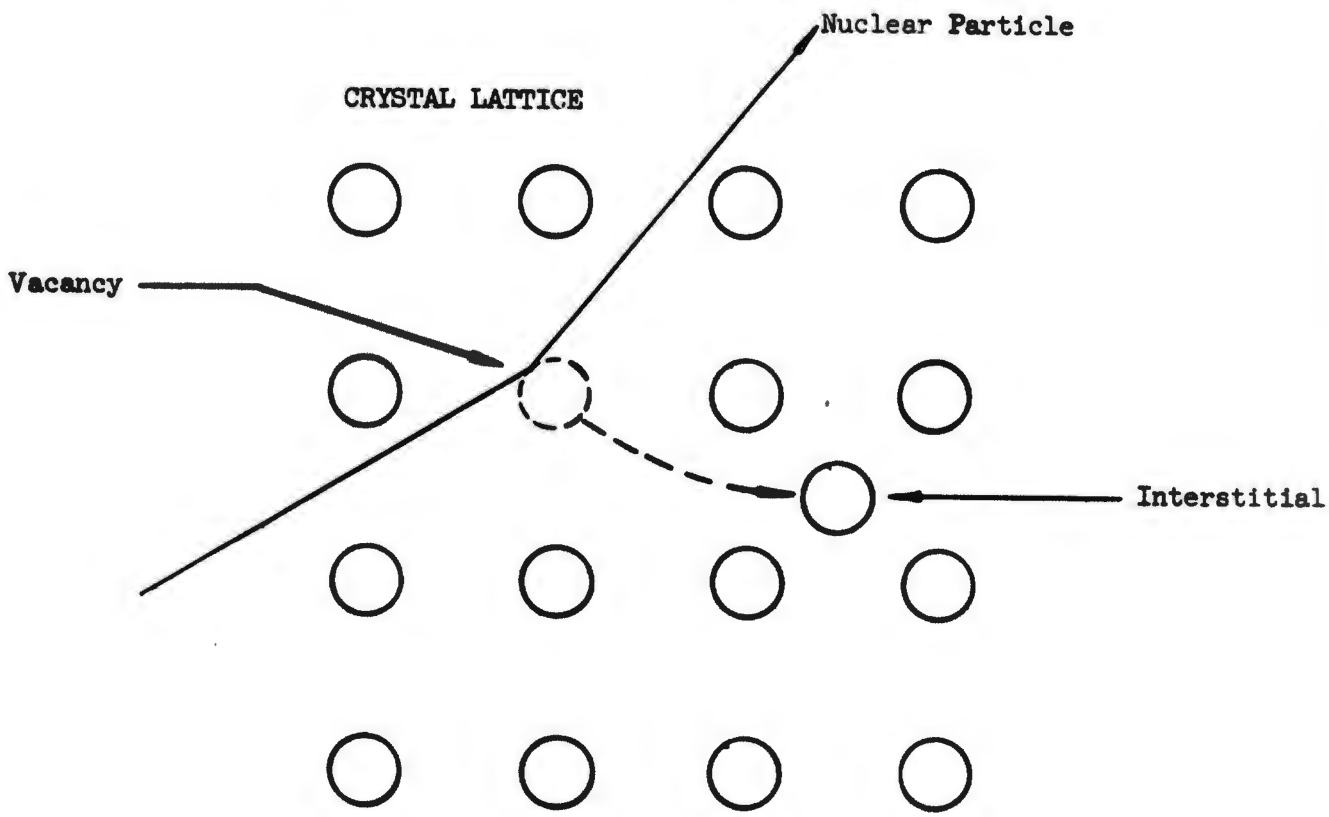

FIGURE 1: Production of lattice defects by collision of high energy particles with semiconductor nuclei.

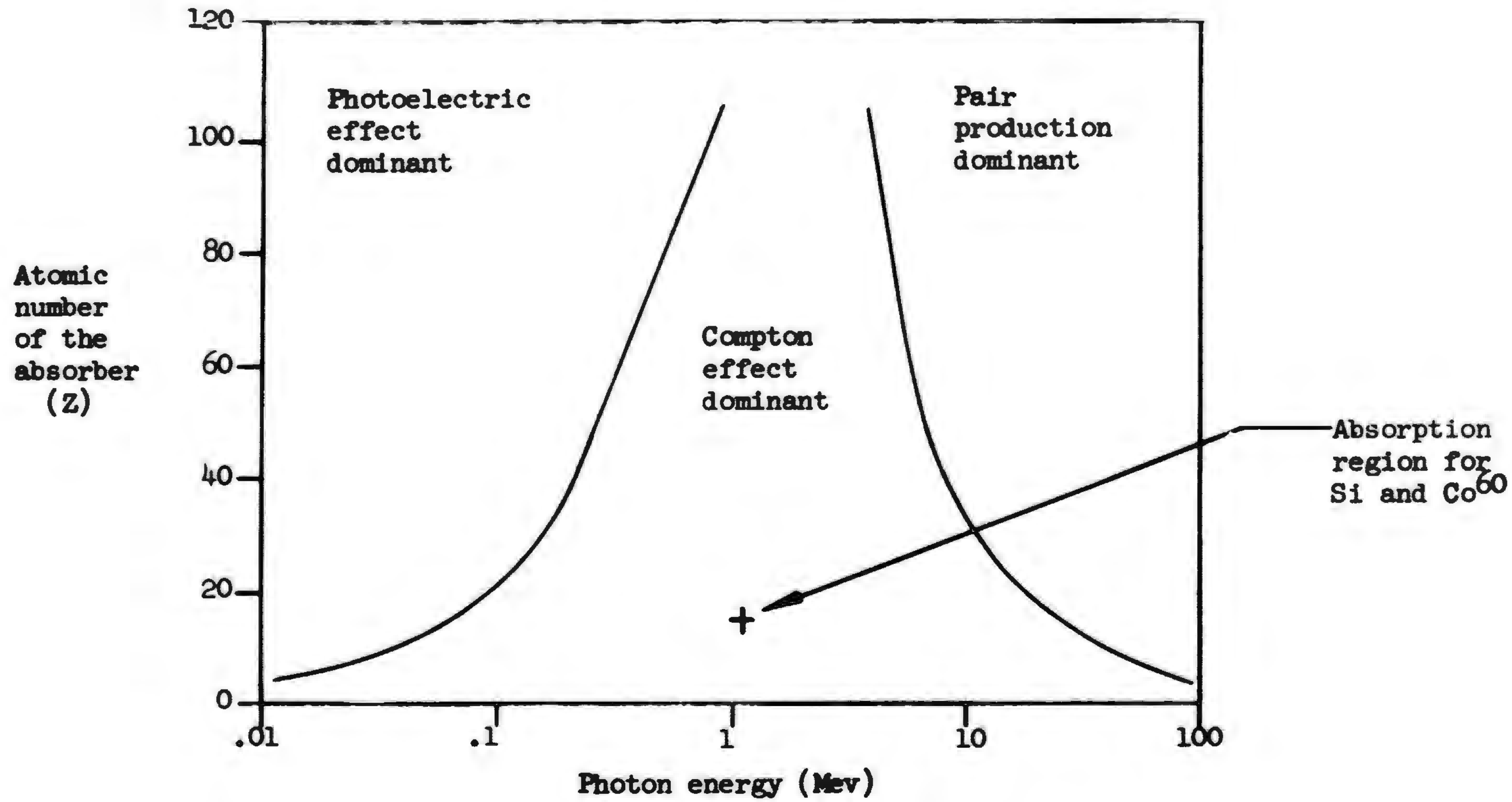

FIGURE 2: Energy region over which the three primary absorption processes dominate* as a function of photon energy and Z.

*Redrawn from Reference #17, page 15.

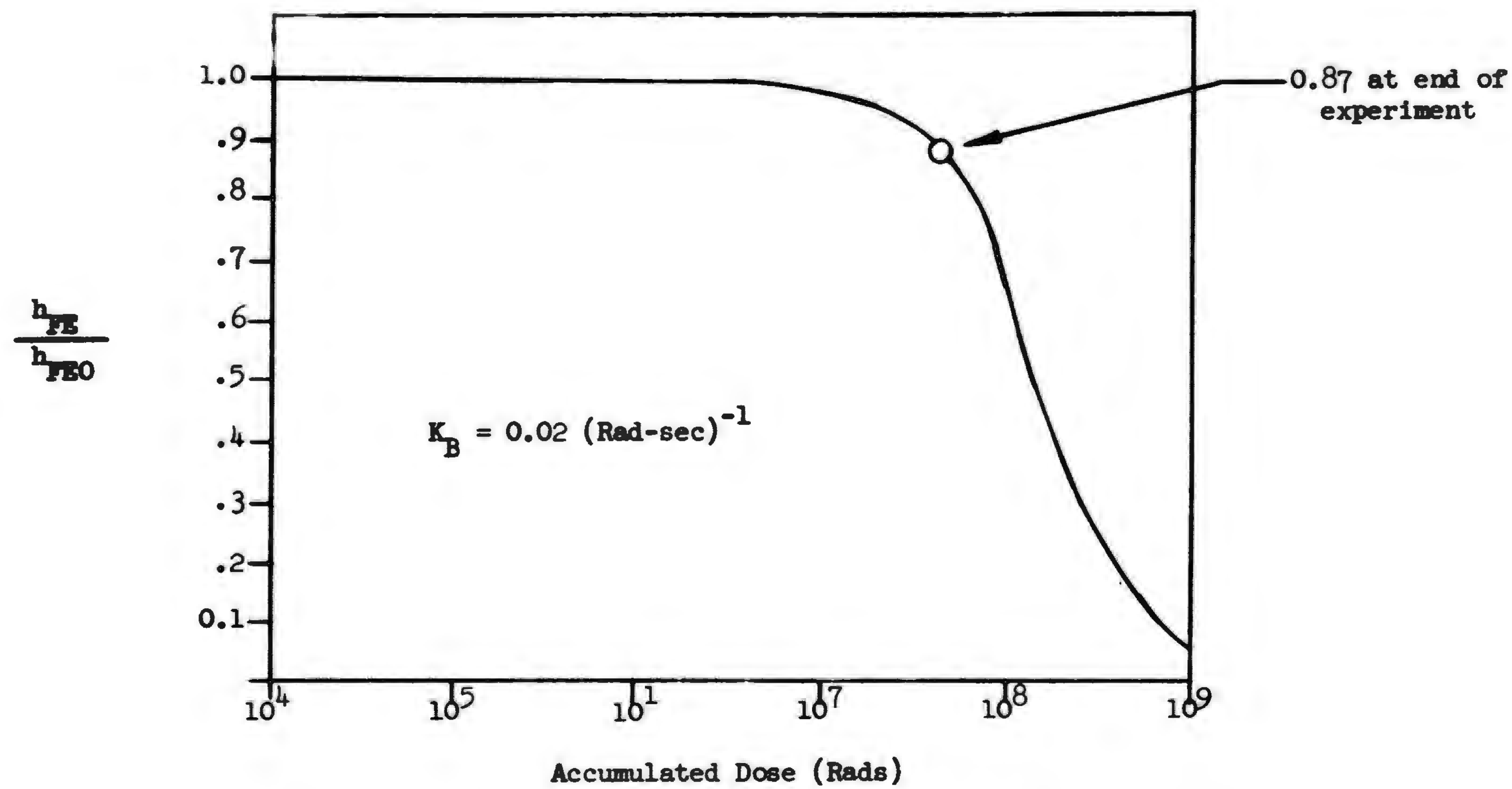

FIGURE 3: Predicted bulk damage for the transistors irradiated in this experiment, using h_{FEO} = 100 and f_α = 500 MHz.

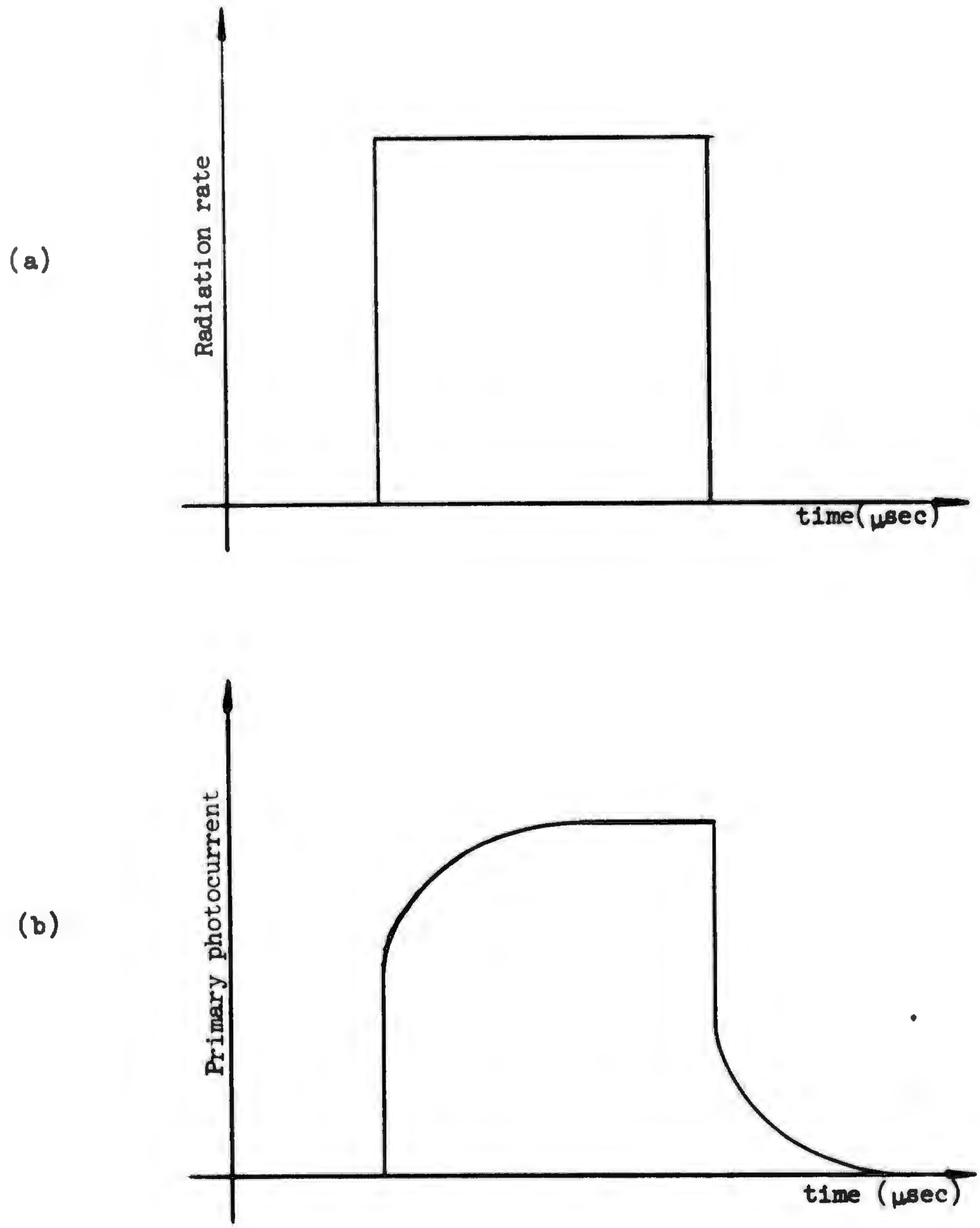

FIGURE 4: (a) Pulse of ionizing radiation.
(b) Primary photocurrent in a semiconductor due to the radiation pulse.

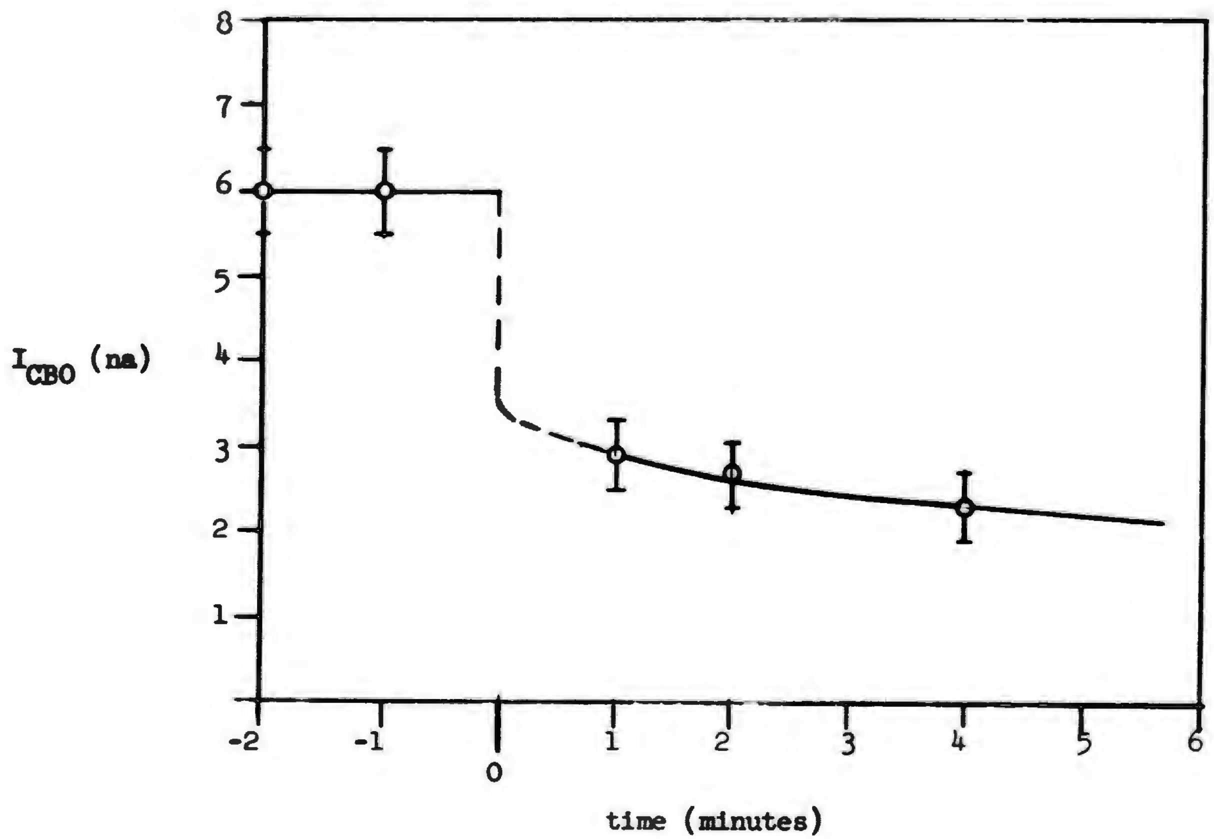

FIGURE 5: Collector leakage current vs. time at an accumulated dose of 3.8×10^7 Rads. The transistors were removed from radiation at t = 0.

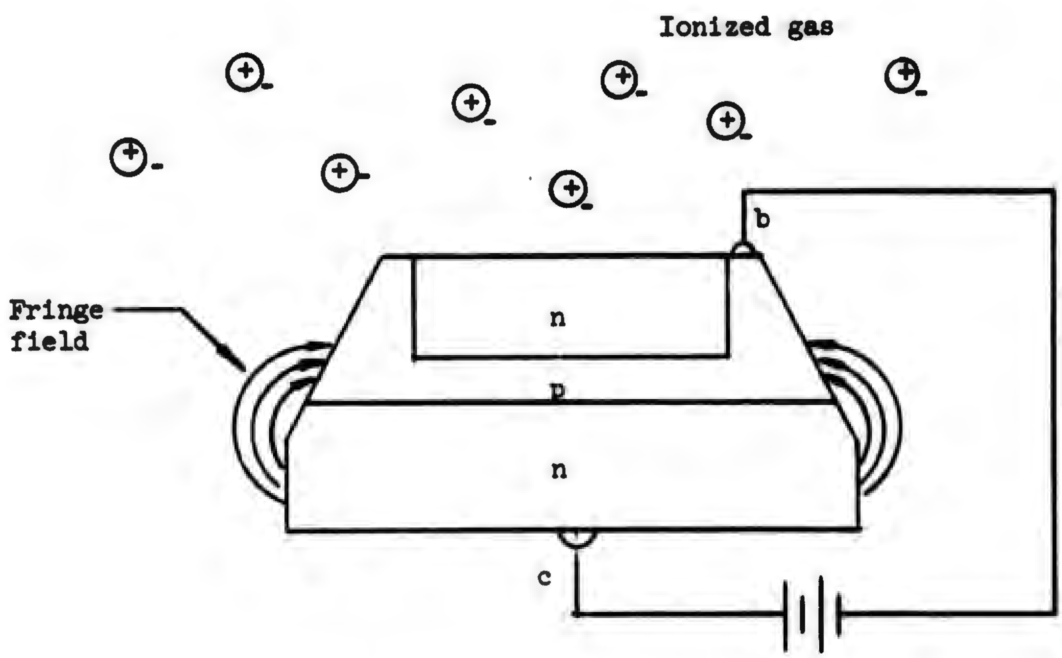

FIGURE 6: Illustration of the gas model for surface damage due to ionizing radiation.*

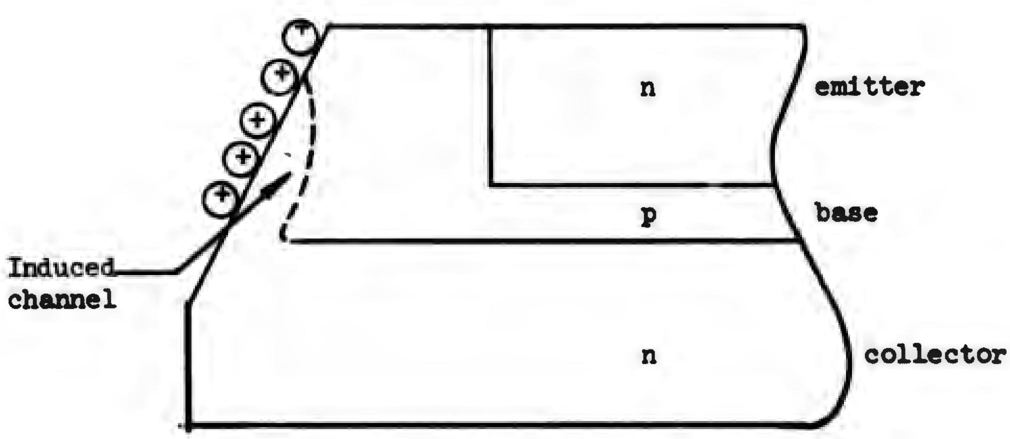

FIGURE 7: Ionized gas reacts with surface contaminants and extends the collector region over the base.*

*Redrawn from Reference #2, pages 101, 102.

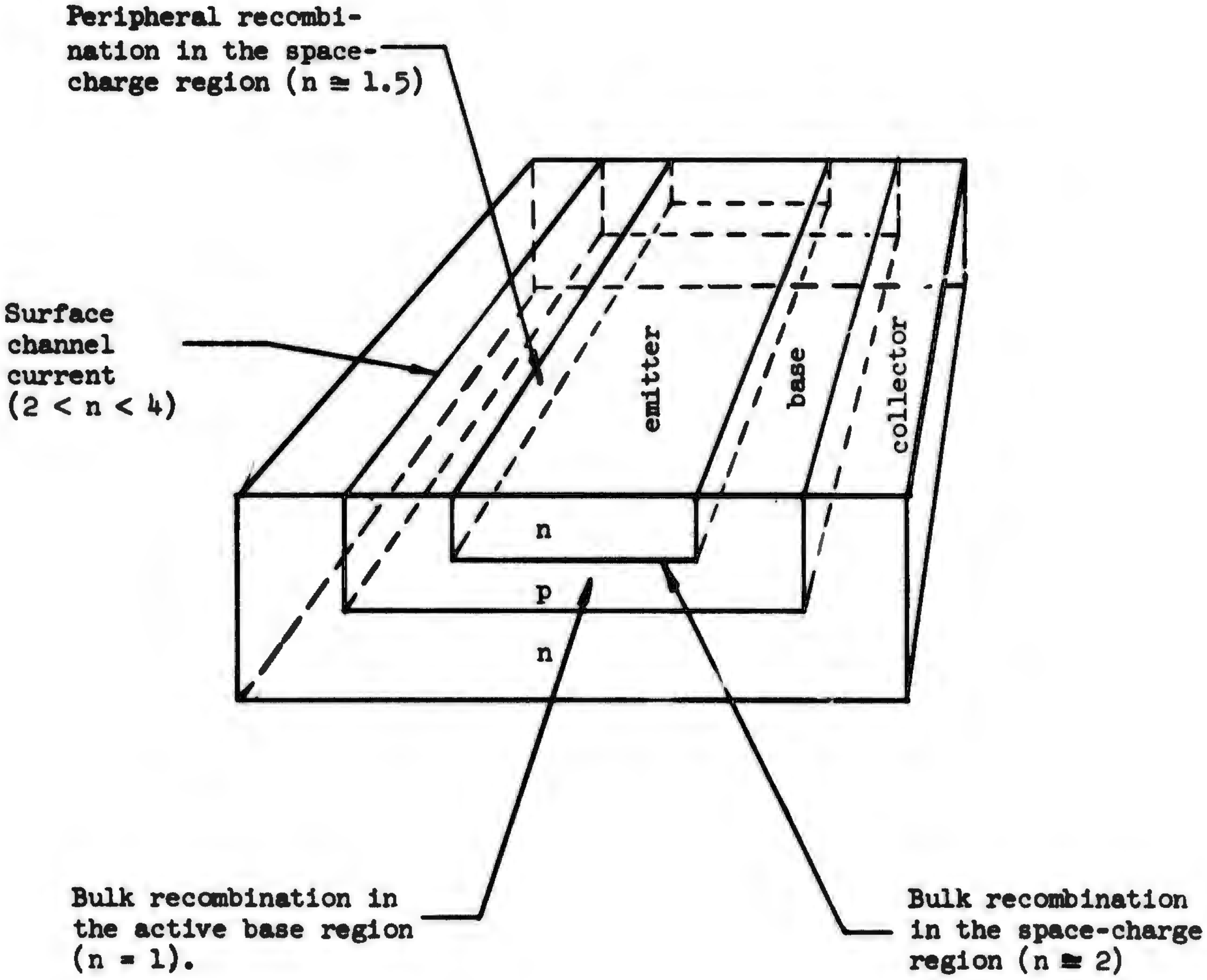

FIGURE 8: Regions which cause the four known base current components.

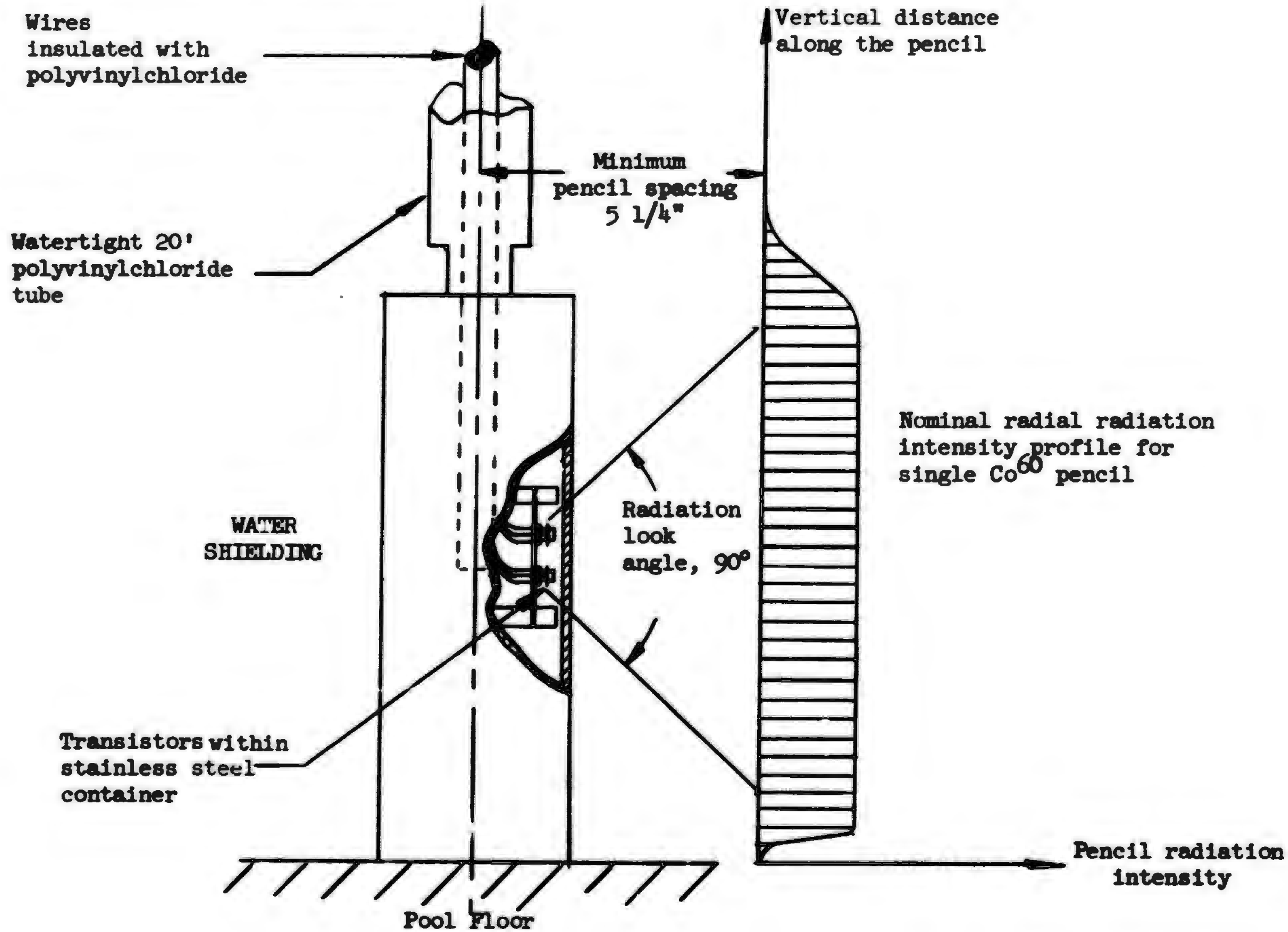

FIGURE 9: Nominal arrangement of transistors and source. The intensity profile is shown for a single Co^{60} pencil. In the experiment pencils are placed in a circle around the transistors.

(a)

(b)

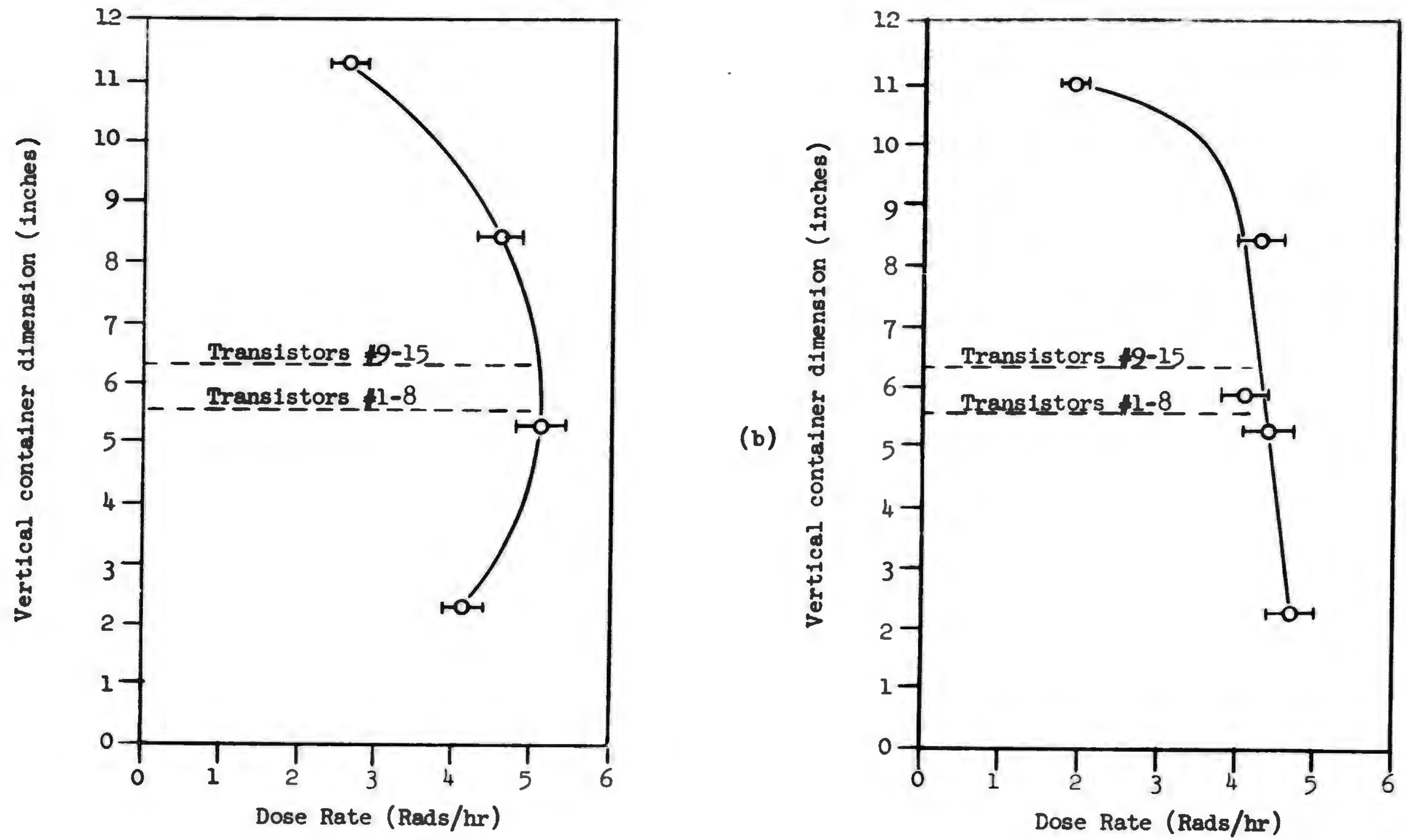

FIGURE 10: Dose rate profile from the dosimetry for
(a) 5000 curie source (nominal)
(b) 1500 curie source (nominal)

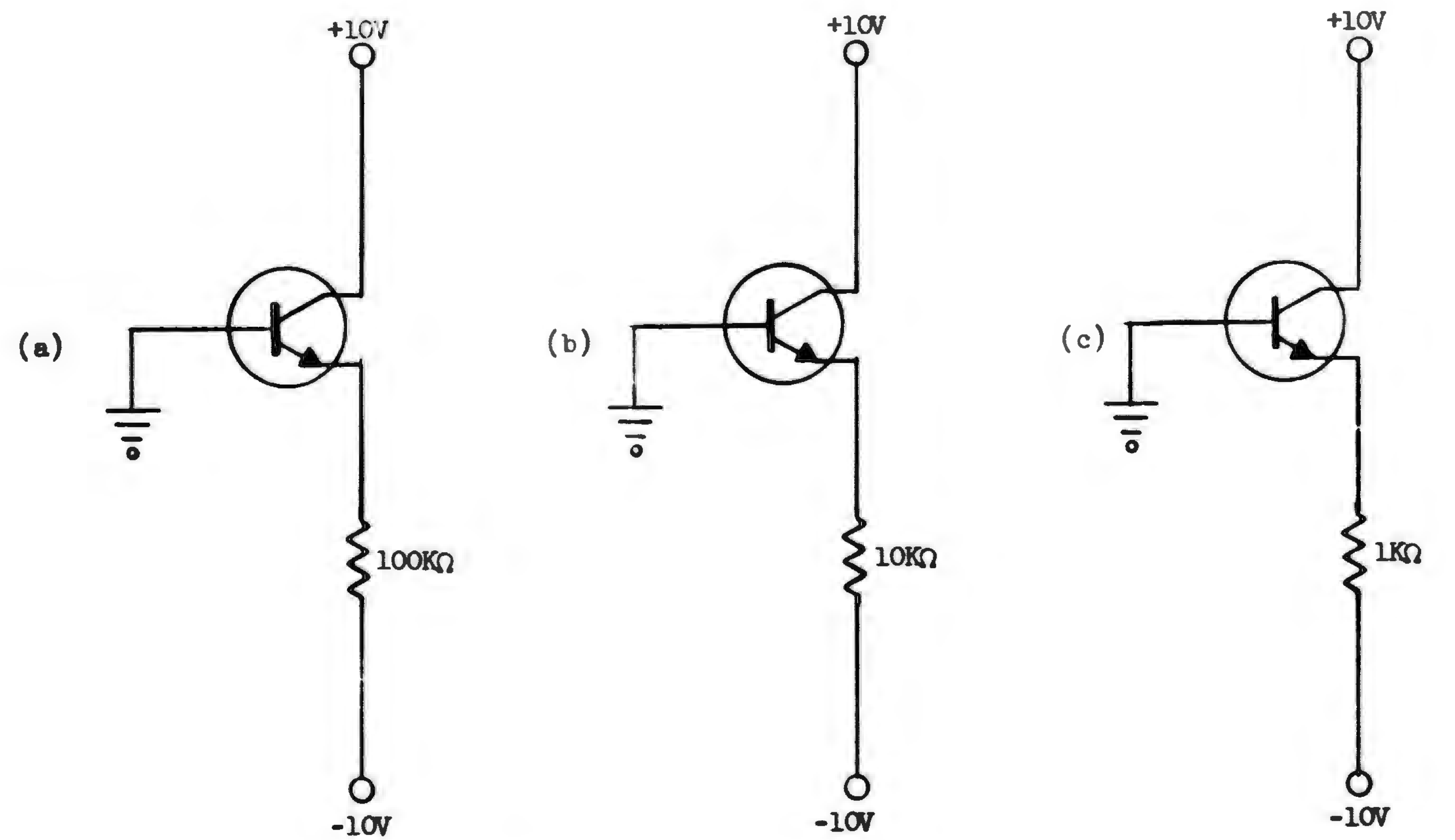

FIGURE 11: Bias circuit during irradiation for
(a) Units 1 thru 5
(b) Units 6 thru 10
(c) Units 11 thru 15

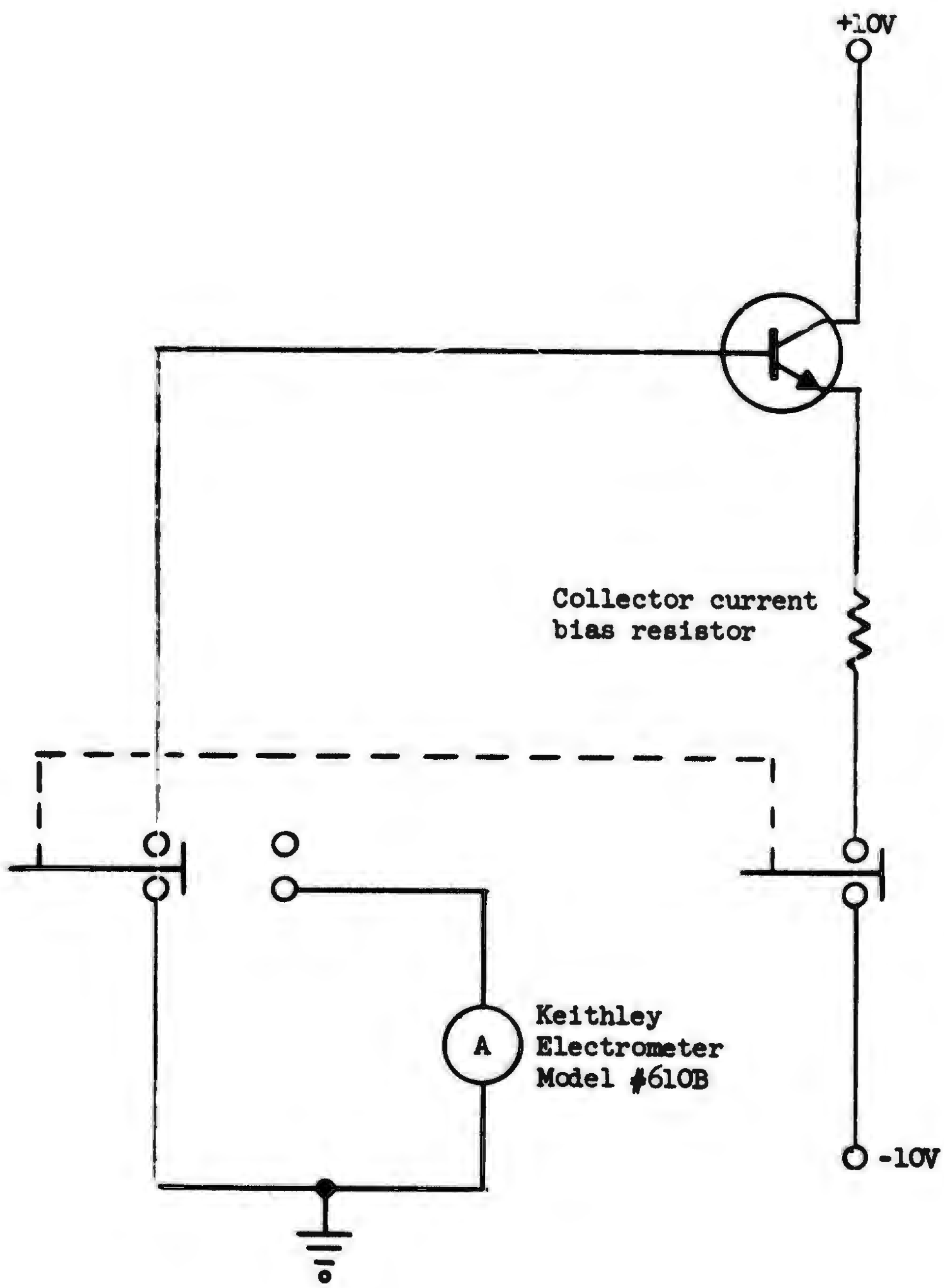

FIGURE 12: Circuit which allows measurements of I_{CBO} while transistors are still in the container.

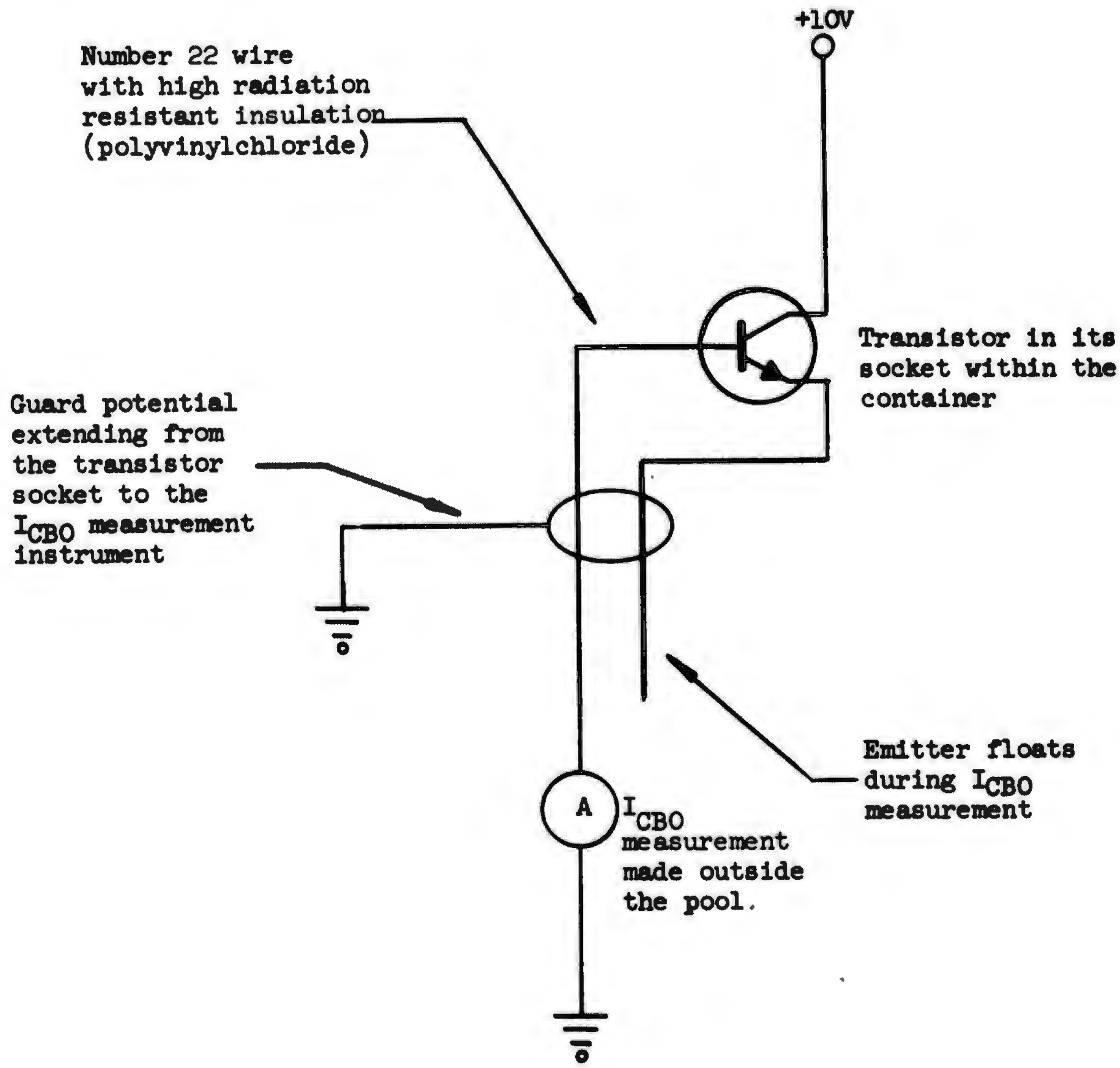

FIGURE 13: Guard circuit. Each base lead has a guard shield establishing zero potential across its insulation.

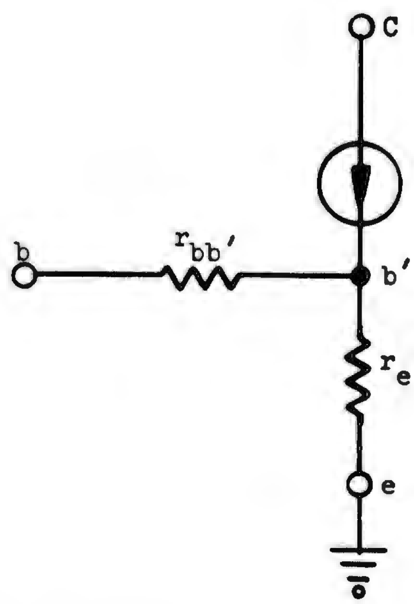

FIGURE 14: Basic low frequency common emitter T-equivalent circuit

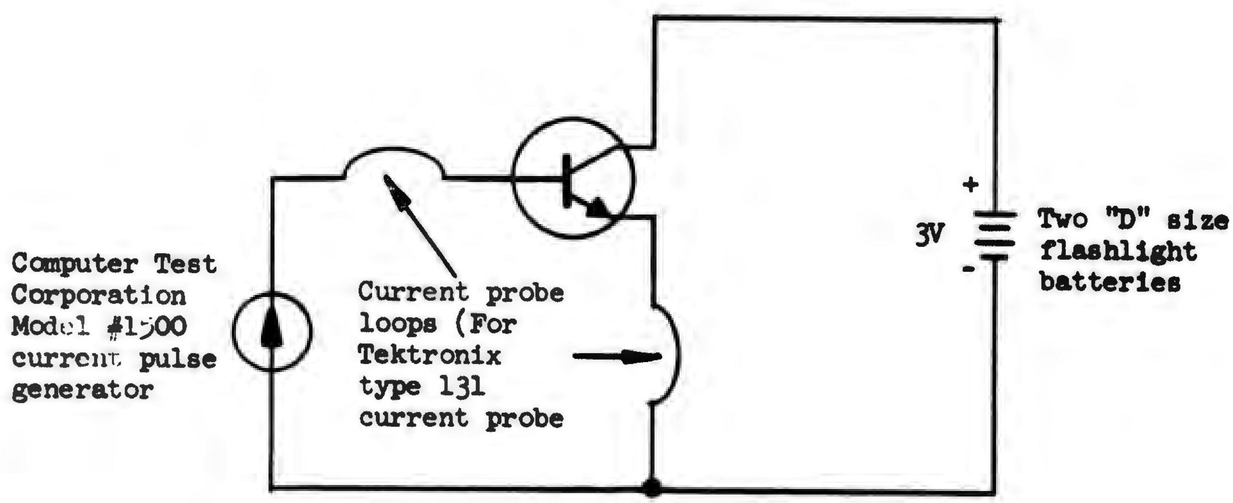

FIGURE 15: This circuit is used to measure ΔI_B, ΔI_E, and ΔV_{BE} in order to obtain $r_{bb'}$.

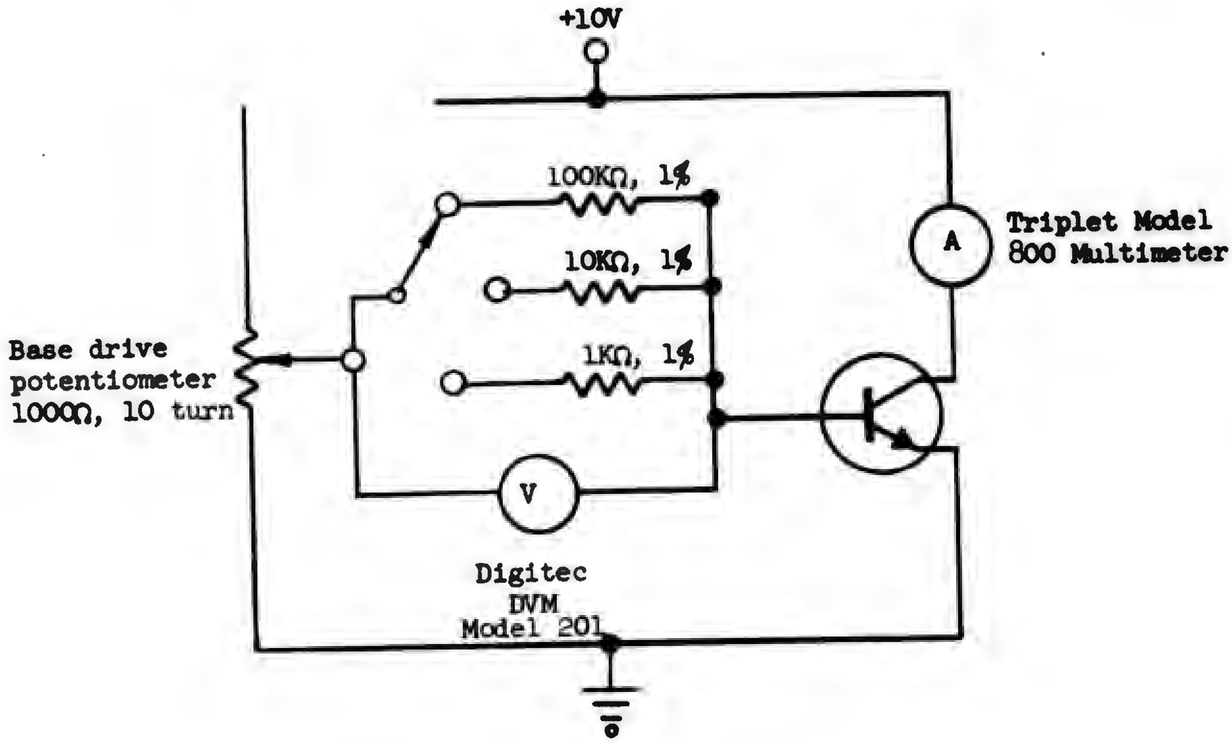

FIGURE 16: h_{FE} measurement circuit.

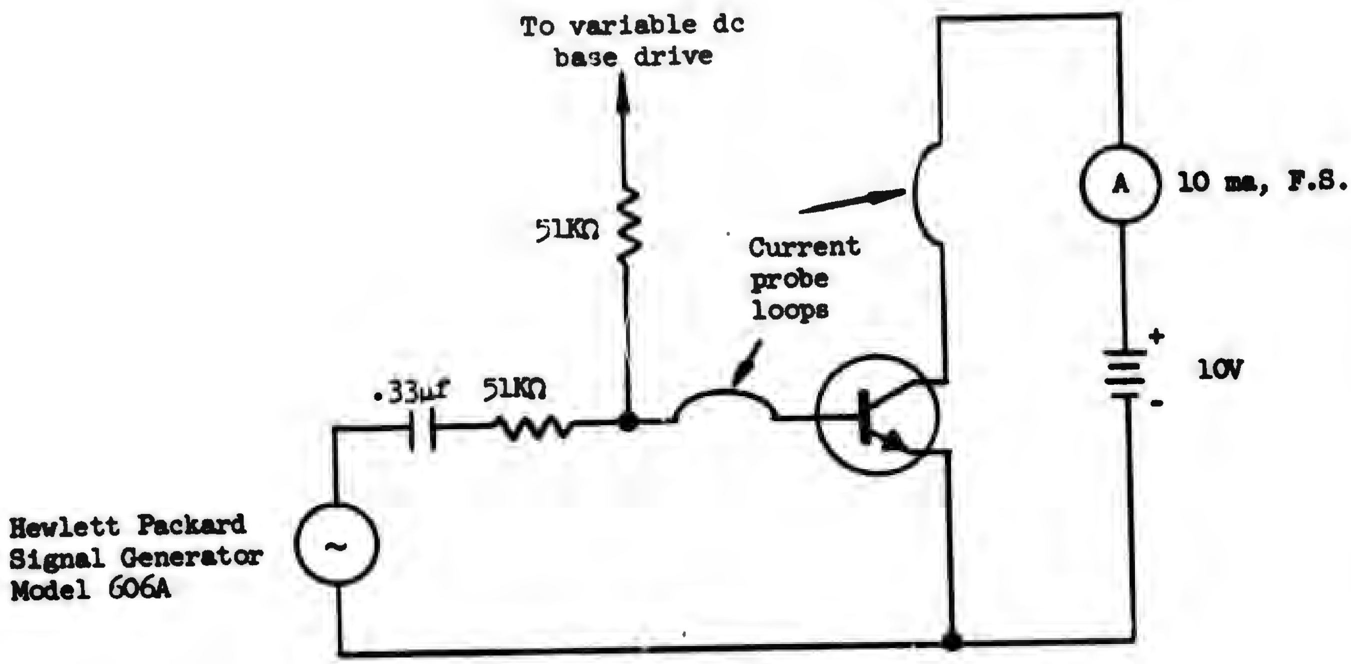

FIGURE 17: Gain-bandwidth measurement circuit.

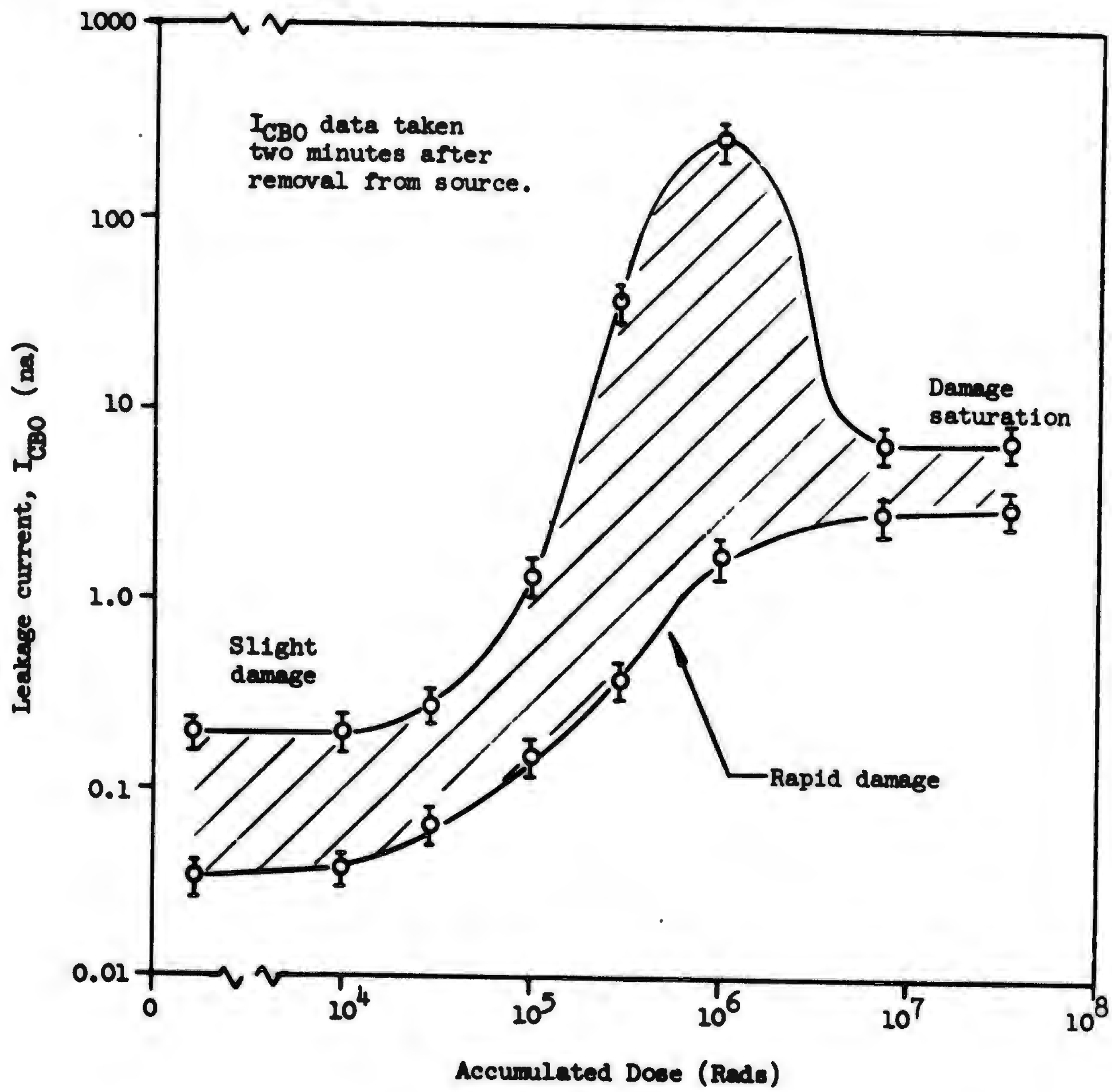

FIGURE 18: Maximum and minimum data points of I_{CBO} vs. accumulated radiation dose.

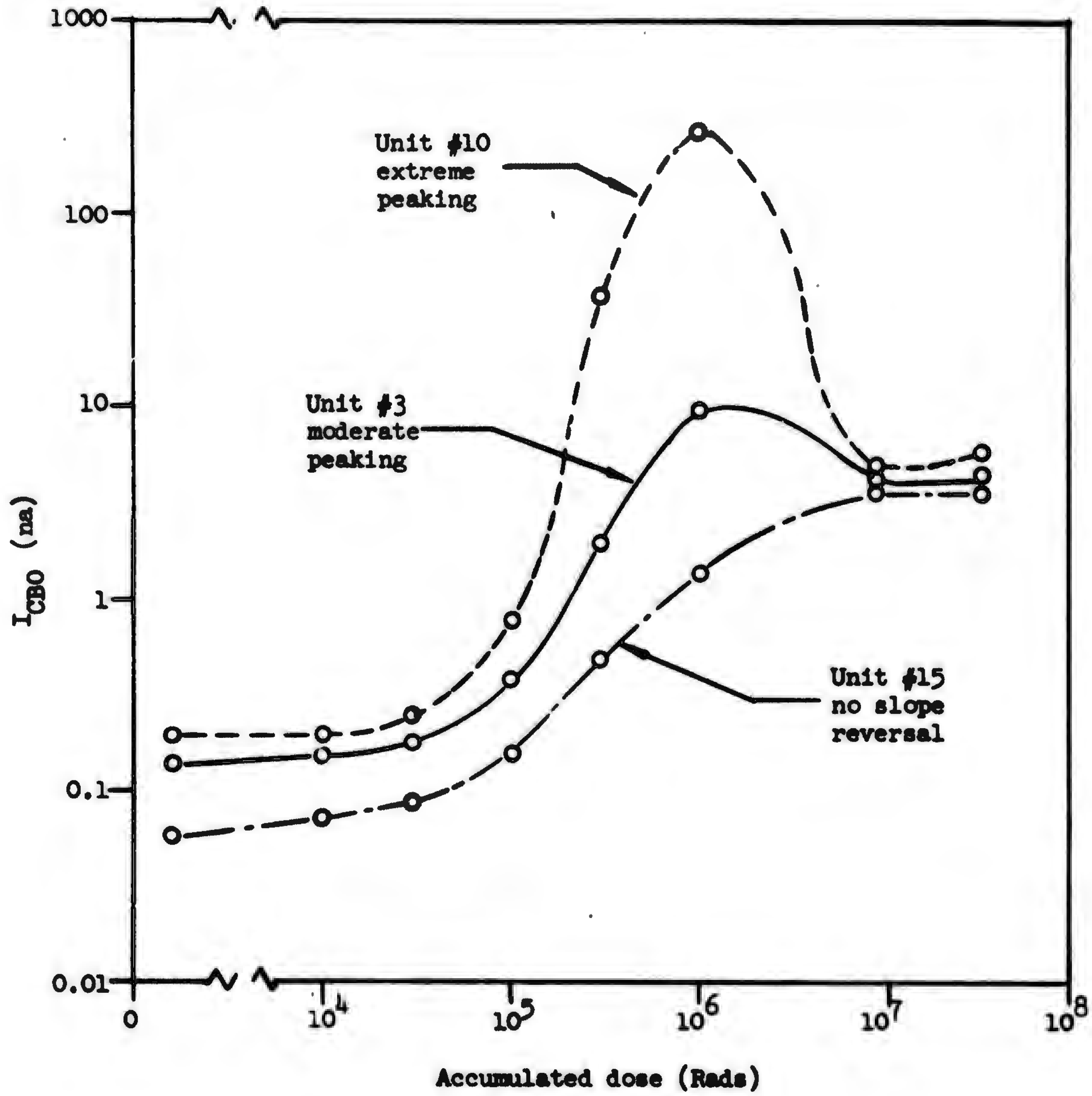

FIGURE 19: I_{CBO} vs. accumulated radiation dose showing the large variation in behavior among three of the units tested.

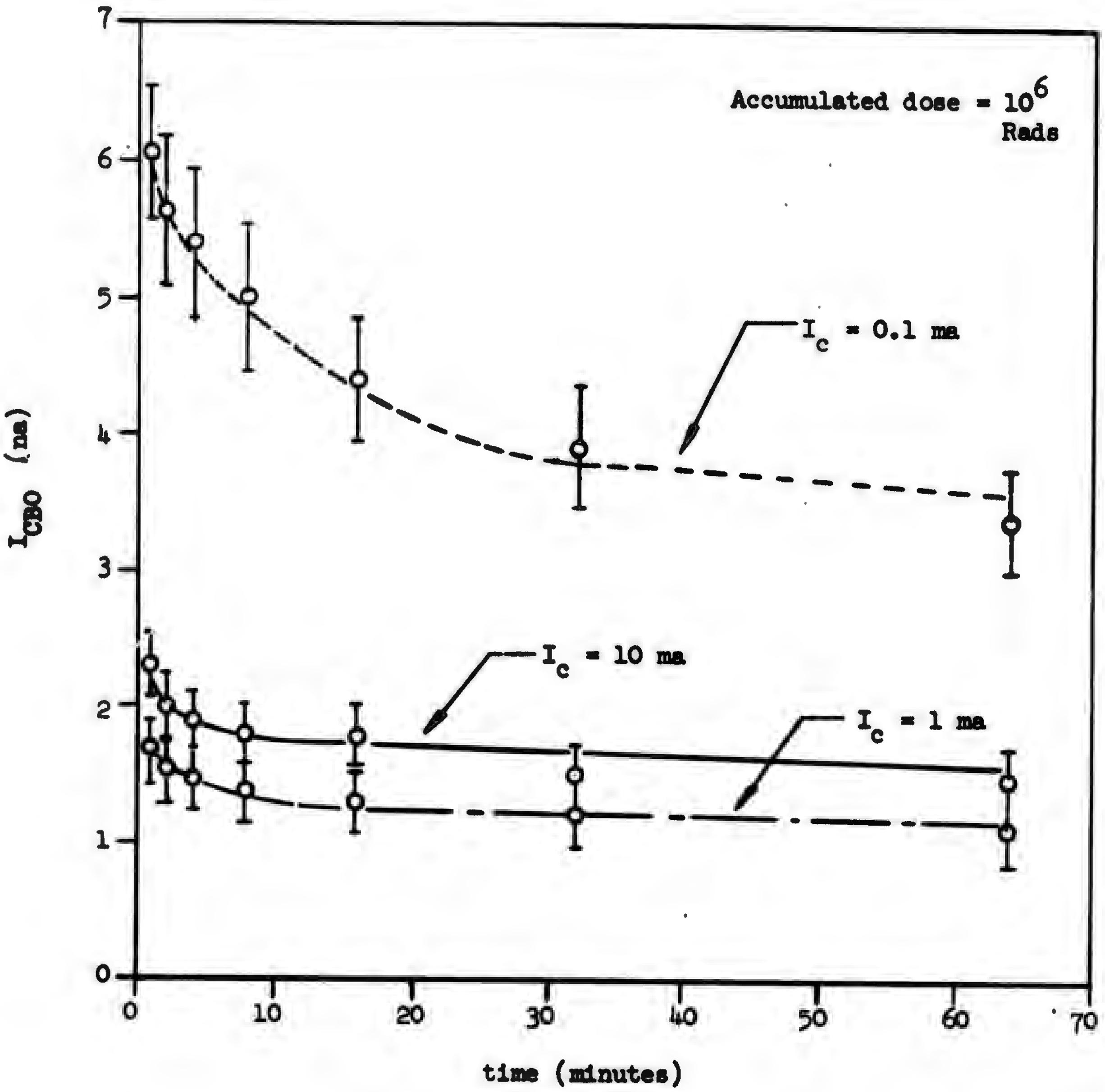

FIGURE 20: Leakage current vs. time for the three irradiation bias currents. Data for each group of five transistors is averaged.

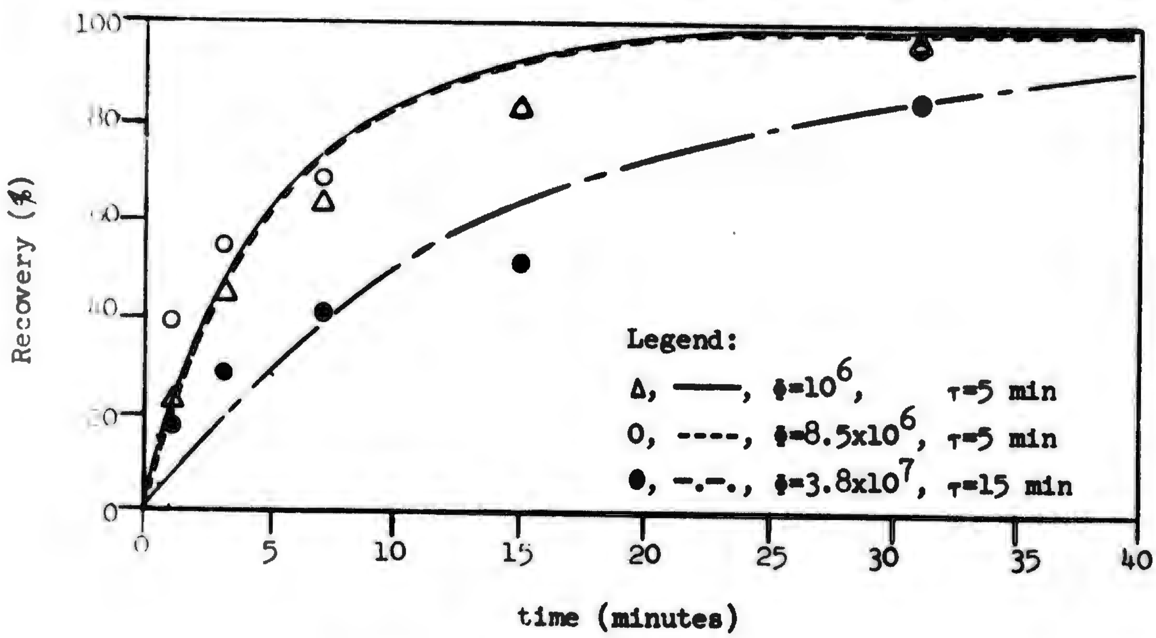

FIGURE 21: Percent recovery vs. time after removal from radiation. Data from the fifteen transistors are averaged. Accuracy = ±20%.

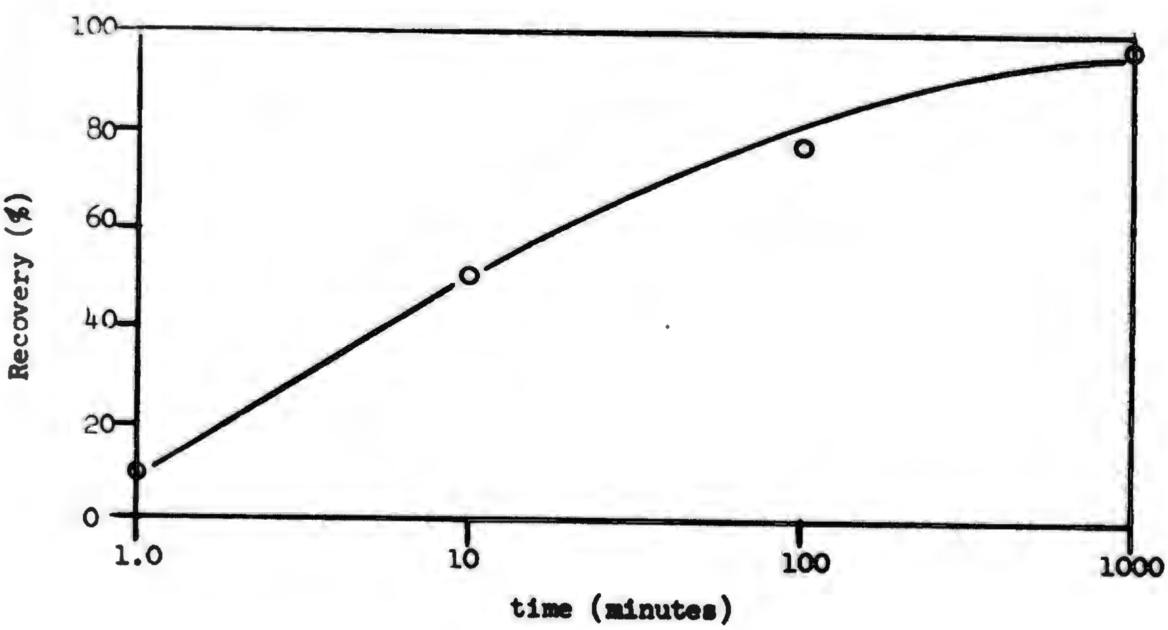

FIGURE 22: Percent recovery as a function of time after the final radiation dose. Data from the fifteen transistors are averaged. Accuracy = ± 20%.

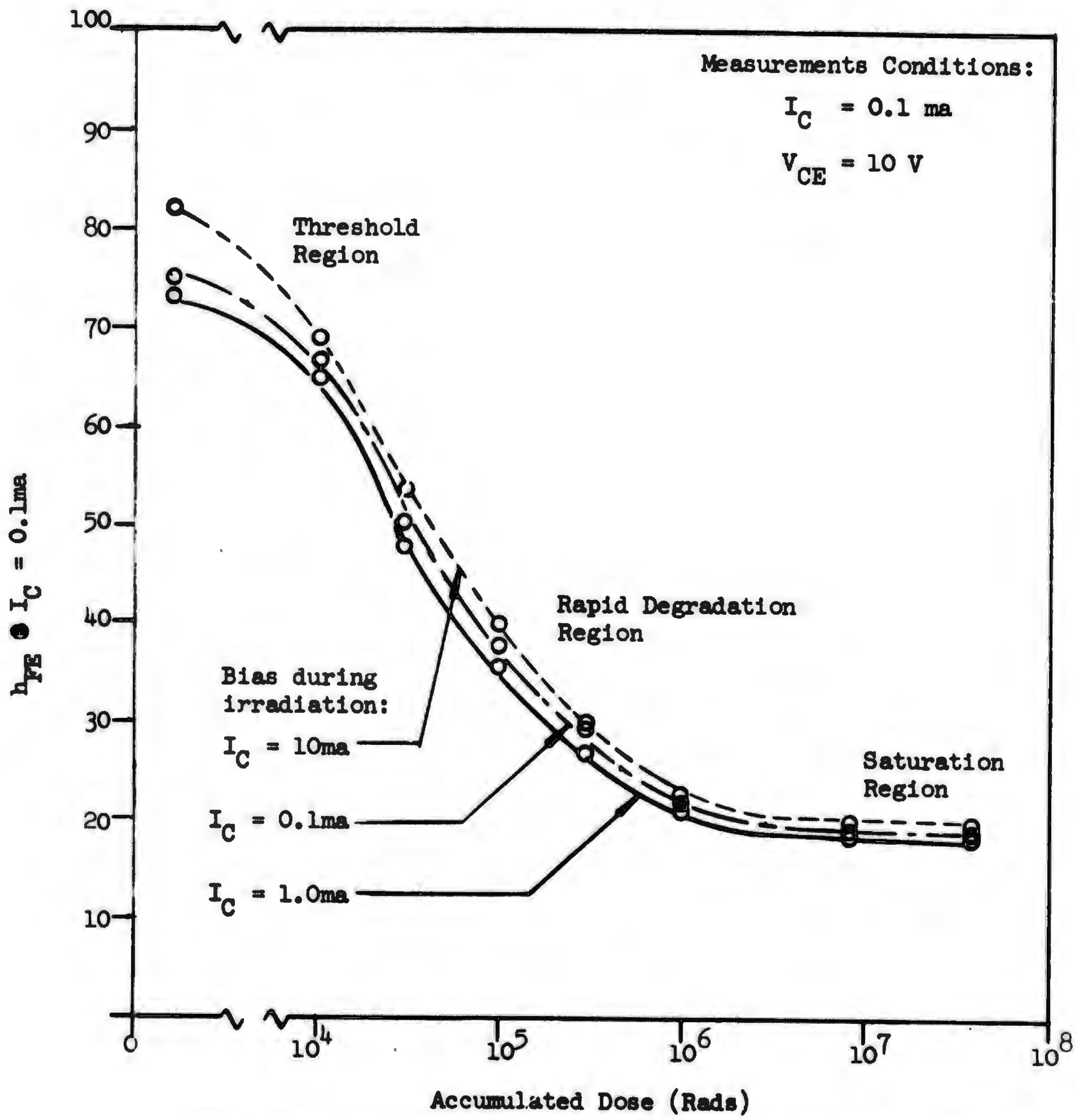

FIGURE 23: DC beta degradation measured at a collector current of 0.1ma for the three irradiation bias currents. Damage is not related to irradiation bias current according to this experiment. Accuracy = ± 5%.

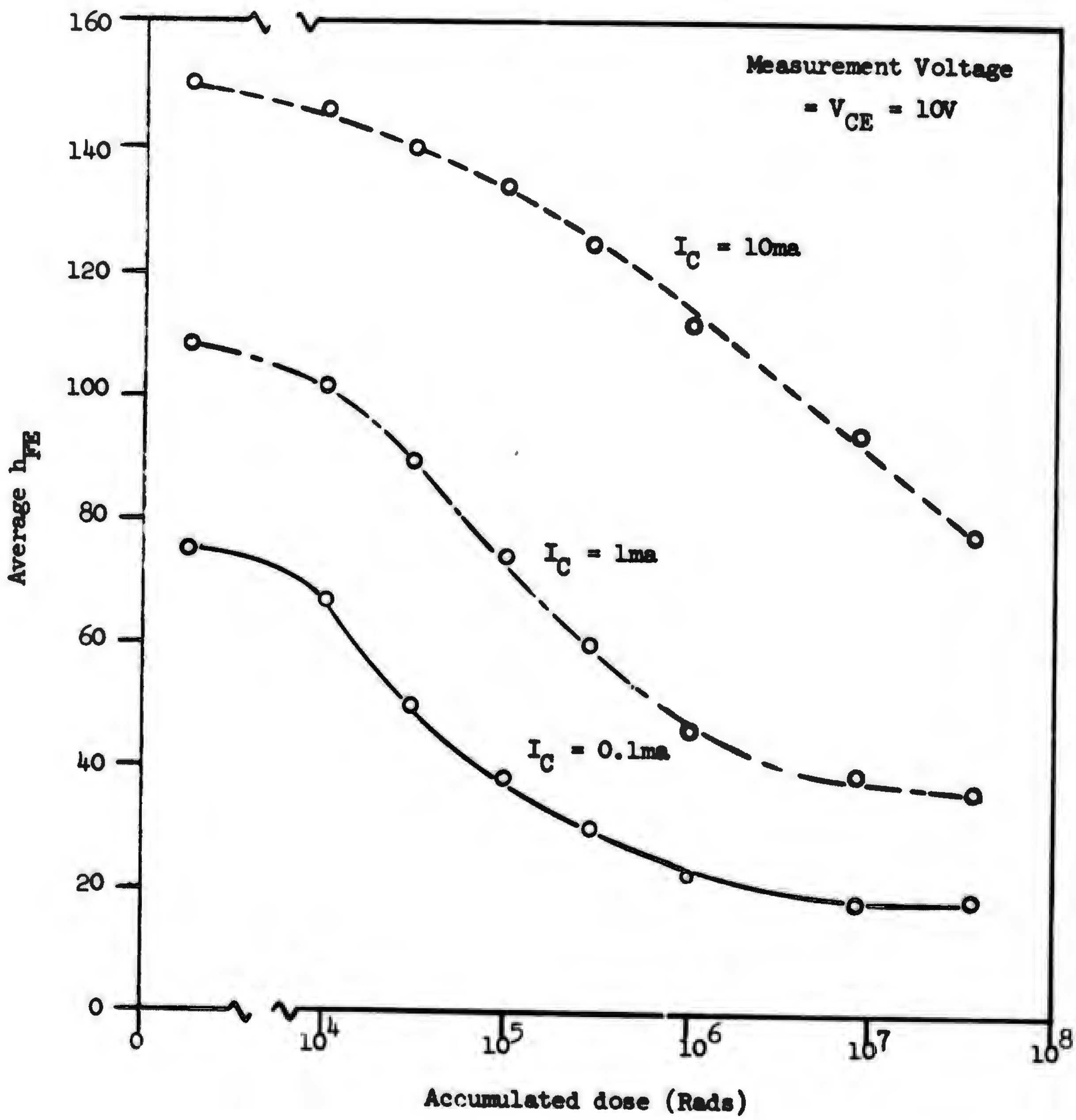

FIGURE 24: The fifteen transistor average h_{FE} vs. accumulated dose for three measurement collector currents. Accuracy = ± 5%.

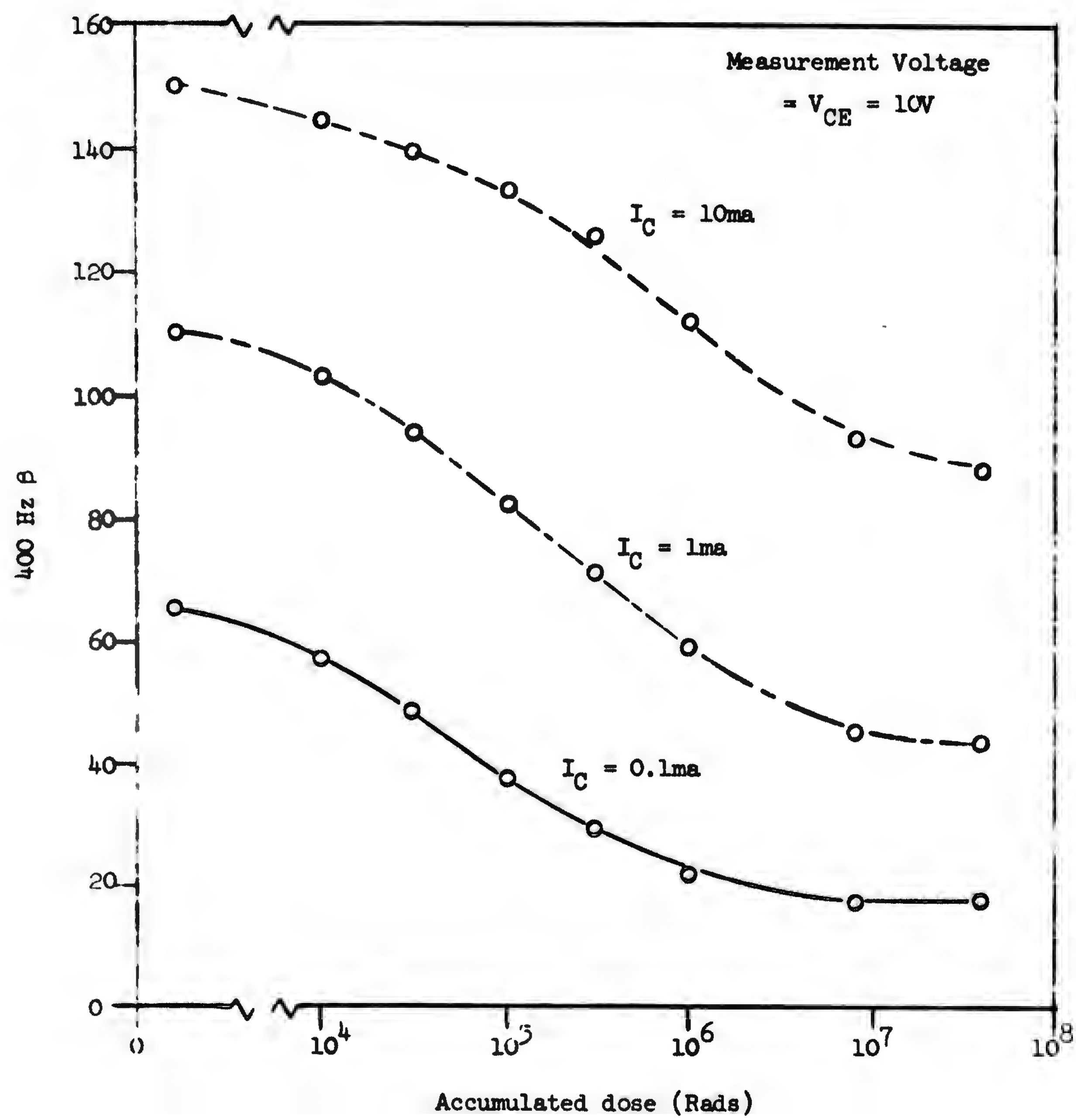

FIGURE 25: Degradation o. 400 Hz common emitter current gain for three measured collector currents. Data for the fifteen transistors are averaged. Accuracy = ± 5%.

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13. ABSTRACT

An experiment, in which 15 npn bipolar silicon transistors were exposed to Co^{60} gamma radiation, is described. The known theory concerning the radiation damage of transistors is presented. In addition, the distinguishing characteristics of ionizing radiation damage are discussed, and a method of estimating bulk damage is developed.

During the experiment, the following transistor parameters were measured: AC and DC common emitter current gain, collector-to-base leakage current, gain-bandwidth product, and base spreading resistance. The damage curves for leakage current and AC and DC common emitter current gain are plotted and discussed. The relation between transistor parameter degradation and bias current is investigated by dividing the transistors into three equal groups and biasing them at three different collector levels during irradiation. The recovery of leakage current is plotted and an exponential curve fitted to the data. Recovery time of current gain is qualitatively observed.

Data indicate that in some transistors damage to leakage current peaks near an accumulated radiation dose of 10^6 rad. The value of this peak is as large as 300 times the final damage value. The recovery time constant of leakage current damage is less than 15 minutes for the transistors tested.

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