REPORT NO. 3310
COPY NO. /

STUDY TO INVESTIGATE THE EFFECTS OF IONIZING RADIATION ON TRANSISTOR SURFACES

Contract NAS 8-20135

Second Quarterly Report for the Period
October 1 through December 31, 1965

FACILITY FORM 602

N66-23826	
(ACCESSION NUMBER)	(THRU)
30	1
(PAGES)	(CODE)
CR-71888	09
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

GPO PRICE $ ____________

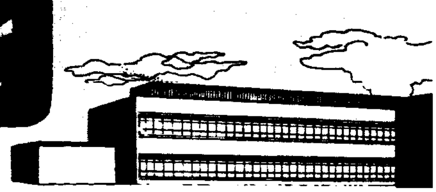
CFSTI PRICE(S) $ ____________

Hard copy (HC) 2.06

Microfiche (MF) .50

ff 653 July 65

Bendix CORPORATION



RESEARCH LABORATORIES DIVISION
SOUTHFIELD, MICHIGAN

Bendix Project 2400 | Report No. 3310

STUDY TO INVESTIGATE THE EFFECTS OF
IONIZING RADIATION ON TRANSISTOR SURFACES

Contract NAS8-20135

SECOND QUARTERLY REPORT
FOR THE PERIOD
OCTOBER 1, 1965 - DECEMBER 31, 1965

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812, Attn: PR-EC

February 11, 1966

The Bendix Corporation
Research Laboratories Division
Southfield, Michigan

Prepared by: David L. Nelson
David L. Nelson

Approved by: Donald J. Niehaus
Donald J. Niehaus

1.0 SUMMARY

This report describes the investigation, during the second three-month period of ionizing radiation surface effects on transistor parameters using 150 kV X-rays. Four tests were conducted on Fairchild 2N1613 n-p-n planar devices during this period. These tests were designed to provide information on the following:

(1) the effects of electrical bias conditions during irradiation on radiation damage

(2) the effect of different measurement conditions on the magnitude of degradation

(3) techniques for identifying the various surface damage mechanisms

(4) a technique for damage removal which will permit devices to be screened by an irradiation test followed by annealing to remove the damage.

Other work performed during the period included: (a) analysis of the results of the four tests, (b) construction of a special test fixture to enable irradiation at reduced rates as low as 5000 r/hr, (c) a dosimetry test, and (d) design and partial construction of a new high-vacuum test fixture for irradiating evacuated devices in the next quarter.

The damage induced by X-rays in the aforementioned tests varied greatly with different bias conditions during irradiation, and the amount of damage was a strong function of measurement conditions, with low current measurements sustaining much higher gain degradation. Three gain damage components were identified: (1) channel current, apparently due to inversion of the p-type base region, (2) surface space charge recombination-generation current, identified by its exponential behavior, and (3) a damage component effective only at high measurement currents, apparently due to a recombination of carriers injected very near the surface.

Annealing cycles were investigated which were combinations of temperature, electrical bias, and X-ray irradiation; and a temperature recovery cycle which completely removes X-ray induced damage was defined. The occasional failure of some temperature-recovered devices to repeat their initial damage buildup curves is attributed to incomplete redistribution of charge species in the passivating oxide.

2.0 X-RAY TEST DESCRIPTIONS

Four X-ray irradiation tests were performed on Fairchild 2N1613 transistors during this period. Purposes of the first test were to investigate the effects of electrical bias during irradiation on the damage produced, the magnitude of gain degradation at various measurement currents, and the effectiveness of a damage removal cycle consisting of X-ray irradiation combined with electrical bias. The other three tests were designed to complement the results of the first test.

2.1 TEST No.1

In this test, 12 type 2N1613 Fairchild transistors were irradiated in six groups of two devices each. Various junction bias conditions were placed on the transistors during irradiation to determine the influence of electrical bias conditions on the changes in I_{CBO} and h_{FE} produced by X-rays. The test consisted of four steps with a different set of bias conditions for each group of two devices during each irradiation test step. Table 1 lists the bias conditions used for each test step.

Table 1. Bias Conditions for First X-ray Test

Transistor Group	Bias Conditions	
	Test Steps 1 and 3	Test Steps 2 and 4
A	V_{cb} = 12V, I_e = 0	V_{cb} = 6V, I_e = 10mA
B	Passive	I_c = -10mA (fwd), I_e = 0
C	I_c = -10mA(fwd), I_e = 0	V_{cb} = 6V, I_e = 10mA
D	V_{be} = -3V, I_c = 0	V_{be} = 3V, I_c = -10mA
E	I_b = 10mA, I_c = 0	I_b = 1mA, I_c = 0
F	V_{cb} = 6V, I_e = 10mA	V_{cb} = 6V, I_e = 1mA

A total X-ray exposure in excess of 7×10^6 r (rate $\approx 5 \times 10^5$ r/hr) was delivered during each test step. I_{CBO} (V_{CB} = 5.3 volts) and $1/h_{FE}$ (100 nA $\leq I_C \leq$ 300 mA) were measured at several points during each test step to monitor the rate of damage buildup.

After completion of the second test step (see Table 1), all devices were exposed to a damage removal cycle, which consisted of forward biasing the base emitter junction (I_B = 100 mA) and irradiating the devices with X-rays for 24 hours at the above rate, followed by a second 24-hour period with the bias remaining but without irradiation. This cycle removed the X-ray induced h_{FE} and I_{CBO} degradation. Test steps 3 and 4 were then performed with the same bias conditions as steps 1 and 2 respectively (see Table 1). The purpose of this repetition of bias conditions was to determine the effect of the X-ray removal cycle on subsequent irradiations.

h_{FE} degradation data for Test 1 were analyzed by two different methods: ΔI_B versus V_{BE} plots, and $\Delta(1/h_{FE})$ versus I_C plots. The plots were used to obtain slope constants which are indicative of the type of mechanism producing the damage. Differences in damage between two points represent the damage component which was introduced in the interval between these two points. Figure 1 depicts a typical plot of ΔI_B versus V_{BE} for a transistor which had a collector-base reverse bias of 12 volts during irradiation. Curve 1 was taken relatively early in the irradiation period, while damage was still building up; and curve 2 was taken at the end of the test step when damage at all measurement levels appeared to be at a saturation level. The exponential slope constant n was greater than 3.7, which is indicative of channel current, I_{ch}.[1] After the damage approached the saturation level, n approached a value very close to 2 indicating that the primary damage mechanism was space charge recombination-generation current, I_{srg}. The presence of a channel current at low doses was typical of all devices irradiated with reverse biased, collector-base or base-emitter junctions.

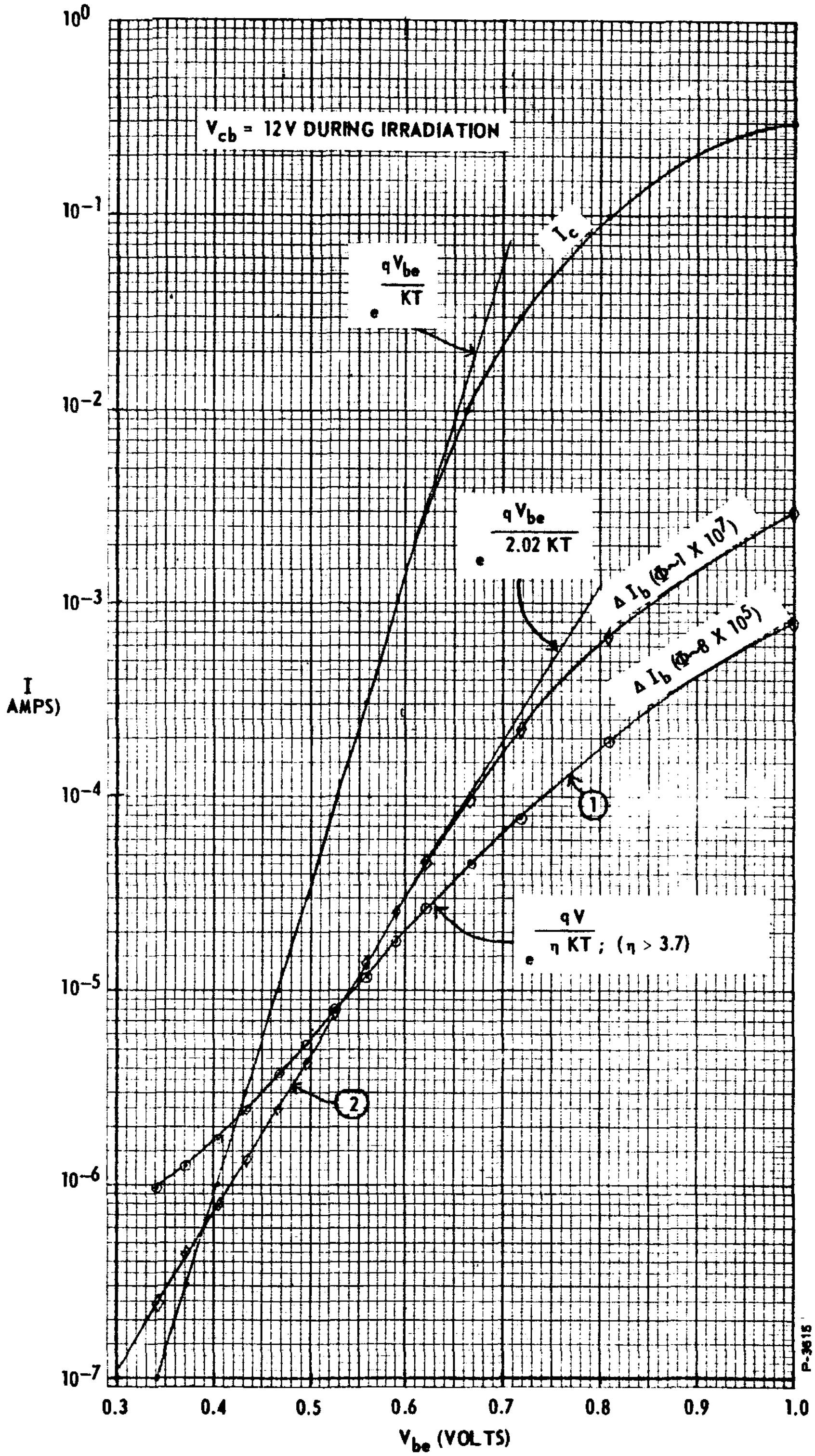


Figure 1 - X-Ray Damage Produced with a Reverse Biased Collector

Figure 2 is a plot of $\Delta \frac{1}{h_{FE}}$ versus I_C for several of the irradiation bias conditions of Test 1. These plots show that a forward bias on either junction produced less damage at low levels than passive (no bias) irradiation, and that reverse bias on the base-emitter junction produced more damage than passive irradiation. The exponential slope constant n is determined in the linear region of these curves from the formula

$$\frac{\Delta\left(1/h_{FE1}\right)}{\Delta\left(1/h_{FE2}\right)} = \left(\frac{I_{C2}}{I_{C1}}\right)^{1 - \frac{1}{n}} \tag{1}$$

Departure from linearity at low measurement currents was observed when a collector-to-base reverse bias was present during radiation (Groups A and F of Table 1). Figure 3 shows typical $\Delta \frac{1}{h_{FE}}$ versus I_C plots for the same conditions as above. In addition, the figure includes a plot of a passive test to enable comparisons with the curves of Figure 2. Curve 4 was obtained early in the irradiation period for a device with a reverse biased base-collector junction. Curves 1, 2, and 3 were taken at a large dose after apparent saturation had been reached. Curve 4 is typical of a channel current component. Curves 1 and 2, although their slopes are greater than 2 in the .1 to 10 mA region, decrease in slope at low current levels, producing a "droopy" effect at very low measurement current levels. The cause of this effect is not well understood; however, it was not observed at higher measurement conditions where the device is more likely to be used.

Digital computer techniques were used to analyze the $1/h_{FE}$ test data. The computer was programmed to perform a least square straight line fit of the data at low measurement current levels to determine the exponential slope constant and the relative linearity of the data, thereby eliminating laborious graphical techniques. A summary of the results of this analysis is given in Table 2.

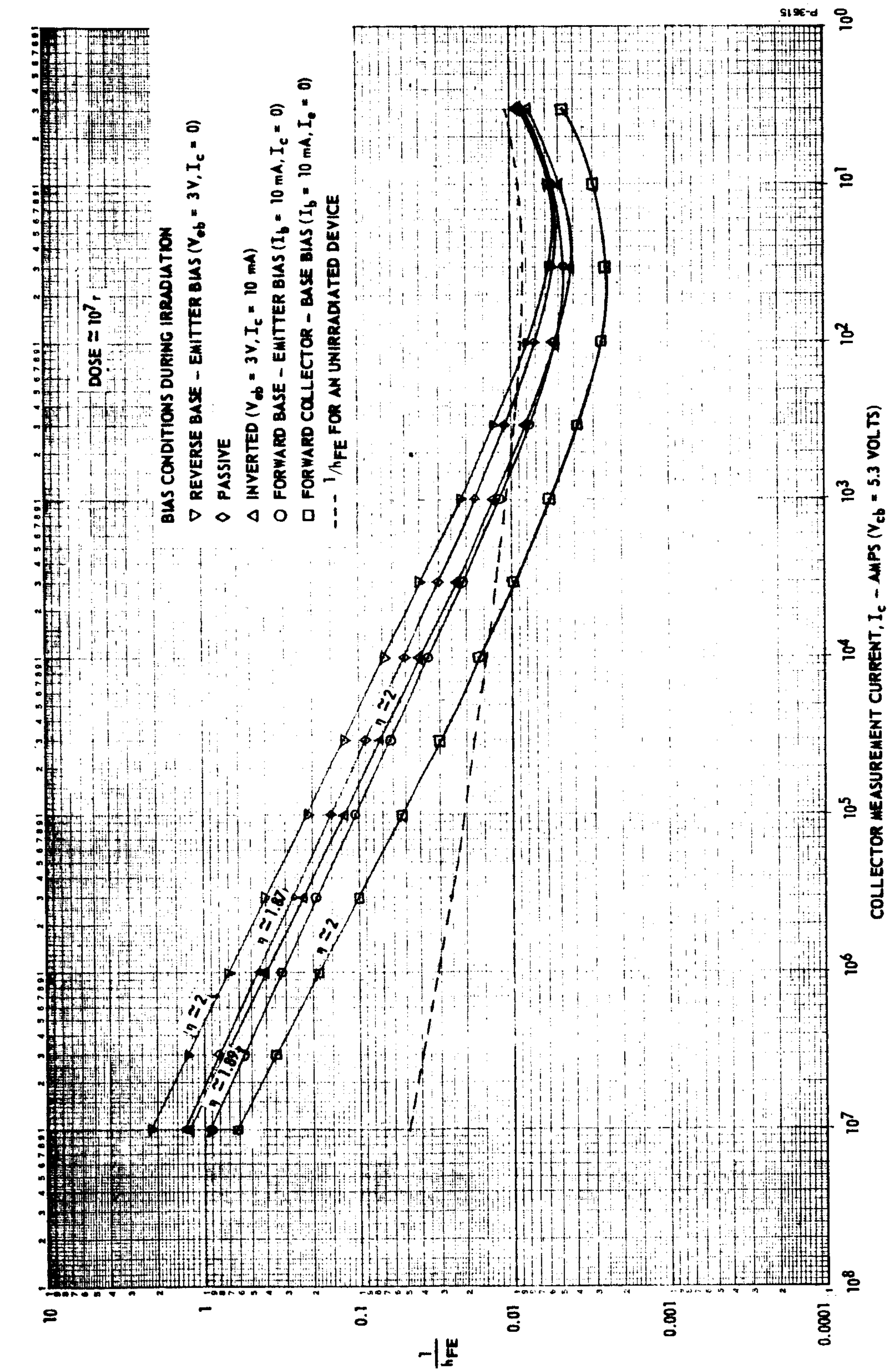


Figure 2 - Effect of Bias Conditions on X-Ray Induced Damage

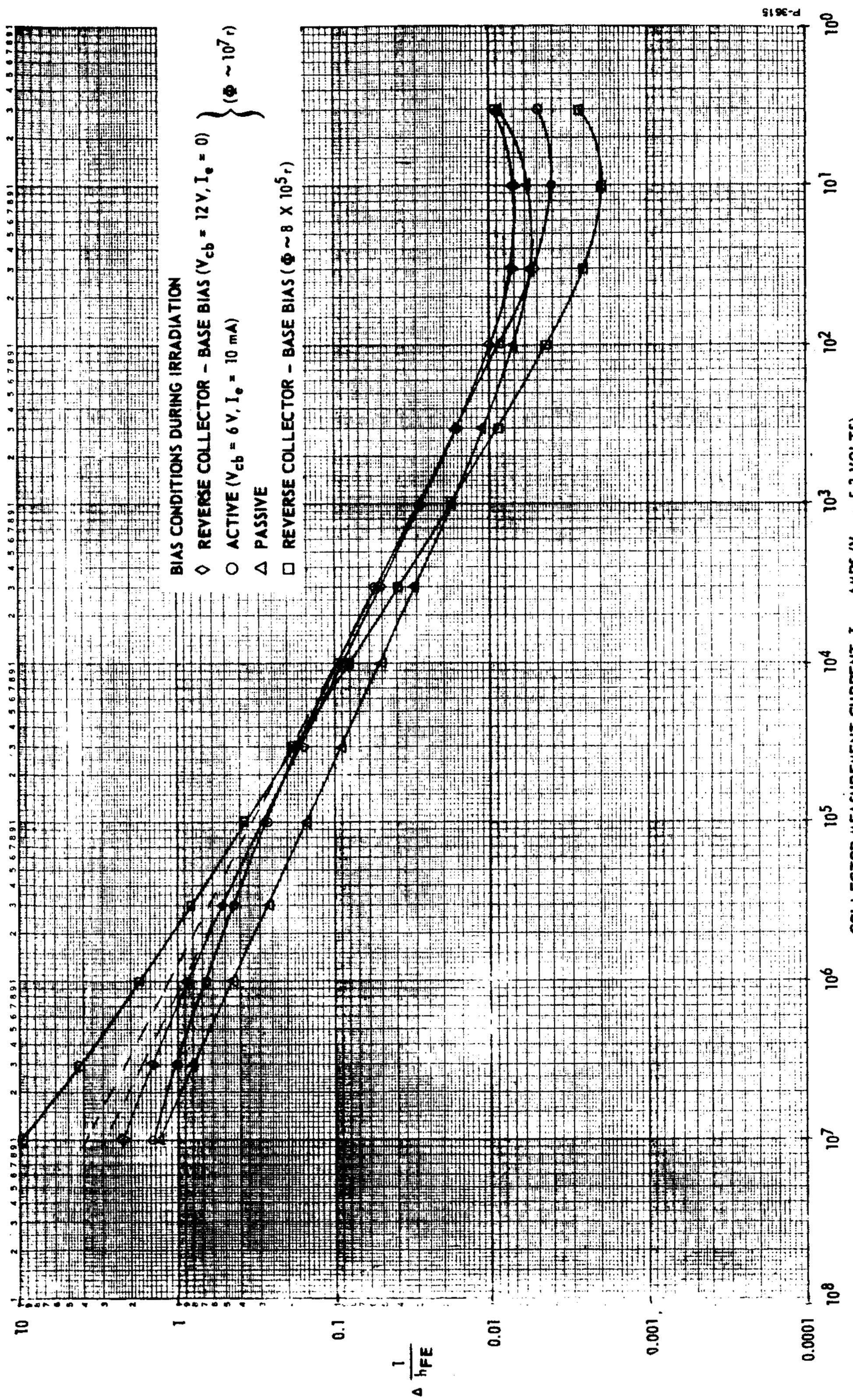


Figure 3 - Effect of Reverse Collector-Base Bias on X-Ray Damage

Table 2. Exponential Slope Constants for Damage Produced During Test No. 1

Radiation Bias Conditions	Low Dose n	Maximum Dose n
V_{CB} = 6 V, I_e = 0	3.10* / 2.15	2.00* / 2.00*
Passive	1.83 / 1.86	1.88 / 1.86
I_b = 10 mA, I_e = 0	1.92 / 1.79	2.00 / 1.90
V_{BE} = -3 V, I_C = 0	2.62 / 2.04	1.93 / 1.90
I_b = 10 mA, I_C = 0	1.84 / 1.87	1.92 / 1.90
V_{CB} = 6 V, I_e = 10 mA	2.09* / 2.04*	2.07* / 1.72*

*These devices exhibited the "droop" discussed above

Two entries are made in each position of this table since two devices were tested for each condition.

A further difference between the two low current damage mechanisms, I_{ch} and I_{srg}, is depicted by the buildup of damage at low levels as a function of dose. I_{ch} changes very rapidly during early stages of damage buildup and is rarely detected at large doses when damage saturation occurs. I_{srg} on the other hand, responds relatively slowly to dose increases but ultimately is the predominant mechanism of damage. This behavior is shown in curve 1 of Figures 4a, b, and c, where the passively irradiated devices show no evidence of high n or rapid damage buildup. The reverse biased collector base and active devices undergo a much more rapid buildup of damage accompanied by slope constants exceeding 2. However, these slopes decrease with accumulated dose, approaching values less than 2. A further indication that the early rapid gain degradation is caused by channeling is the similarity between low level gain degradation and I_{CBO} increases at low doses. Since I_{CBO} is a collector junction property and current gain is a base-emitter junction property, this similarity suggests that both these changes are due to a phenomenon taking place over the whole base region rather than locally.

Significant degradation was also observed at high measurement currents, as shown in Figures 2 and 3 by the upward turn of $1/h_{FE}$ at high currents. This degradation cannot be attributed to I_{srg} or I_{ch} since these mechanisms have diminished to negligible levels at high injection levels. The degradation is believed to be due to recombination of carriers injected across the base-emitter junction very close to the surface.

As discussed above, one of the goals of Test No. 1 was to evaluate the X-ray-electrical bias removal cycle by determining if damage buildup after a recovery cycle was similar to that observed for a new device. Curves 2 of Figures 4a, b, and c show the results of this test. As can be seen, damage buildup for passively irradiated devices and actively irradiated devices differs greatly from that for a new device. However, the reverse-biased collector-to-base response is very similar to that of a new device. This response indicates that although the recovery cycle restores the gain to its pre-irradiation value, some memory is induced into the device because the recovery cycle does not produce conditions that allow the device to return to its original state.

2.2 Test No. 2

The second X-ray test was performed to investigate the effectiveness of a modified recovery cycle on devices irradiated in Test 1. In addition, the effect of a reduction in X-ray rate on induced damage was investigated.

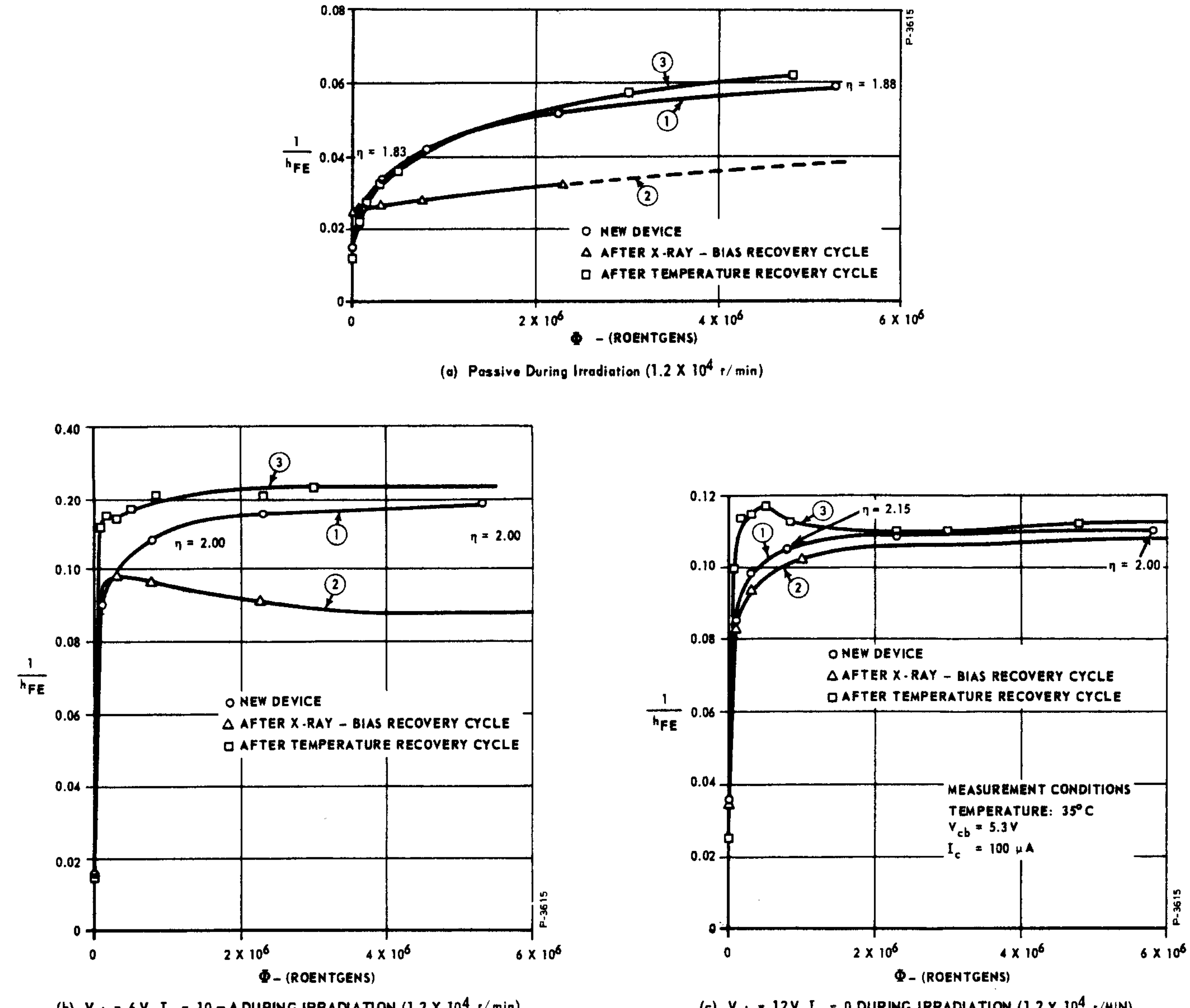


Figure 4 - Damage Buildup Before and After Recovery Cycles

Three Fairchild 2N1613 with different bias histories were selected from the devices irradiated in Test 1. Results of Test 1 had indicated that buildup of damage versus dose, after a device had been irradiated and exposed to an X-ray recovery cycle, differed from the buildup when the device was new. In an attempt to produce more complete recovery, transistors selected for Test 2 were subjected to a modified X-ray recovery cycle consisting of: (a) one day of X-ray exposure with a forward bias of 100 mA applied to both collector-base and base-emitter junctions, (b) a second day of the same bias but without X-rays, and (c) a 270°C bake for several hours with no bias. The temperature bake cycle was included with the expectation that accelerated aging might eliminate the apparent memory discussed in the previous section. Following this modified recovery cycle, three devices were irradiated with the same bias conditions as for Step 1 of Test 1 (one reverse biased collector-base, one active and one passive). Temperature controlled gain and leakage data were taken at several points during the irradiation to determine the rate of damage buildup versus dose. After sufficient radiation had been applied to cause saturation of the damage, the X-ray rate was decreased by a factor of three to determine the effect of a lower rate on the ultimate damage level.

Results of this test indicated that the modified recovery cycle permits damage buildup which more closely simulates buildup in a new device than did the normal X-ray recovery cycle used in Test 1. A reduction of the X-ray rate by a factor of three had little or no effect on the ultimate damage level of the devices tested, producing only small perturbations immediately after the rate was changed. The damage eventually settled out at a level which would have been expected had the rate not been changed. It should be noted that this rate change was made at a large dose when low current damage was predominantly I_{srg}.

2.3 Test No. 3

Due to the improvements in the recovery cycle of Test 2 produced by a temperature bake, we decided to study the effects of temperature alone on annealing X-ray induced damage. The devices irradiated in Test 2 were subjected to 30-second temperature step stresses at temperatures of 150°C, 180°C, 210°C, 240°C, 270°C, 290°C, and 320°C. Later, the same devices were subjected to longer stress periods at 320°C. Figure 5 shows the results of these tests. The bar graphs show the percent of X-ray induced damage remaining in the device after successive temperature stresses. The damage is shown at measurement currents of 1 microamp, 100 microamps, and 100 milliamps for the passively irradiated device, the actively irradiated device and the reverse-biased collector-to-base device. Devices irradiated under passive and reverse collector-to-base bias conditions exhibited considerable annealing at low temperature stresses. The actively irradiated device, however, was more difficult to anneal at low measurement currents, retaining 85 percent of its low level damage after the 270°C stress. After a 30-minute bake at 320°C, very little damage remained (less than 2 percent) and an additional five-hour 320°C bake completely recovered the devices. The gain characteristics of these three devices were as good or better than those measured when the devices were new.

2.4 Test No. 4

Test 4 was performed to (a) evaluate the temperature recovery cycle developed in Test 3 by re-irradiating these devices, (b) determine the effects of different collector-to-base reverse biases during irradiation for temperature recovered devices and (c) determine if junction capacitance changes can be detected during irradiation since a channel or extension of the base-emitter junction should produce additional junction capacitance.

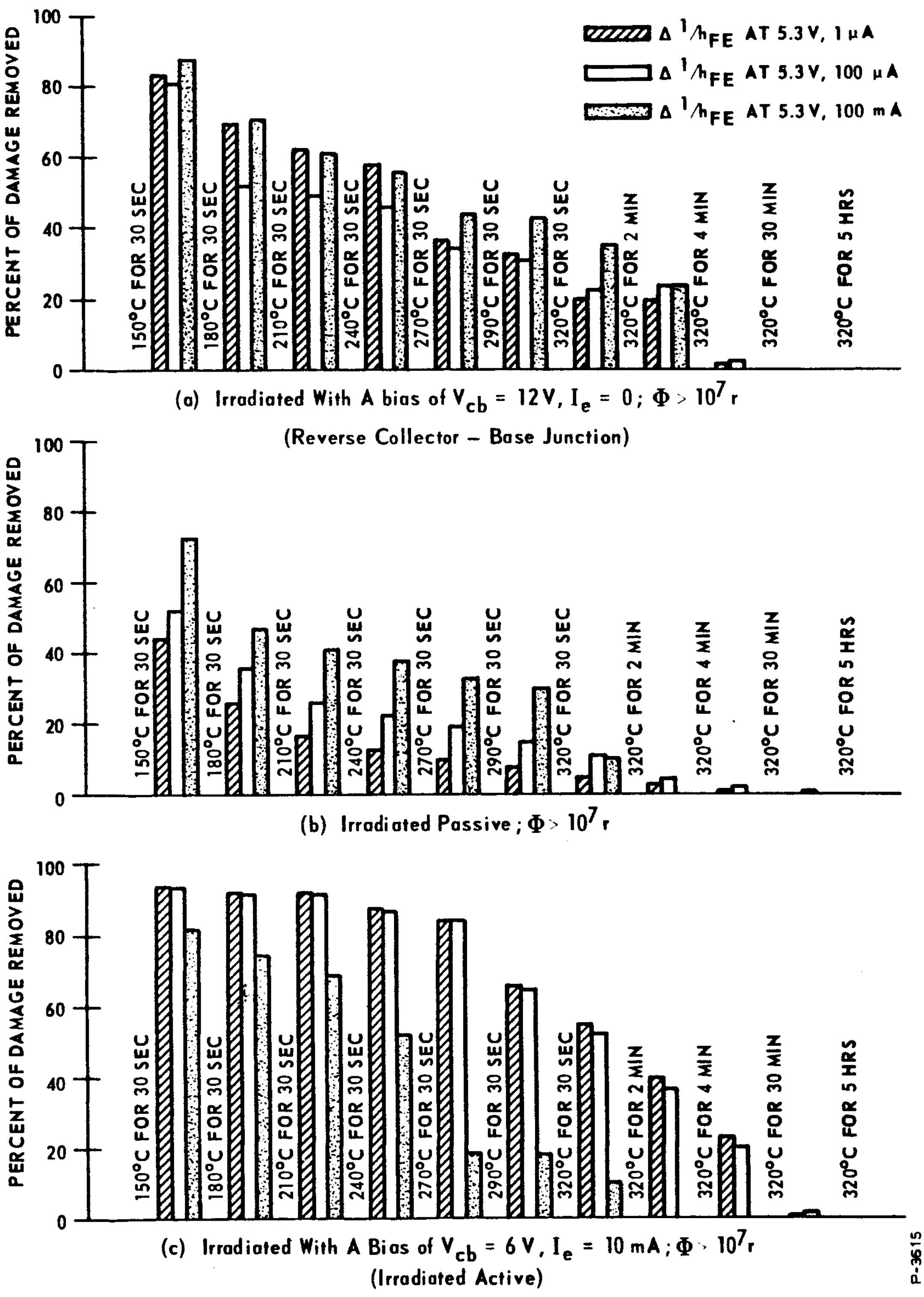


Figure 5 - Effect of Temperature Stress on Ionizing Radiation Damage Removal

To determine the effectiveness of the temperature recovery cycle, six devices having prior bias-radiation histories of active, passive, forward biased collector, and reverse biased collector were recovered by the temperature stress method. These devices were then subjected to ionizing radiation, and gain and I_{CBO} data were recorded. Junction capacity was also measured with a Wayne-Kerr Model B201 Impedance Bridge before irradiation, early in the irradiation, and at the end of the irradiation.

Curves 3 of Figures 4a, b, and c, show damage buildup characteristics for the passive, active and reverse bias collector devices. Unlike the X-ray recovery cycle, the temperature recovery cycle permitted a damage buildup curve for a passively irradiated device which was very similar to the new device. The active and 12-volt reverse biased collector devices were also very similar to the new device at high doses. However, during the initial damage buildup these devices differed from the "new" by exhibiting a somewhat higher rate of buildup and also a slight peaking of damage at early doses. The three reverse biased collector-to-base junction devices (6, 12, 50 volts) appeared to produce damage proportional to their reverse biased voltages. However, this comparison is difficult to make since these three devices may have different sensitivities to X-ray irradiation.

All devices which had reverse biased collector-to-base junctions exhibited large changes in junction capacitance, while the devices irradiated passively and the device irradiated with a forward biased collector-to-base junction showed no significant change in junction capacity throughout the test. The four devices which did exhibit large capacitance changes at low doses returned approximately to their pre-irradiation capacitance values after a large dose, suggesting that a channel had been induced in the early stages of the irradiation but that it had receded by the time a large dose was received.

Table 3 shows the junction capacity changed by X-ray irradiation.

Table 3. Junction Capacitance Changes
Produced by X-ray Irradiation

Bias Conditions During X-ray	Junction Capacitance* (pF)			
		Before X-ray	1.5×10^5 r	1.5×10^7 r
V_{CB} = 6 volts	B-E	60.84	71.70	61.52
	B-C	48.96	55.42	50.48
V_{CB} = 12 volts	B-E	62.83	66.49	62.95
	B-C	49.81	86.47	50.25
V_{CB} = 50 volts	B-E	62.35	156.60	62.34
	B-C	47.99	150.22	49.69
Passive	B-E	61.70	61.75	61.77
	B-C	47.16	48.13	47.65
I_b = 10 mA	B-E	58.80	58.63	58.64
I_e = 0	B-C	48.64	51.00	51.24
V_{CB} = 6 volts	B-E	63.42	81.77	63.85
I_e = 10 mA	B-C	48.85	48.43	49.89

*Capacitance measured at 0 volts with a Wayne-Kerr Model B201 Impedance Bridge

The 50 volt collector-to-base reverse bias during irradiation produced the largest changes in junction capacity. Collector-to-base capacity more than tripled, and base-emitter capacity increased two and one-half times early in the irradiation period. Accompanying this large increase in capacitance was a large channel term in gain degradation with a slope constant of approximately 3.7 (see Figure 6). At the end of the irradiation period junction capacities decreased to near their pre-irradiation values, and the slope constant decreased to a value of about 1.92, indicating that the channel had disappeared.

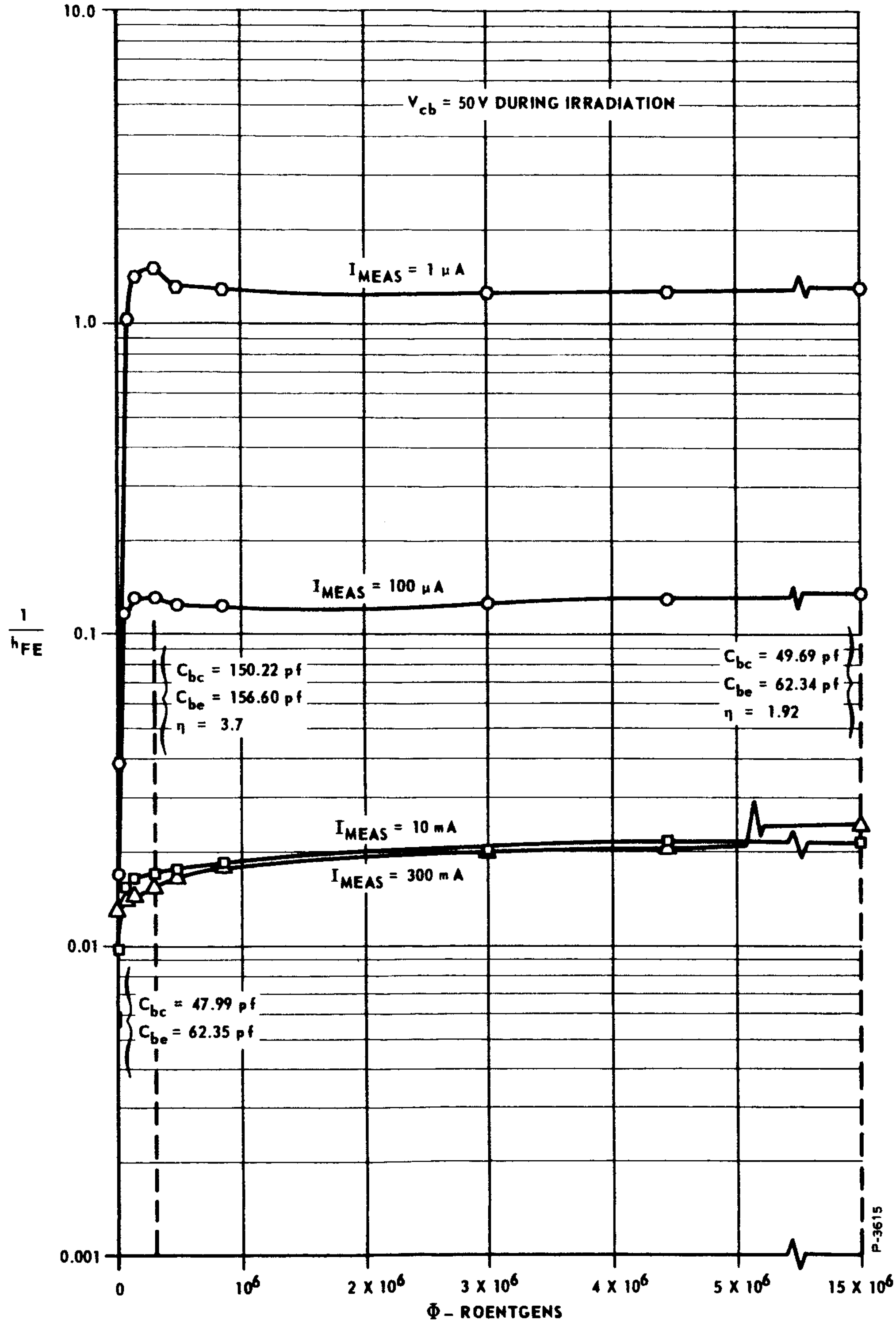


Figure 6 - Damage Buildup at Different Measurement Currents

3.0 TEST ANALYSIS AND CONCLUSIONS

This section includes a summary of observations made during the test program of this Quarter, a summary of the conclusions drawn from these tests, and recommendations for further actions required to accomplish the goals for Phase I of this program. Due to the many interrelationships between observations, conclusions and required further action, these sections are in an itemized format to make cross reference convenient.

3.1 Summary of Observations

1. Collector-to-base reverse bias during irradiation is more damaging than base-emitter reverse bias. A reverse bias of either junction produces a fast responding damage component with an exponential slope constant greater than 2 at low measurement currents.
2. A reverse biased collector-to-base junction produces a large fast-rising increase in low level gain damage accompanied by a large fast-rising increase in I_{CBO} during the initial buildup of damage.
3. Collector-to-base and base-to-emitter junction capacitances undergo a large increase early in the damage buildup cycle for devices irradiated with a reverse biased collector-to-base junction. These capacitances decrease to near their initial values after large doses.
4. The tendency of low level gain degradation after large doses is to approach an exponential slope constant n of 2 or less.
5. In the absence of a reverse bias on both junctions, damage builds up at a relatively low rate and has an exponential slope constant, n, less than or equal to 2.
6. A temperature bake of damaged devices for five hours at temperatures in excess of 300°C removes all the X-ray induced

gain degradation, but re-irradiation has a fast-rising damage component in excess of that observed when the device was new.

7. The X-ray recovery cycle removes most of the damage induced by radiation, but re-irradiation produces less damage for devices irradiated passive or active.
8. A relatively slow buildup of gain degradation measured at high collector currents is observed which resembles the normal base spreading resistance term at high measurement currents for normal transistors.

3.2 Summary of Conclusions

Based on the observations discussed in the preceding section and on recent radiation effects and semiconductor physics literature, the following conclusions and theories are presented:

1. Observations 1 through 4 support the existence of a channel component in gain degradation which increases at rapid rates and produces an exponential slope constant in excess of 2. This component can be produced by a reverse bias on either device junction; however, a reverse bias on the collector-base junction is a more severe condition, even though the channel component is a base-emitter property. Since the collector-base junction fringing field is too far from the base-emitter junction to exert a strong influence, the most likely explanation for this behavior is that proposed originally by Bell Telephone Laboratories,[2] whereby electric fields in the ambient surrounding the transistor cause collection of positive gas ions produced by the ionizing radiation on the oxide over the base and emitter regions which are biased negative with respect to the collector region and encapsulating can. A more recent proposal[3] is that actual deposition of the gas molecule on the device surface does not occur but that the positive ion in traveling very close to the silicon dioxide

ambient interface gives up its positive charge by taking on an electron from a "site" on the SiO_2 surface. This accumulation of a positive space charge over the base region surface can account for the sensitivity of damage to collector-base junction reverse bias and, if the space charge magnitude is high enough, explain the creation of an inversion layer or channel on the base region surface. This mechanism alone cannot explain the behavior observed since no means is supplied for removal of the channel at large doses. Work reported by Kang[4] supplies this mechanism. Mobile charge species in the oxide will migrate under the influence of an electric field. The presence of this type of charge migration in ionizing radiation is verified by recent studies of ionizing radiation effects on MOS structures, where the combination of radiation and a field across the SiO_2 layer causes charge species in the oxide to migrate. Figure 7 is a pictorial description of this model.

In the case of junction transistors, the field is produced by the accumulated SiO_2 surface charge. Positively charged species migrate to the Si-SiO_2 interface. Due to the proximity of this charge to the silicon beneath the interface, a strong inversion layer is formed, which produces a channel or extension of the n-type emitter region under base region passivating oxide. The proximity of the positive oxide space charge to the negatively charged channel creates very high fields across the silicon dioxide interface, exceeding the potential barrier for this junction. Electrons then cross the interface junction and discharge the positive charged species at the interface, reducing the oxide space charge. This in turn reduces the inversion layer, and eventually the channel recedes. Evidence to support this theory was presented by Kang using both MOS structures and "metal protected junction transistors."

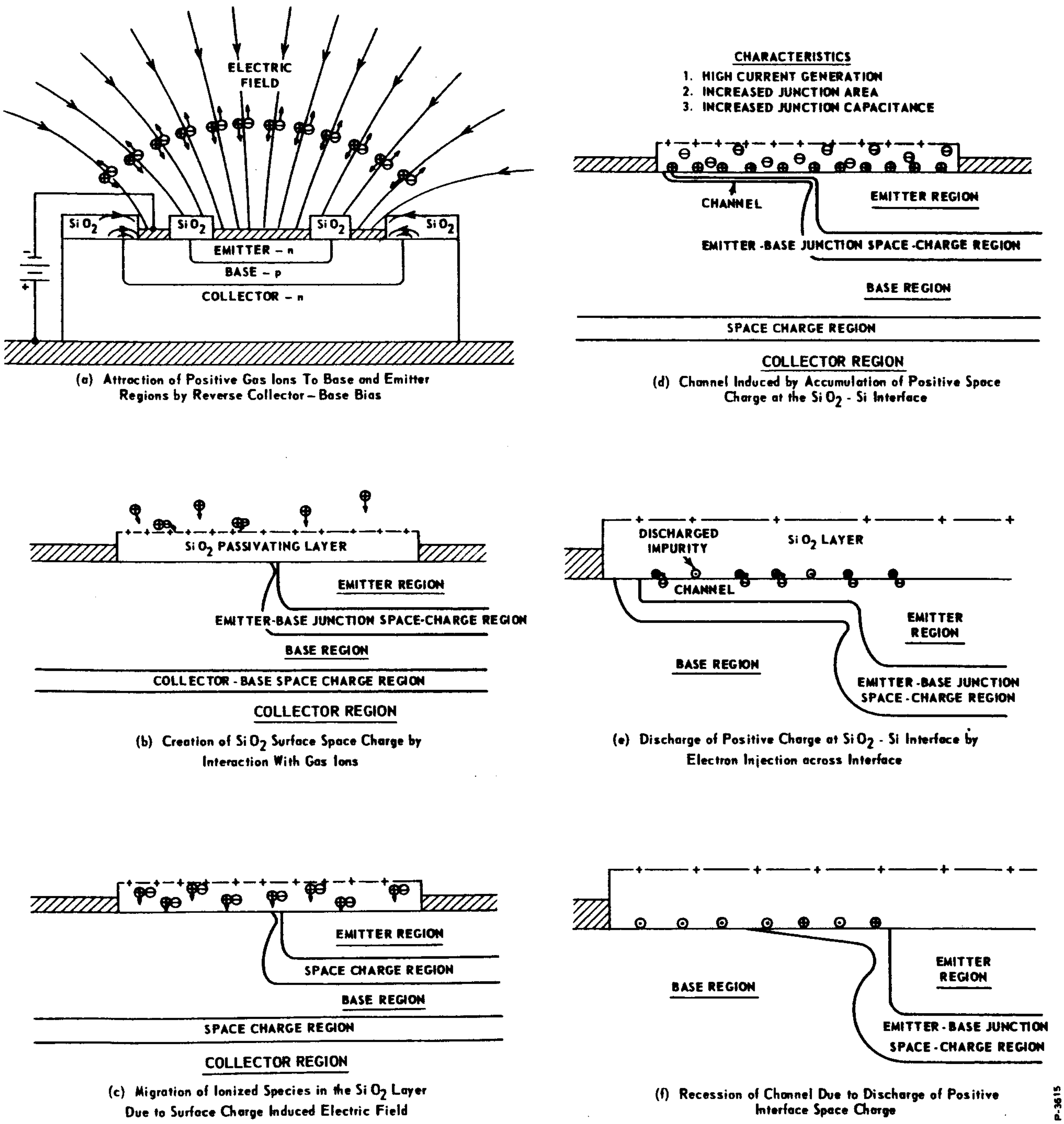


Figure 7 - Preliminary Model for Ionizing Radiation Surface Effects

Assuming a limited number of charge carriers originally available in the SiO_2, the net result is to concentrate these species at the SiO_2-Si interface in an uncharged state. Redistribution of these carriers throughout the oxide layer requires that they be ionized (with temperature or radiation) and that the oxide electric field which originally produced migration be removed. This model may eventually explain the difference in temperature and X-ray recovery cycles observed during the test program; however, a better understanding of the effects of the fringing field at the base-emitter junction is required.

2. Observations 3, 4, 5 and 7 indicate that a slower responding gain degradation component due to surface space charge recombination-generation current is present with an exponential slope constant n of 2 or less. This component usually dominates after large ionizing doses. Exposure to X-ray recovery cycle tends to suppress the I_{srg} component, possibly due to the redistribution of charge carriers in the SiO_2 layer caused by the forward junction bias present during this recovery cycle.

   The presence of an I_{srg} component fits well with the model discussed in the first conclusion. After a sufficient portion of the positive space charge at the oxide interface has been neutralized, the inversion layer or channel disappears, leaving a space charge layer beneath the interface which acts as an extension of the base-emitter junction space charge region. This causes a large portion of the space charge region to be exposed to the high recombination rate present at the interface. This model explains the dominance of channeling very early in the damage buildup followed by dominance of I_{rg} during latter portions of the irradiation period.

3. Although temperature causes removal of all X-ray gain degradation, the tendency toward channeling exists with a reverse biased collector-to-base junction early in the irradiation which was not observed on irradiation of a new device. This behavior is possibly due to incomplete redistribution of of positive charge carrier species in the SiO_2 layer due to a too short or too low temperature stress. If these charge carriers are not allowed to return to an equilibrium condition, a different damage response would be expected upon re-irradiation due to their proximity to the Si-SiO_2 interface.
4. Observation 8 indicates the presence of a gain degradation component effective at high measurement currents which builds up slowly with dose. This component is tentatively identified as recombination of injected carriers near the base surface. The component behavior is similar to the base spreading component in a normal planar transistor. This type of degradation could occur due to an X-ray induced reduction of the base-emitter junction barrier potential at the region where the base-emitter junction meets the Si-SiO_2 interface. The combination of a reduced barrier potential in this region and the resistive voltage drop which occurs across the bulk base region at high currents, could cause a significant amount of current to be injected near the surface. Due to device geometry and the high recombination rate present in the base region at the surface the probability of recombination of carriersis very high.

4.0 FURTHER ACTIONS REQUIRED

Goals for Phase I of this program consist of: (1) identification of ionizing radiation damage components as a function of bias conditions during irradiation, dose, and rate, (2) determination of an acceptable annealing cycle which will enable device screening, (3) comparison of ionizing radiation damage in the normal device ambient and in vacuum, and (4) comparison of temperature and ionizing radiation stresses to determine if correlations exist.

1. Damage Identification - Further work required to satisfy this goal will consist of (a) further investigation of the capacitance method of detecting junction channels, (b) an investigation of damage temperature coefficients to enable identification of the high current damage component, (c) investigation of low ionizing rate damage effects and (d) performance of a series test which will enable description of bias effects during irradiation on a single device.
2. Annealing Cycle - Further tests will be performed to determine the acceptability of the temperature recovery cycle.
3. Vacuum Test - Design of the vacuum test was completed during this quarter. The fixture is being fabricated and the test will take place in the next period.
4. Temperature Ionization Relationships - A test has been designed and will be performed during the next quarter in an attempt to determine if correlations exist between temperature stress and ionizing radiation stresses on surface stability.

REFERENCES

1. C. T. Sah, "Effect of Surface Recombination and Channel on P-N Junction and Transistor Characteristics," IRE Trans on Electron Devices, 94-108, January 1962

2. D. S. Peck et al, "Surface Effects of Radiation on Transistors," Bell System Technical Journal, 42, p. 95, January 1963

3. P. J. Estrup, "Surface Charge on Silicon Induced by Ambient Ionization," Solid State Electronics, 8, 535-541, 1965

4. K. D. Kang, "Detailed Study of Deleterious Effects on Silicon Transistors," RADC-TR-65-35, Final Report by Motorola under Contract AF 30(602)-3244, May 1965

5. H. L. Hughes, "Surface Effects of Space Radiation on Silicon Devices," IEEE Trans on Nuclear Science, 53-63, December 1965