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Determination of Late-time γ-Ray (^{60}Co) Sensitivity of Single Diffusion Lot 2N2222A Transistors

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Determination of Late-time γ-Ray (^{60}Co) Sensitivity of Single Diffusion Lot 2N2222A Transistors

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Abstract

Sandia National Laboratories (SNL) has embarked on a program to develop a methodology to use damage relations techniques (alternative experimental facilities, modeling, and simulation) to understand the time-dependent effects in transistors (and integrated circuits) caused by neutron irradiations in the Sandia Pulse Reactor-III (SPR-III) facility. The development of these damage equivalence techniques is necessary since SPR-III was shutdown in late 2006. As part of this effort, the late time γ-ray sensitivity of a single diffusion lot of 2N2222A transistors has been characterized using one of the ^{60}Co irradiation cells at the SNL Gamma Irradiation Facility (GIF). This report summarizes the results of the experiments performed at the GIF.

ACKNOWLEDGMENTS

The authors appreciate the GIF staff (particularly Don Hanson) for their efforts during our irradiations. Dave Vehar and Chuck Holm provided valuable assistance with our dosimetry. Ed Thomas helped us greatly with the statistical analyses. Finally, the authors would like to thank Louis Merriken and Don King for their assistance with the transistor gain measurements.

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NOMENCLATURE

BJT	Bipolar Junction Transistor
ELDRS	Enhanced Low Dose Rate Sensitivity
FBR	Fast Burst Reactor
GIF	Gamma Irradiation Facility
QASPR	Qualification Alternatives to the Sandia Pulse Reactor
SIMS	Surface Ion Mass Spectroscopy
SNL	Sandia National Laboratories
SPR-III	Sandia Pulse Reactor-III
TLD	Thermoluminescent Dosimeter

1. INTRODUCTION

Sandia National Laboratories (SNL) committed to decommissioning the Sandia Pulse Reactor-III (SPR-III) facility in late 2006. The decommissioning of SPR-III and the shut down of all but one other Fast Burst Reactor (FBR) in the United States means that alternative methods of testing electronic components for radiation damage survivability need to be developed. The program initiated by SNL to develop these damage relations techniques is called Qualification Alternatives to the Sandia Pulse Reactor (QASPR). The techniques that will be used by the QASPR program include testing at alternative experimental facilities, modeling, and simulation. The goal of the QASPR program is to develop alternative methods of qualifying weapon system components and sub-systems in the absence of the test capabilities previously available at the SPR facility.

Neutron radiation fields generate secondary γ-ray fields which cause additional damage. The effects of γ-ray damage in electronics needs to be better understood and quantified so it can be separated out from the neutron caused damage. To this end, the late-time γ-ray sensitivity of a single diffusion lot of 2N2222A transistors has been characterized. The gain degradation of these transistors for γ-ray ionizing doses ranging from 2.5 krad[H_2O] – 9.8 Mrad[H_2O] at 3 different dose rates irradiated with the ^{60}Co source of SNL's Gamma Irradiation Facility (GIF) was studied. The transistors were then annealed to determine how well the transistors recovered their original properties. Understanding the variability in γ-ray sensitivity of this small portion of a single lot will also help us understand the overall variability in the effects of γ-rays on all the transistors in the lot.

1.1. Experimental Procedures

1.1.1. 2N2222A Transistors

The experiments were performed on commercial 2N2222A NPN bipolar junction transistors (BJTs) purchased as part of a 10000 die single diffusion lot. The experiments used a 100 BJT subset of this single diffusion lot. The BJTs were supplied by Microsemi Lawrence of Lawrence, MA. The die size of the purchase was 023F-MSCL, and the lot number was 2054-8 WF#8. SNL arranged for the dies that were used in these experiments to be packaged in TO-18 cans. Each TO-18 can is laser etched with a unique identifying number. The QASPR program requires surface ion mass spectroscopy (SIMS) and deconstruction analysis of each single diffusion lot purchase. In addition, the program requires careful tracking of each transistor from each single diffusion lot purchase.

1.1.2. Pre-Irradiation Gain Measurements

After receiving the BJTs from the QASPR program, a measurement of the current-voltage characteristics was performed on each transistor by a computer-controlled HP 4155C parameter analyzer. The measurement technique used is described in ASTM International E 1855-96 [1]. The gain measurement of interest (h_{PRE}) is determined by Equation (1):

$$h_{PRE} = \frac{I_C}{I_B} \quad @ \quad I_C = 1\, mA \tag{1}$$

where I_C is the collector current and I_B is the base current in a common emitter circuit. These measurements were carried out at ambient room temperature (~20° C) in the dark. See Figure 1 for a schematic of the common emitter circuit.

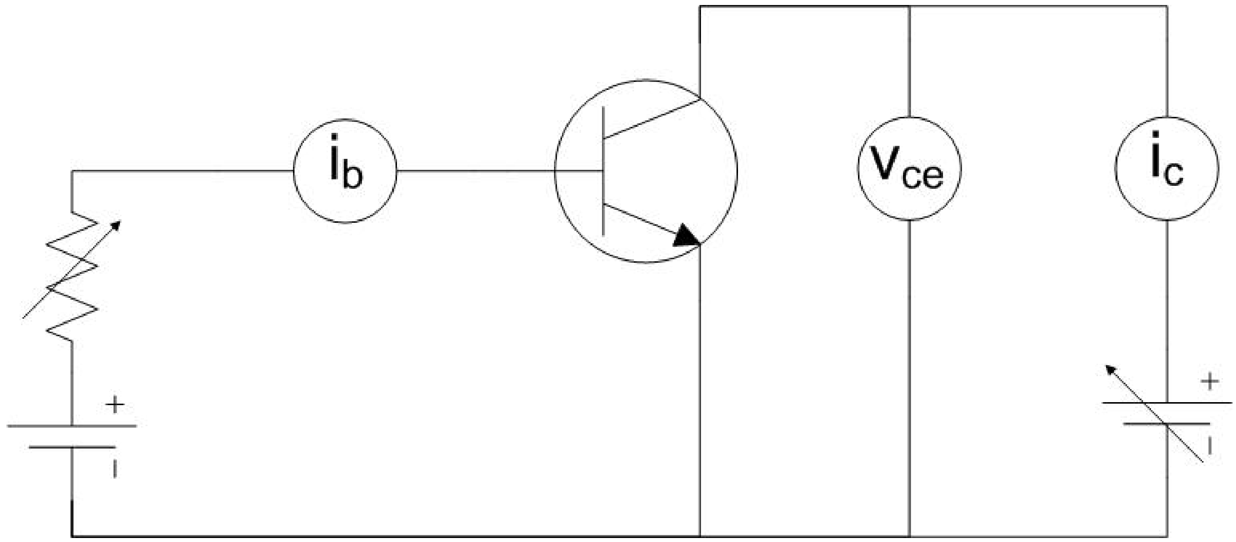

Figure 1. Common Emitter Circuit for Gain Measurements

In order to adjust for variations in the ambient room temperature during future gain measurements, 3 transistors (out of the 100 total) were designated as temperature control transistors. The unirradiated temperature control transistors are read during each subsequent gain measurement and a temperature correction factor (T_c) is determined for the measurement using Equation (2):

$$T_c = \frac{1}{n}\sum_{i=1}^{n}\frac{C_i}{R_i} \quad (2)$$

where n is the number of control transistor measurements, C_i is the transistor gain measured for the i^{th} control transistor in the pre-irradiation gain measurement, and R_i is the transistor gain measured for the i^{th} control transistor in the present readout.

1.1.3. Irradiations

The irradiations were performed in GIF Irradiation Cell #2. GIF Irradiation Cell #2 contains a 200 kCi ^{60}Co cylindrical source array. The cylindrical source array consists of 20 ^{60}Co source pins arranged to approximate a right circular cylinder with a radius of ~18.1 cm and a height of ~41 cm. Before beginning the irradiations, the GIF staff determined the dose rate at three locations. Location 1 had a measured dose rate of 881.7 +/- 12.7 rad[H_2O]/s and is located inside the cylindrical source array. The dose rates at locations 2 and 3 were 125.5 +/- 3.5 and 10.15 +/- 0.41 rad[H_2O]/s, respectively. All 3 locations used lead-aluminum filter boxes to shield out the low-energy scattered photons [2]. The target irradiation conditions for the various locations are found in Table 1. For the initial irradiations, 3 transistors along with the associated dosimetry (3 alanine pellets in a single equilibrator and 4 SNL normal equilibrated CaF_2:Mn thermo-luminescent dosimeters [TLDs]) were placed at each location to provide a statistical sample of the transistor dose response. The transistors were irradiated with the leads shorted by aluminum foil to establish clear electrical boundary conditions. A sample of an exposure fixture and geometry is found in Figure 2.

Table 1. Target Doses for Irradiations

Target for Total Dose in H_2O*	Dose Rates in Rad[H_2O]/second		
	10.15	125.5	881.7
2.5 krad [H_2O]	✓	---	---
5 krad[H_2O]	✓	---	---
7.5 krad[H_2O]	✓	---	---
10 krad[H_2O]	✓	✓	---
25 krad[H_2O]	✓	✓	---
50 krad[H_2O]	✓	✓	---
75 krad[H_2O]	✓	✓	---
100 krad[H_2O]	✓	✓	✓
250 krad[H_2O]	✓	✓	✓
500 krad[H_2O]	✓	✓	✓
750 krad[H_2O]	✓	✓	✓
1 Mrad[H_2O]	✓	✓	✓
2.5 Mrad[H_2O]	✓	---	---
5 Mrad[H_2O]	---	---	✓
7.5 Mrad[H_2O]	---	---	✓
10 Mrad[H_2O]	---	---	✓

***The actual doses were determined using either equilibrated alanine dosimeters or SNL normal Al-equilibrated CaF_2:Mn TLDs.**

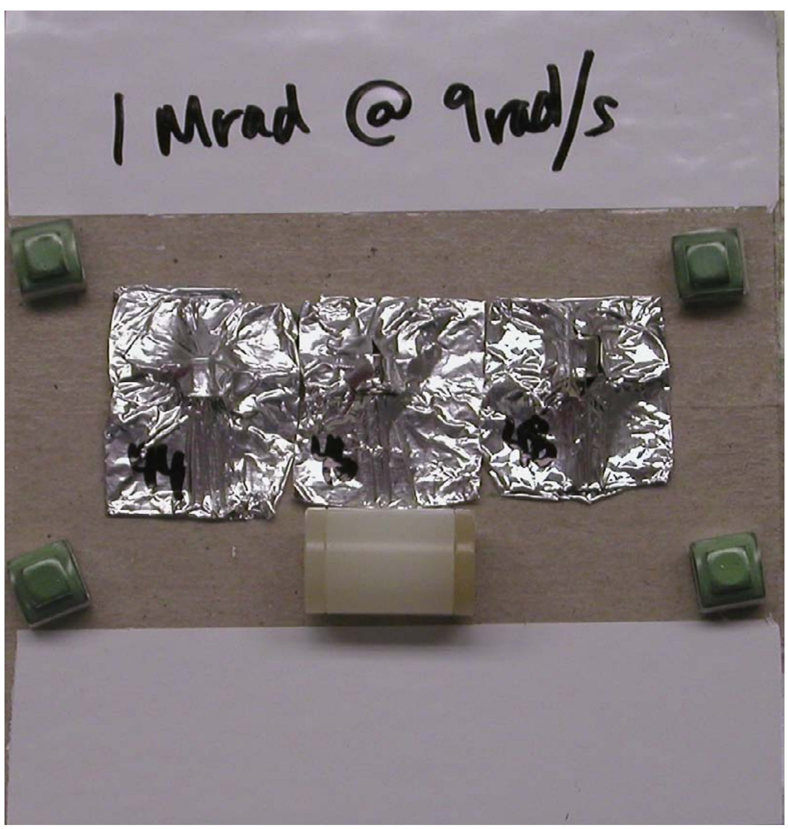

Figure 2. Typical Exposure Setup and Geometry

1.1.4. Post-Irradiation Gain Measurements

After the irradiations, the transistors were typically stored less than a week at ambient room temperature until the gain measurements could be made. A measurement of the current-voltage characteristics was performed on each irradiated transistor and the temperature control transistors by a computer-controlled HP 4155C parameter analyzer using the same technique as the pre-irradiation gain measurement. The gain measurement in this step must be adjusted for the temperature differences that may have occurred between the pre-irradiation and post-irradiation gain measurements by using Equation (3):

$$h_{POST} = T_c \cdot h'_{POST} \qquad (3)$$

where h_{POST} is the temperature corrected post-irradiation gain and h'_{POST} is the uncorrected post-irradiation gain.

1.1.5. Stabilization Anneal and Additional Gain Measurements

Following the post-irradiation gain measurement, an annealing step was performed. The annealing step consisted of exposing the transistors to 80^o C for 2 hours. The annealing step is known as a temperature stabilization (or “light”) anneal and is performed to remove variations associated with ambient temperature annealing during and after the irradiation [1]. After the transistors return to ambient room temperature, the gain measurements were performed again. Using Equation (3), the gain measurement after the stabilization anneal ($h_{POST-SA}$) was corrected for temperature.

1.1.6. Hard Anneal and Additional Gain Measurements

Following the post-stabilization anneal gain measurement, an additional “hard anneal” step was performed. This annealing step consisted of exposing the transistors to 180^o C for 24 hours. The annealing step is performed to reset the gains for the next irradiation and extend the useful life of the dosimeter for multiple irradiations [1]. After the transistors return to ambient room temperature, the gain measurements were performed again. Using Eqn (3), the gain measurement after the hard anneal ($h_{POST-HA}$) was corrected for temperature.

1.1.7. Additional Irradiations

In order to determine whether the γ-sensitivity of the transistors changed after multiple exposures and annealing, an additional series of irradiations was performed at the 10.15 rad[H_2O]/s dose rate. Using statistical sampling from the irradiated transistors at all 3 previous dose rates, 7 transistors were selected to be exposed over 3 orders of magnitude of total doses. After the irradiations, a stabilization anneal (described above) was performed, and then a transistor gain measurement (also described above) was made. Using Equation (3), the gain measurement after the stabilization anneal ($h_{MULTIPLE}$) was corrected for temperature.

1.1.8. Reciprocal Gain Calculations

The standard test method [1] defines a change in the reciprocal gain. This is calculated using Equation (4):

$$\Delta\left(\frac{1}{h}\right)=\left(\frac{1}{h_{POST}}\right)-\left(\frac{1}{h_{PRE}}\right) \quad (4)$$

where $\Delta\left(\frac{1}{h}\right)$ is the change in reciprocal gain. This quantity is used with the Messenger-Spratt equation to determine the silicon 1-MeV equivalent fluence for neutrons. Since these experiments were γ-ray exposures, this quantity can be used to determine the late-time γ-ray sensitivity coefficient (K_γ), which is used to correct the dosimeter when used as a neutron monitor in a mixed n/γ field. The standard test procedure [1] assumes that the γ-ray sensitivity is a linear function in the useful range. This series of experiments will be used to establish the total dose range where this assumption is applicable. In addition, any change in the correct shape of the late-time γ-ray sensitivity curve will be determined by this experiment series.

2. EXPERIMENTAL RESULTS

2.1. Pre-Irradiation Gain Measurements

After obtaining the 2N2222A NPN BJTs, an initial measurement of the current-voltage characteristics was performed on each transistor by a computer-controlled HP 4155C parameter analyzer. The following parameter analyzer source setup was used for all the transistor characterizations:

- The measurements of the current-voltage characteristics are made in steady state mode rather than pulse mode due to the limitations of the parameter analyzer.
- The collector-emitter voltage (V_{CE}) is set as a fixed parameter of 10 V.
- The emitter voltage (V_E) is set as a fixed parameter of 0 V.
- The base current (I_B) is varied in the "sweep" mode from 1 nA to 1 mA using 50 points per decade for a total of 301 points.
- The maximum collector current (I_C) is set as 1.1 mA.
- Parameters recorded: I_B, I_C, I_E (emitter current),V_{BE} (base-emitter voltage), V_{CE}, and V_E

The characterization of the transistors with the above settings results in information that can be plotted as Gummel curves. Figure 3 shows an example of the pre-irradiation transistor characterization curves.

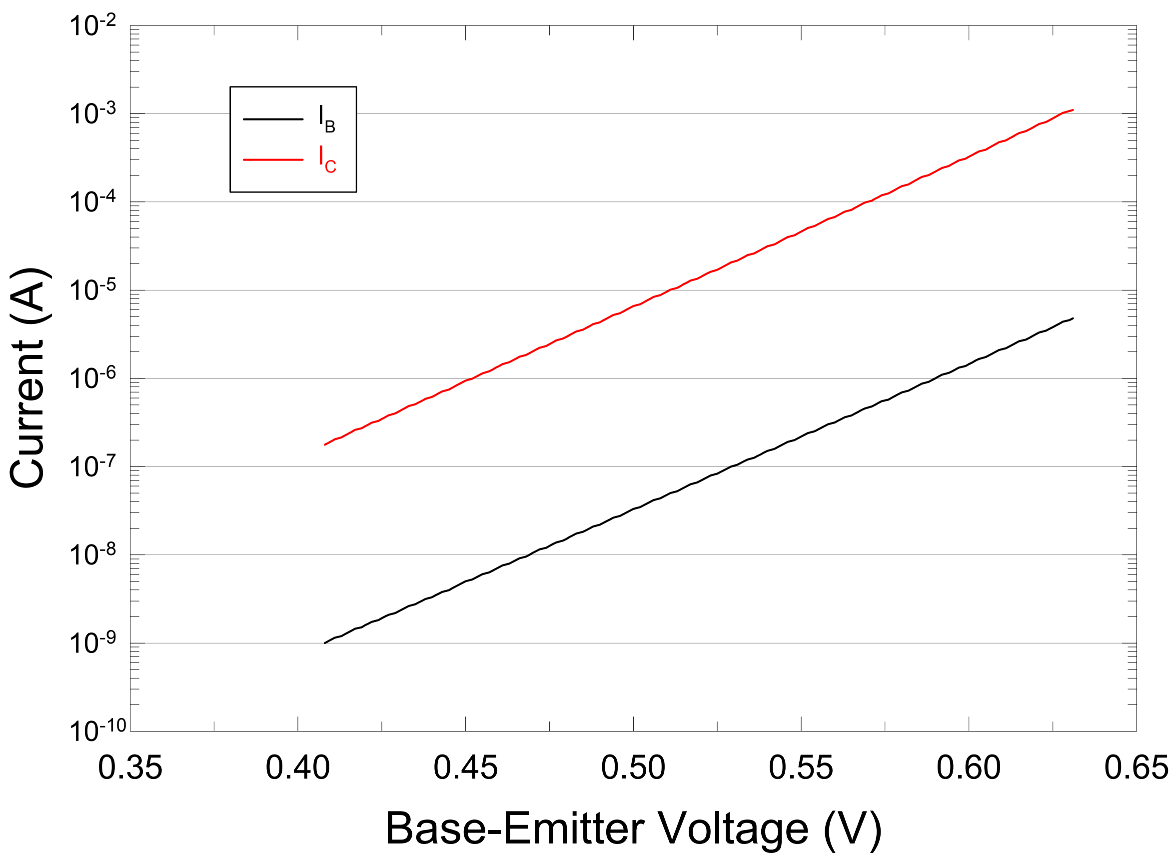

Figure 3. Pre-Irradiation Characterization of Transistor ID #801

As noted above in Equation (1), we need to determine the transistor gain with I_C = 1 mA. As the sweep of I_B is performed, there is no guarantee that an I_C = 1 mA will be measured. Thus, a linear interpolation of I_C values above and below 1 mA is used to determine the gain defined in Equation (1). The linear interpolation technique used to determine the gain is defined in Equation (5):

$$y = y_0 + \left(\frac{x - x_0}{x_1 - x_0} \right) (y_1 - y_0) \quad (5)$$

where y is the interpolated gain, x is 1 mA, y_0 and y_1 are the gains at I_{C1} and I_{C2}, and x_0 and x_1 are I_{C1} and I_{C2}. The interpolated pre-irradiation gains for the 100 2N2222A transistors used in these experiments are found in Table 2.

Table 2. Pre-Irradiation Transistor Gains

Transistor ID	Gain @ 1 mA	Transistor ID	Gain @ 1 mA	Transistor ID	Gain @ 1 mA
801	233.28	835	237.71	868	259.07
802	235.88	836	239.81	869	236.04
803	237.53	837	215.37	870	244.89
804	237.71	838	239.81	871	242.10
805	233.82	839	233.82	872	206.57
806	235.88	840	246.27	873	237.01
807	237.91	841	239.16	874	237.53
808	208.77	842	246.83	875	234.90
809	235.72	843	236.04	876	239.16
810	201.61	844	235.88	877	239.81
811	198.19	845	220.70	878	238.54
812	251.26	846	237.53	879	237.71
813	207.52	847	242.05	880	239.81
814	233.48	848	246.83	881	239.36
815	242.21	849	244.25	882	218.41
816	237.01	850	235.42	883	235.72
817	251.26	851	231.24	884	242.01
818	233.38	852	236.04	885	235.72
819	241.96	853	258.25	886	224.59
820	224.47	854	253.81	887	233.70
821	244.07	855	238.95	888	235.29
822	235.72	856	256.66	889	238.32
823	244.44	857	235.72	890	241.92
824	216.56	858	215.37	891	237.53
825	242.10	859	235.29	892	239.81
826	223.06	860	223.16	893	245.01
827	237.91	861	242.10	894	244.07
828	203.16	862	235.42	895	242.10
829	235.57	863	235.29	896	239.36
830	211.03	864	233.09	897	244.25
831	235.42	865	238.77	898*	238.41
832	235.03	866	212.51	899*	237.22
833	248.51	867	237.17	900*	245.66
834	220.92				
***These transistors were selected as the temperature control transistors. These gain measurements are the C_i values used with Eqn (2) to make temperature correction for all of the following gain measurements.**					

2.2. Initial GIF Irradiations

The irradiations of the transistors were performed in GIF Irradiation Cell #2 under GIF Experiment Plan #53. For the first series of irradiations, three transistors were placed at a given dose rate location. Using multiple transistors at each location provides a statistical sample of the transistor population. The transistors were irradiated with the leads shorted by aluminum foil to keep a clear electrical boundary. Table 3 provides information on the GIF operation numbers and exposure setups for the irradiation in this test series. The typical exposure setup is shown above in Figure 2.

(NOTE: The doses in the main body of this report rely on the alanine dosimetry results and are presented as Gy[H_2O] (1 Gy[H_2O] = 100 Rad[H_2O]). Appendix A contains dose conversion calculations. This appendix will allow readers to convert to from Rad[H_2O] to either Rad[TLD] or Rad[Si] for a ^{60}Co irradiation.)

Table 3. GIF Irradiation Summary (1st Irradiation)

GIF Operation Number	Number of BJTs @ 10.15 Rad[H_2O]/s	Number of BJTs @ 125.5 Rad[H_2O]/s	Number of BJTs @ 881.7 Rad[H_2O]/s	Time (seconds)
2-269	3	3	0	11000
2-270	3	3	3	1100
2-271	3	3	3	825
2-272	3	3	3	550
2-273	3	0	0	55000
2-274	3	3	0	2750
2-275	3	3	3	275
2-276	3	3	3	110
2-277	3	3	0	5500
2-278	3	3	0	8250
2-279	3	0	0	27500
2-280	3	0	0	82500
2-281	3	0	0	259114
2-282	3	0	0	110000
2-283	0	0	3	5500
2-284	0	0	3	8250
2-285	0	0	3	11000

2.3. Post-Irradiation Gain Measurements and Anneals

2.3.1. Post-Irradiation Characterization – No Stabilization Anneal

A post-irradiation (no stabilization anneal) measurement of the current-voltage characteristics was performed on each of the irradiated transistors by a computer-controlled HP 4155C parameter analyzer using the source setup described above in the "Pre-Irradiation Gain Measurements" section. The characterization of the transistors results in information that can be plotted as Gummel curves.

An example of the post-irradiation (no anneal) transistor characterization curves is found in Figure 4. The data in Figure 4 also shows that the typical meaning of the term "gain" is lost for collector currents (I_C) less than ~4.0 x 10^{-7} A. For collector currents less than 4.0 x 10^{-7} A, the base current (I_B) is greater than the collector current. Thus, the "gain" is less than 1.0, and is not really a gain.

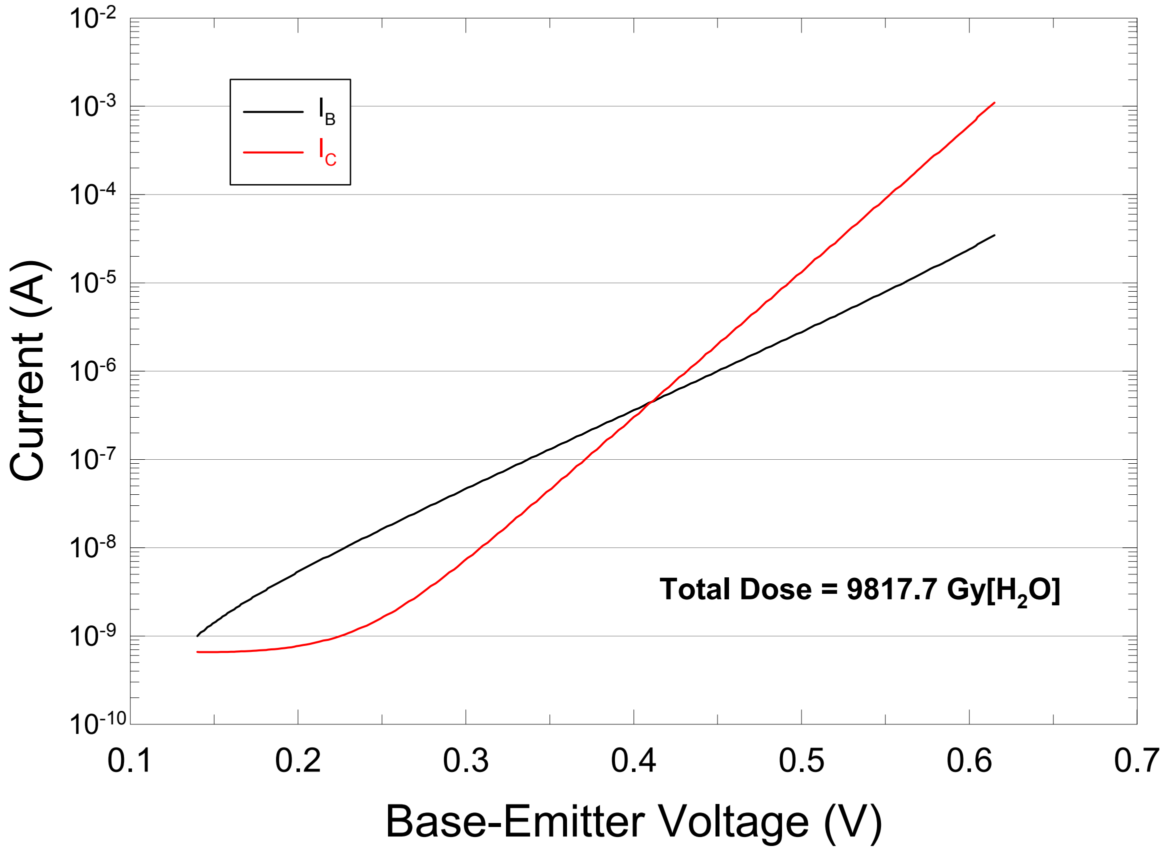

Figure 4. Post-Irradiation (No Anneal) Characterization of Transistor ID #801

2.3.2. Stabilization Anneal

The transistors that were irradiated were all subjected to the stabilization anneal step [1]. The stabilization anneal consists of baking the transistors at 80° C for 2 hours. The intent of the stabilization anneal is to remove the variations associated with ambient temperature annealing during and after the irradiation. This step helps ensure that the transistors produce reproducible results. (*NOTE: The temperature control transistors identified in the "Pre-Irradiation Gain Measurements" section are not subjected to any of the anneal steps.*)

2.3.3. Post-Irradiation Characterization – Stabilization Anneal

A post-irradiation (stabilization anneal) measurement of the current-voltage characteristics was performed on each of the irradiated transistors by a computer-controlled HP 4155C parameter analyzer using the source setup described above in the "Pre-Irradiation Gain Measurements" section. The characterization of the transistors results in information that can be plotted as Gummel curves.

An example of the post-irradiation (stabilization anneal) transistor characterization curves is found in Figure 5. The data in Figure 5 (like Figure 4) shows that definition of the term "gain" breaks down for collector currents (I_C) less than ~1.0 x 10^{-7} A. For collector currents less than 1.0 x 10^{-7} A, the base current (I_B) is greater than the collector current. Thus, the "gain" is less than 1.0, and is not really a gain.

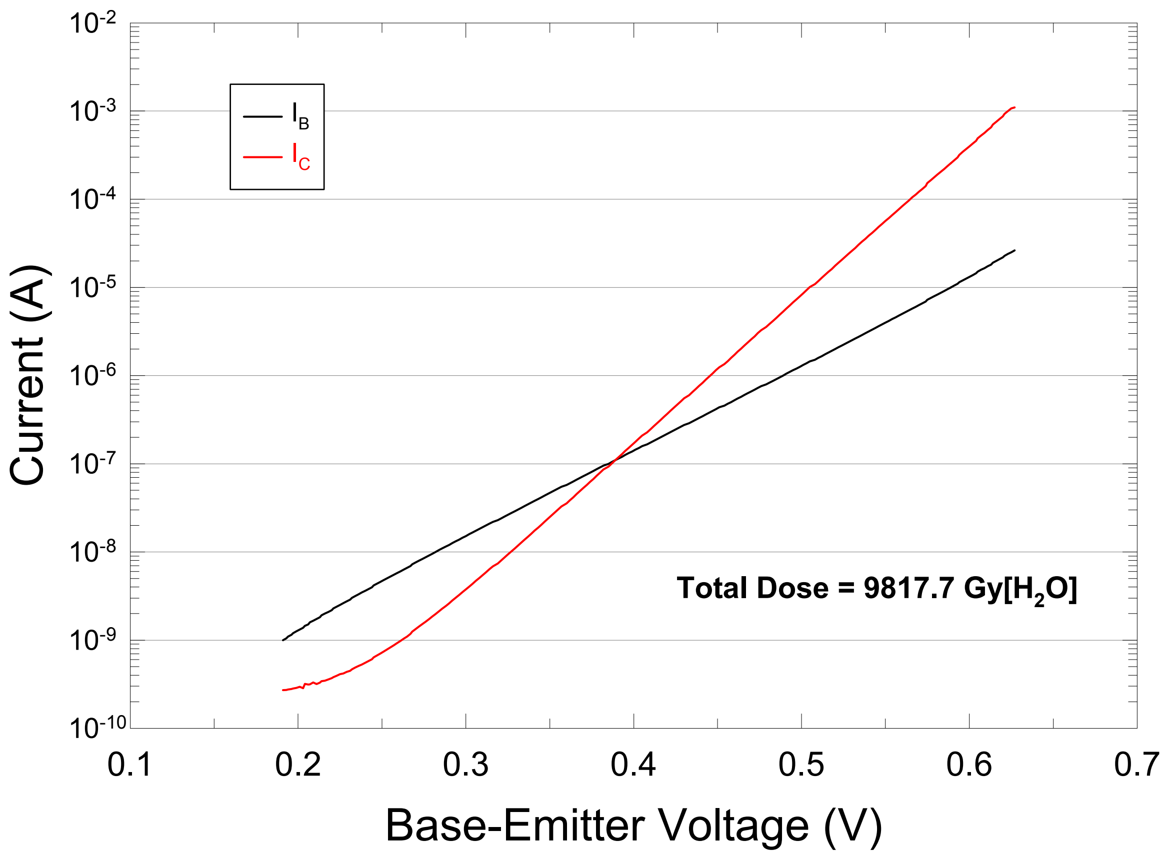

Figure 5. Post-Irradiation (Stabilization Anneal) Characterization of Transistor ID #801

A comparison of the Gummel curves with and without the stabilization anneal is found in Figure 6. The figure shows the "recovery" of the transistor that takes place during the stabilization anneal. The recovery in the figure represents the variations that are possible due to differences in the time between irradiation and characterization, storage conditions, and other environmental factors. According to [1], no further annealing has been observed for transistors that undergo this stabilization anneal as long as the environmental conditions during the subsequent handling of the transistors do not include exposures to temperatures above 60^{o} C.

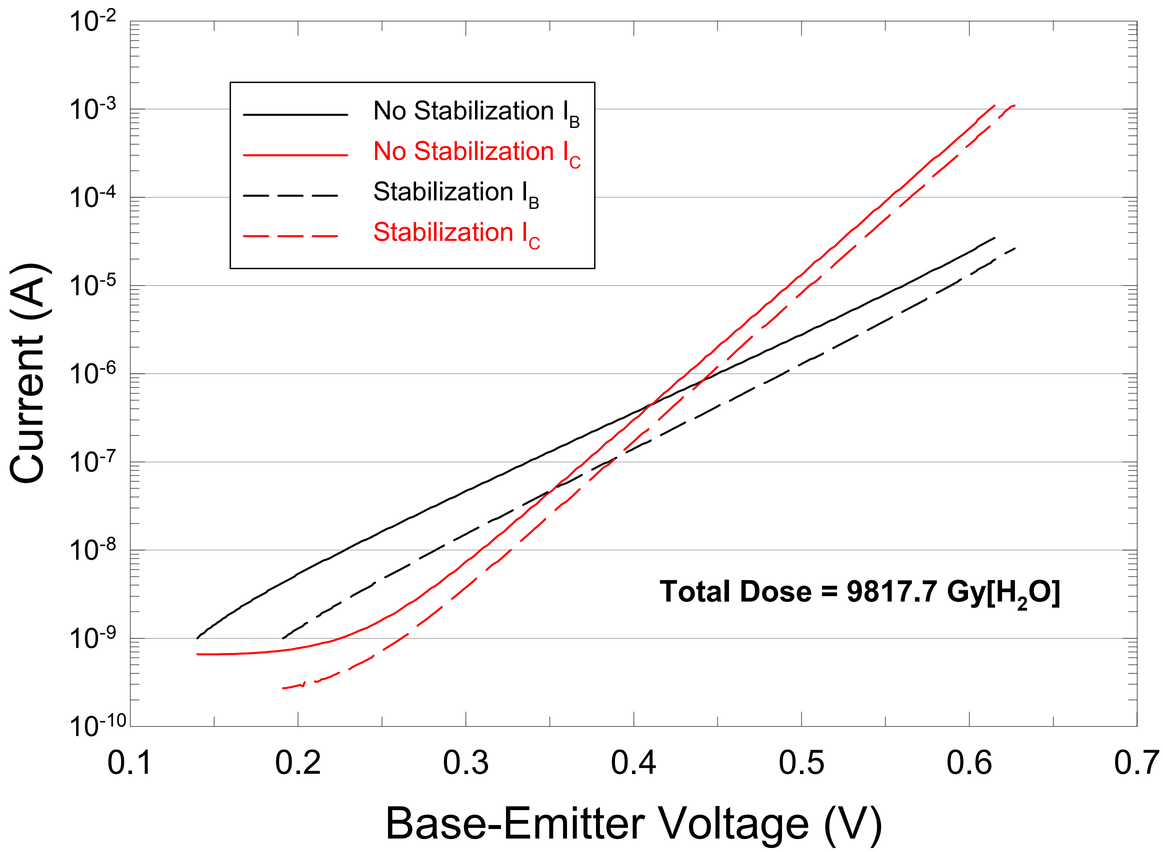

Figure 6. Characterization of Transistor ID #801 With and Without Stabilization Anneal

2.3.4. Hard Anneal

Following the characterizations, the transistors that were irradiated were all subjected to a hard anneal step [1]. The hard anneal consists of baking the transistors at 180^o C for 24 hours. The intent of the hard anneal is to further stabilize and reset the gains before the next exposure. The gain measurement made after this hard anneal becomes the baseline gain that is used for the next irradiation.

2.3.5. Post-Irradiation Characterization – Hard Anneal

A post-irradiation (hard anneal) measurement of the current-voltage characteristics was performed on each of the irradiated transistors by a computer-controlled HP 4155C parameter analyzer using the source setup described above in the "Pre-Irradiation Gain Measurements" section. The characterization of the transistors results in information that can be plotted as Gummel curves.

An example of the post-irradiation (hard anneal) transistor characterization curves is found in Figure 7. The transistor characteristics found in the figure are very similar to the pre-irradiated characterization for the transistor.

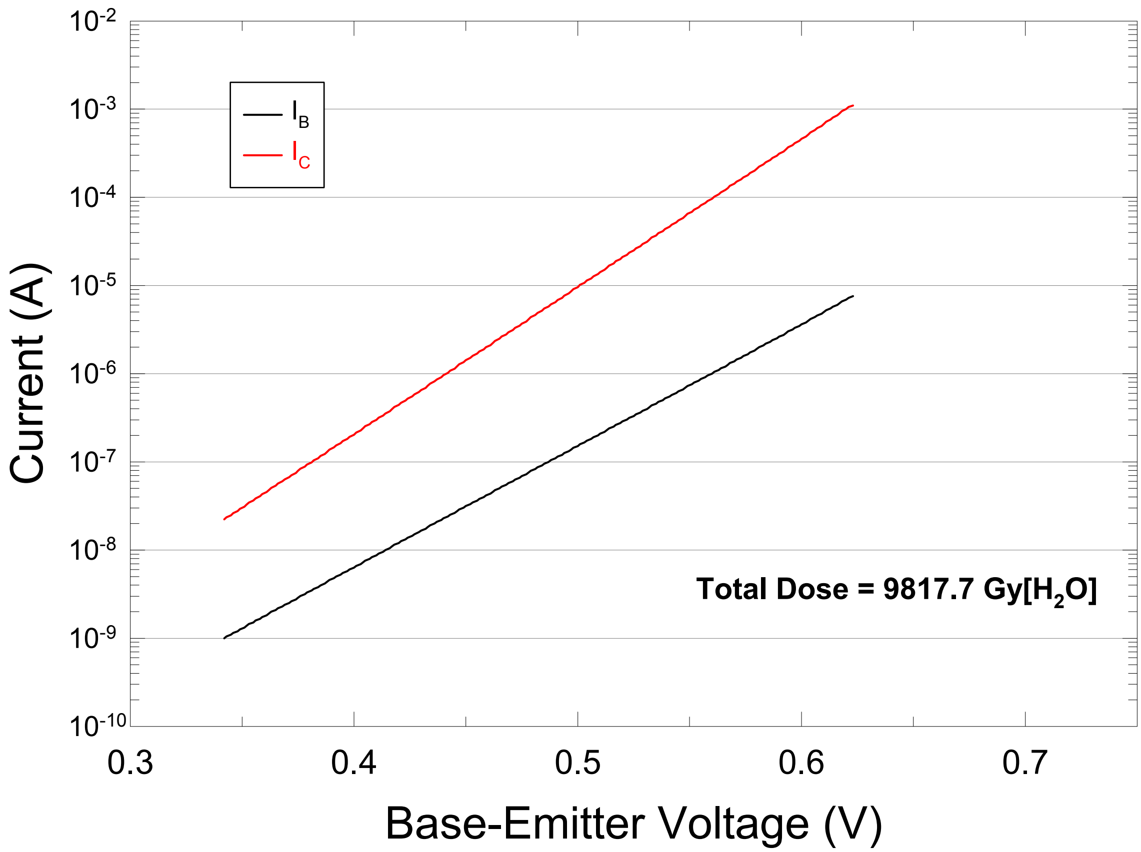

Figure 7. Post-Irradiation (Hard Anneal) Characterization of Transistor ID #801

However, the characteristics of the transistor have not been completed recovered. Figure 8 demonstrates this by the comparing of the pre-irradiated characterization to the hard anneal characterization. It is clear in the figure that the base current (I_B) undergoes a more drastic change in the radiation field. The slope of the collector current (I_C) does not appear to change, but it does appear to be shifted from the pre-irradiation characterization.

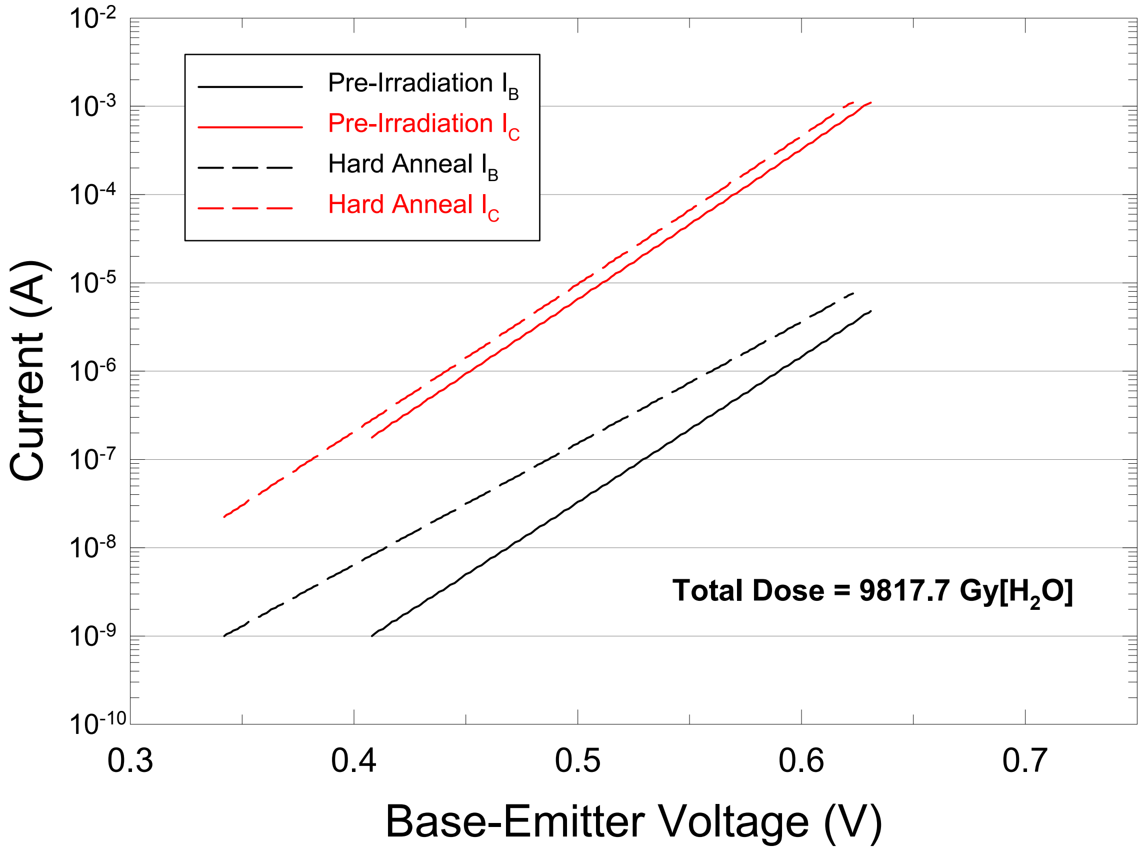

Figure 8. Pre-Irradiation and Hard Anneal Characterization of Transistor ID #801

2.4. Gain Summary of Initial GIF Irradiations

Using the interpolation method described in Equation (4), the gain measurements (transistor characterizations) were performed. In addition to the pre-irradiation gain measurements, each of the irradiated transistors has the following temperature corrected gain measurements:

- Post-irradiation gain with no stabilization anneal;
- Post-irradiation gain with stabilization anneal;
- Post-irradiation gain with hard anneal.

Table 4 contains the summary of the gain measurements for the transistors that were irradiated at 10.15 rad[H_2O]/s along with the total dose delivered to the transistors. Table 5 contains the summary of the gain measurements for the transistors that were irradiated at 125.5 rad[H_2O]/s along with the total dose delivered to the transistors. Table 6 contains the summary of the gain measurements for the transistors that were irradiated at 881.7 rad[H_2O]/s along with the total dose delivered to the transistors.

Table 4. Gains for Transistors Irradiated at 10.15 Rad[H_2O]/s

Transistor ID	Dose^ (Gy[H_2O])	Gain @ 1mA (No Stabilization)*	Gain @ 1 mA (Stabilization Anneal)*	Gain @ 1 mA (Hard Anneal)*
808	29085.4 (300.1)	19.91	31.21	119.59
810	29085.4 (300.1)	18.74	29.98	117.68
811	29085.4 (300.1)	25.73	36.83	123.34
819	1110.2 (9.1)	62.54	78.23	175.09
820	1110.2 (9.1)	55.02	70.05	168.81
821	1110.2 (9.1)	59.52	74.03	174.02
827	113.7 (11.1)	170.44	178.73	214.97
828	113.7 (11.1)	147.39	156.40	185.35
829	113.7 (11.1)	173.98	181.89	210.77
838	5449.7 (37.2)	32.25	44.86	150.44
839	5449.7 (37.2)	30.43	42.52	147.23
840	5449.7 (37.2)	25.96	38.28	155.28
844	11208.0 (37.2)	22.42	33.54	139.06
846	11208.0 (37.2)	26.42	37.70	138.51
848	11208.0 (37.2)	24.74	35.85	141.62
850	815.3 (6.7)	69.58	84.45	173.88
851	815.3 (6.7)	63.98	79.99	159.70
853	815.3 (6.7)	78.26	95.06	188.12
854	549.0 (2.4)	102.36	118.37	194.19
855	549.0 (2.4)	96.91	113.06	185.27
856	549.0 (2.4)	102.47	118.50	195.66
857	52.2 (1.4)	194.28	201.55	223.08
858	52.2 (1.4)	175.80	183.79	201.51
860	52.2 (1.4)	188.27	192.50	212.60
868	2725.6 (16.6)	38.11	51.15	168.90
869	2725.6 (16.6)	35.72	48.16	159.43
870	2725.6 (16.6)	37.86	50.35	161.39
875	270.4 (10.2)	125.66	141.51	195.66
876	270.4 (10.2)	127.08	144.18	200.48
878	270.4 (10.2)	125.56	141.51	198.90
880	95.9 (3.5)	181.59	187.44	217.28
881	95.9 (3.5)	182.06	188.09	216.49
882	95.9 (3.5)	165.36	175.41	200.45
887	8349.3 (80.0)	24.06	35.16	144.15
888	8349.3 (80.0)	24.07	35.20	142.75
889	8349.3 (80.0)	24.70	35.17	145.17
895	26.6 (0.7)	217.19	220.71	233.24
896	26.6 (0.7)	214.72	218.90	230.82
897	26.6 (0.7)	218.51	222.63	233.40

***Gains contain the temperature correction described in Eqn (2).**
^Value in parentheses is the uncertainty in Gy[H_2O].

Table 5. Gains for Transistors Irradiated at 125.5 Rad[H_2O]/s

Transistor ID	Dose^ (Gy[H_2O])	Gain @ 1mA (No Stabilization)*	Gain @ 1 mA (Stabilization Anneal)*	Gain @ 1 mA (Hard Anneal)*
804	13644.4 (130.6)	24.77	35.67	143.98
806	13644.4 (130.6)	25.44	36.61	140.56
807	13644.4 (130.6)	26.51	38.01	141.95
815	1350.3 (10.4)	68.79	84.57	175.58
816	1350.3 (10.4)	63.99	80.03	174.53
818	1350.3 (10.4)	65.68	81.43	172.03
823	169.7 (6.1)	164.53	177.18	214.62
824	169.7 (6.1)	147.23	158.39	192.30
826	169.7 (6.1)	151.08	163.71	199.16
834	6811.2 (27.3)	31.25	42.52	144.06
835	6811.2 (27.3)	29.62	40.81	151.96
836	6811.2 (27.3)	29.62	40.87	154.07
841	684.2 (5.8)	101.76	117.66	188.92
842	684.2 (5.8)	100.87	115.83	190.48
843	684.2 (5.8)	95.37	110.64	185.14
845	10358.5 (7.1)	27.53	38.97	137.53
847	10358.5 (7.1)	26.21	37.52	147.04
849	10358.5 (7.1)	26.22	37.59	148.20
865	3409.8 (8.8)	39.87	52.76	161.24
866	3409.8 (8.8)	34.48	46.26	149.46
867	3409.8 (8.8)	37.80	50.66	162.51
871	368.3 (10.6)	140.43	152.64	200.96
872	368.3 (10.6)	108.20	125.07	174.16
874	368.3 (10.6)	129.09	143.23	195.95
890	1034.2 (7.1)	80.79	97.71	180.48
893	1034.2 (7.1)	88.32	106.42	183.24
894	1034.2 (7.1)	78.79	95.13	182.53

***Gains contain the temperature correction described in Eqn (2).**
^Value in parentheses is the uncertainty in Gy[H_2O].

Table 6. Gains for Transistors Irradiated at 881.7 Rad[H_2O]/s

Transistor ID	Dose^ (Gy[H_2O])	Gain @ 1mA (No Stabilization)*	Gain @ 1 mA (Stabilization Anneal)*	Gain @ 1 mA (Hard Anneal)*
801	9817.7 (56.9)	30.64	41.60	145.89
802	9817.7 (56.9)	34.59	46.33	143.24
803	9817.7 (56.9)	28.72	39.83	147.13
805	49088.5 (284.5)	23.03	33.58	116.91
809	49088.5 (284.5)	24.03	34.49	113.32
812	1120.9 (6.5)	85.77	105.51	188.59
813	1120.9 (6.5)	71.95	88.81	165.42
814	1120.9 (6.5)	82.48	99.27	178.67
817	49088.5 (284.5)	23.74	34.74	123.38
822	73632.7 (426.8)	21.76	32.26	104.43
825	73632.7 (426.8)	23.14	33.82	101.80
830	4850.8 (22.7)	34.98	45.98	147.06
831	73632.7 (426.8)	23.32	33.74	97.77
832	4850.8 (22.7)	38.81	50.02	156.45
833	4850.8 (22.7)	37.82	49.64	162.55
837	98177.0 (569.0)	19.41	29.60	89.22
852	98177.0 (569.0)	22.56	32.70	91.26
859	98177.0 (569.0)	21.56	31.66	93.98
861	2459.2 (26.7)	65.90	80.56	171.76
862	2459.2 (26.7)	54.24	68.43	166.24
864	2459.2 (26.7)	57.96	73.56	166.98
883	7168.3 (53.6)	33.58	44.59	149.27
884	7168.3 (53.6)	32.06	43.15	152.73
886	7168.3 (53.6)	28.41	39.53	150.79
*Gains contain the temperature correction described in Eqn (2). ^Value in parentheses is the uncertainty in Gy[H_2O].				

2.5. Additional GIF Irradiations, Anneals, and Gain Measurements

2.5.1. Transistor Sorting and Additional Irradiations

An additional series of irradiations were performed to determine if the γ-ray sensitivity of the transistors changed after the irradiation and anneal cycles described above. The previously irradiated (see above) transistors were separated into three groups based on the dose rates utilized in the first irradiation. Then, the transistors were further divided based on the total dose received during the first irradiation. The results of the sub-divisions are found in Table 7.

With Table 7, a statistical sampling technique [3] was used to determine the total dose of an additional irradiation. Seven transistors were selected for each total dose. The selected transistors and irradiation conditions are found in Table 8. The colors of Table 7 and Table 8 are coordinated such that one can see the sampling that was performed. All of the additional irradiations were performed at the 10.15 rad[H_2O]/s location of GIF Irradiation Cell #2.

Table 7. Transistor Irradiation Histories

Dose Rate (rad[H_2O]/s) \ Total Dose (krad[H_2O])	<20 krad[H_2O]	20 -100 krad[H_2O]	100 -500 krad[H_2O]	500 -10000 krad[H_2O]
	Transistor ID Numbers			
10.15	827 828 829 857 858 860 880 881 882 895 896 897	819 820 821 850 851 853 854 855 856 875 876 878	838 839 840 868 869 870	808 810 811 844 846 848 887 888 889
125.5	823 824 826	815 816 818 841 842 843 871 872 874 890 893 894	834 835 836 865 866 867	804 806 807 845 847 849
881.7	---	812 813 814	830 832 833 861 862 864	801 802 803 805 809 817 822 825 831 837 852 859 883 884 886

Table 8. GIF Irradiation Summary (2nd Irradiation @ 10.15 Rad[H_2O]/s)

GIF Operation Number	Total Dose* (Gy[H_2O])	Time (seconds)	7 Transistor ID Numbers
2-290	218.61 (8.85)	2000	803 814 848 856 860 867 874
2-291	102.17 (8.70)	800	802 813 846 855 858 866 872
2-292	68.27 (0.76)	600	801 812 844 854 857 865 871
2-293	46.31 (1.57)	400	818 826 864 878 886 889 897
2-294	19.99 (1.34)^	200	816 824 862 876 884 888 896
2-295	9.02 (0.54)^	80	815 823 861 875 883 887 895
2-296	430.74 (9.12)	4000	805 808 841 845 850 868 880
2-297	848.21 (7.11)	8000	811 817 843 849 853 870 882
2-298	640.37 (4.94)	6000	809 810 842 847 851 869 881
*Value in parentheses is the uncertainty in Gy[H_2O]. ^CaF_2:Mn dose converted to H_2O dose.			

2.5.2. Stabilization Anneal

The transistors that were irradiated were all subjected to the stabilization anneal step [1]. The stabilization anneal consists of baking the transistors at 80^o C for 2 hours. The intent of the stabilization anneal is to remove the variations associated with ambient temperature annealing during and after the irradiation. This step helps ensure that the transistors produce reproducible results.

2.5.3. Post-Irradiation Characterization – Stabilization Anneal

A post-irradiation (stabilization anneal) measurement of the current-voltage characteristics was performed on each of the irradiated transistors by a computer-controlled HP 4155C parameter analyzer using the source setup described above in the "Pre-Irradiation Gain Measurements" section. The characterization of the transistors results in information that can be plotted as Gummel curves.

An example of the post-irradiation (stabilization anneal) transistor characterization curves is found in Figure 9. Note that total dose delivered for the second irradiation is much lower (~150 times less) than the initial dose. When Figure 9 is compared to Figure 5, one notices that the characterization after the second irradiation does not result in a "cross-over" of the base and collector currents.

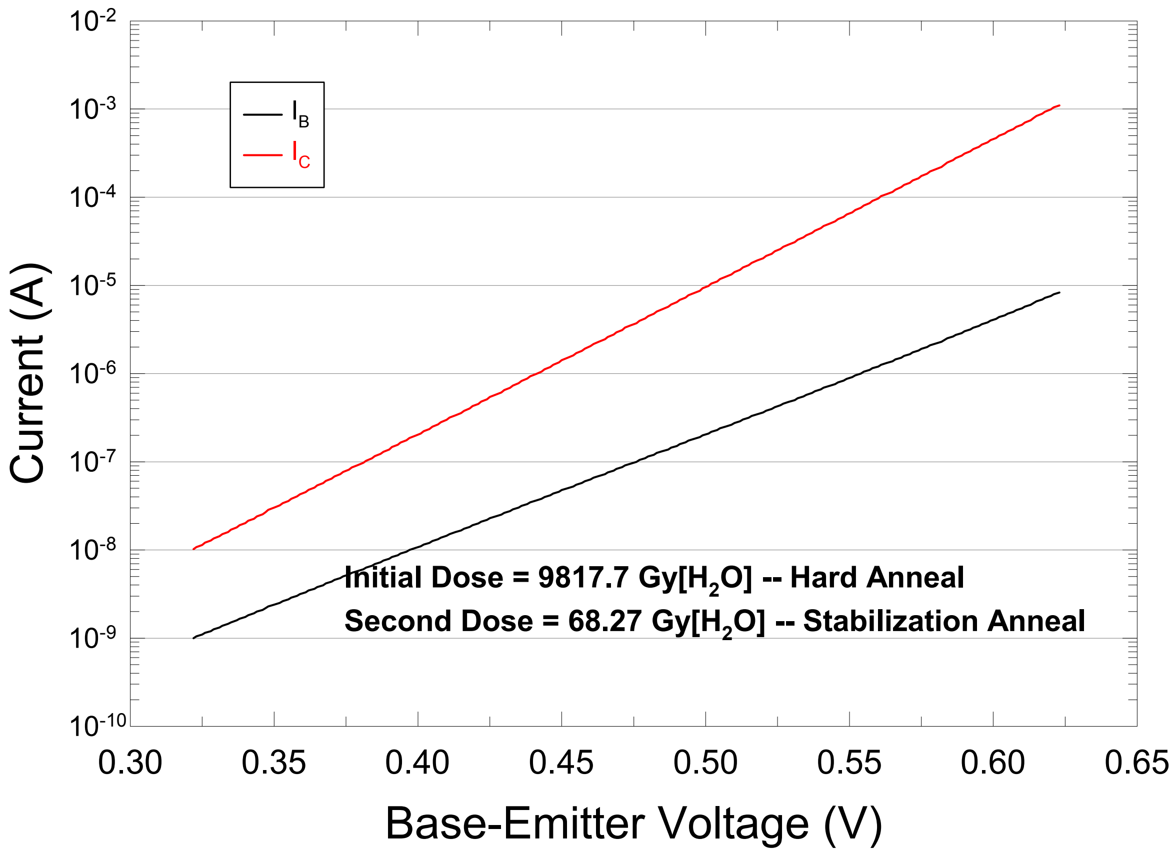

Figure 9. Multiple-Irradiation (Stabilization Anneal) Characterization of Transistor ID #801

Table 9 contains the summary of the gain measurements for the transistors that received a second irradiation at 10.15 rad[H_2O]/s. The total dose delivered to the transistors is also found in the table.

Table 9. Stabilized Gains for Transistors After Multiple Irradiations

Transistor ID	Dose* ($Gy[H_2O]$)	Gain @ 1mA	Transistor ID	Dose* ($Gy[H_2O]$)	Gain @ 1mA
801	68.27 (0.76)	132.27	856	218.61 (8.85)	137.64
802	102.17 (8.70)	126.95	857	68.27 (0.76)	183.70
803	218.61 (8.85)	113.51	858	102.17 (8.70)	161.58
805	430.74 (9.12)	90.29	860	218.61 (8.85)	145.62
808	430.74 (9.12)	85.29	861	9.02 (0.54)^	167.40
809	640.37 (4.94)	83.55	862	19.99 (1.34)^	158.27
810	640.37 (4.94)	74.75	864	46.31 (1.57)	152.85
811	848.21 (7.11)	85.37	865	68.27 (0.76)	143.12
812	68.27 (0.76)	164.23	866	102.17 (8.70)	127.28
813	102.17 (8.70)	137.91	867	218.61 (8.85)	116.14
814	218.61 (8.85)	123.30	868	430.74 (9.12)	100.34
815	9.02 (0.54)^	170.47	869	640.37 (4.94)	80.00
816	19.99 (1.34)^	163.93	870	848.21 (7.11)	73.74
817	848.21 (7.11)	82.67	871	68.27 (0.76)	175.71
818	46.31 (1.57)	155.40	872	102.17 (8.70)	142.92
823	9.02 (0.54)^	205.68	874	218.61 (8.85)	137.47
824	19.99 (1.34)^	177.31	875	9.02 (0.54)^	188.74
826	46.31 (1.57)	173.75	876	19.99 (1.34)^	185.42
841	430.74 (9.12)	108.05	878	46.31 (1.57)	173.75
842	640.37 (4.94)	87.73	880	430.74 (9.12)	109.70
843	848.21 (7.11)	71.67	881	640.37 (4.94)	93.23
844	68.27 (0.76)	125.45	882	848.21 (7.11)	72.60
845	430.74 (9.12)	93.30	883	9.02 (0.54)^	145.89
846	102.17 (8.70)	123.52	884	19.99 (1.34)^	147.11
847	640.37 (4.94)	85.27	886	46.31 (1.57)	137.56
848	218.61 (8.85)	112.51	887	9.02 (0.54)^	140.72
849	848.21 (7.11)	75.15	888	19.99 (1.34)^	136.54
850	430.74 (9.12)	95.80	889	46.31 (1.57)	134.13
851	640.37 (4.94)	75.35	895	9.02 (0.54)^	225.09
853	848.21 (7.11)	75.24	896	19.99 (1.34)^	210.93
854	68.27 (0.76)	167.55	897	46.31 (1.57)	203.34
855	102.17 (8.70)	155.61			
*Value in parentheses is the uncertainty in $Gy[H_2O]$. ^CaF_2:Mn dose converted to H_2O dose.					

2.6. Reciprocal Gain Calculations

2.6.1. Summary from Initial GIF Irradiations

The reciprocal gain calculations described above in the "Reciprocal Gain Calculations" section were performed for the following situations: (1) Post-irradiation with no annealing; (2) Post-irradiation with stabilization anneal; and (3) Post-irradiation with hard anneal. The data for the three transistors at each total dose and dose rate were averaged to produce a single point. Table 10 contains the reciprocal gain calculations from the transistors irradiated at 10.15 $rad[H_2O]/s$. Table 11 contains the reciprocal gain calculations from the transistors irradiated at 125.5 $rad[H_2O]/s$. Table 12 contains the reciprocal gain calculations from the transistors irradiated at 881.7 $rad[H_2O]/s$.

Table 10. Reciprocal Gains for Transistors Irradiated at 10.15 Rad[H_2O]/s

Dose* (Gy[H_2O])	$\left(\Delta \frac{1}{h}\right)_{POST}$ ^	$\left(\Delta \frac{1}{h}\right)_{POST-SA}$ ^	$\left(\Delta \frac{1}{h}\right)_{POST-HA}$ ^
26.6 (0.7)	0.000479 (0.000004)	0.000396 (0.000005)	0.000167 (0.000020)
52.2 (1.4)	0.000927 (0.000109)	0.000744 (0.000047)	0.000261 (0.000052)
95.9 (3.5)	0.001374 (0.000083)	0.001142 (0.000021)	0.000428 (0.000016)
113.7 (11.1)	0.001676 (0.000180)	0.001372 (0.000111)	0.000474 (0.000026)
270.4 (10.2)	0.003720 (0.000045)	0.002813 (0.000060)	0.000832 (0.000024)
549.0 (2.4)	0.005942 (0.000167)	0.004570 (0.000080)	0.001212 (0.000003)
815.3 (6.7)	0.010112 (0.001200)	0.007473 (0.000772)	0.001628 (0.000269)
1110.2 (9.1)	0.012760 (0.000933)	0.009294 (0.000594)	0.001566 (0.000091)
2725.6 (16.6)	0.022823 (0.000811)	0.015998 (0.000460)	0.002070 (0.000039)
5449.7 (37.2)	0.029961 (0.003993)	0.019809 (0.002031)	0.002457 (0.000070)
8349.3 (80.0)	0.036956 (0.000577)	0.024186 (0.000044)	0.002702 (0.000049)
11208.0 (37.2)	0.036791 (0.003382)	0.023911 (0.001631)	0.002990 (0.000034)
29085.4 (300.1)	0.042552 (0.007707)	0.025918 (0.003350)	0.003390 (0.000285)

***Value in parentheses is the uncertainty in Gy[H_2O].**
^Value in parentheses is the standard deviation in the reciprocal gain (3 transistors).

Table 11. Reciprocal Gains for Transistors Irradiated at 125.5 Rad[H_2O]/s

Dose* (Gy[H_2O])	$\left(\Delta \frac{1}{h}\right)_{POST}$ ^	$\left(\Delta \frac{1}{h}\right)_{POST-SA}$ ^	$\left(\Delta \frac{1}{h}\right)_{POST-HA}$ ^
169.7 (6.1)	0.002099 (0.000099)	0.001625 (0.000071)	0.000563 (0.000023)
368.3 (10.6)	0.003643 (0.000711)	0.002782 (0.000367)	0.000880 (0.000030)
684.2 (5.8)	0.005919 (0.000306)	0.004567 (0.000242)	0.001158 (0.000044)
1350.3 (10.4)	0.008027 (0.000703)	0.005944 (0.000566)	0.001388 (0.000017)
1034.2 (7.1)	0.010919 (0.000500)	0.007989 (0.000290)	0.001535 (0.000029)
3409.8 (8.8)	0.022476 (0.001714)	0.015733 (0.001088)	0.001979 (0.000039)
6811.2 (27.3)	0.028873 (0.001212)	0.019862 (0.000754)	0.002370 (0.000047)
10358.5 (7.1)	0.033287 (0.001294)	0.022053 (0.000800)	0.002688 (0.000046)
13644.4 (130.6)	0.034917 (0.001330)	0.023003 (0.000864)	0.002818 (0.000071)

***Value in parentheses is the uncertainty in Gy[H_2O].**
^Value in parentheses is the standard deviation in the reciprocal gain (3 transistors).

Table 12. Reciprocal Gains for Transistors Irradiated at 881.7 Rad[H_2O]/s

Dose* (Gy[H_2O])	$\left(\Delta \frac{1}{h}\right)_{POST}$ ^	$\left(\Delta \frac{1}{h}\right)_{POST-SA}$ ^	$\left(\Delta \frac{1}{h}\right)_{POST-HA}$ ^
1120.9 (6.5)	0.008200 (0.000767)	0.005910 (0.000483)	0.001288 (0.000053)
2459.2 (26.7)	0.012732 (0.001585)	0.009318 (0.001042)	0.001719 (0.000042)
4850.8 (22.7)	0.022593 (0.001181)	0.016289 (0.000653)	0.002109 (0.000041)
7168.3 (53.6)	0.027781 (0.002677)	0.019357 (0.001358)	0.002350 (0.000150)
9817.7 (56.9)	0.027877 (0.002999)	0.019331 (0.001813)	0.002632 (0.000095)
49088.5 (284.5)	0.038223 (0.000888)	0.025020 (0.000419)	0.004328 (0.000233)
73632.7 (426.8)	0.039807 (0.001660)	0.025861 (0.000775)	0.005669 (0.000324)
98177.0 (569.0)	0.039637 (0.001455)	0.027607 (0.001418)	0.006559 (0.000165)

***Value in parentheses is the uncertainty in Gy[H_2O].**
^Value in parentheses is the standard deviation in the reciprocal gain (3 transistors).

The reciprocal gains in Tables 10-12 can be plotted as a function of dose. These plots are found in Figure 10, Figure 11, and Figure 12. Each of the figures contains the averaged data from the 10.15 rad[H_2O]/s location, the 125.5 rad[H_2O]/s location, and the 881.7 rad[H_2O]/s location.

An initial look at the figures reveals that the gain degradation is not a linear function of γ-ray dose above approximately 200 Gy. The figures are shown in semi-log manner in order to visualize all the data points. A linear-linear plot of the figures would highlight the non-linear nature of the gain degradation relationship.

Additional observation of these figures reveals an apparent dose rate effect to the transistor gain degradation function. This apparent effect is found even after the hard anneal step that is intended to "reset" transistors to their pre-irradiation condition. The apparent dose rate effect is examined by rigorous statistical analyses in the "Analysis" chapter that follows.

The different scales for the calculated reciprocal gain axis in Figures 10-12 make it difficult to distinguish how it changes during the anneal steps. In order to remedy this difficulty, the data from each state (no anneal, stabilization anneal, and hard) were placed into their respective pool. The pooled data was then plotted. The result of this manipulation is found in Figure 13. In the figure a vertical line can be drawn through three points. The three points represent the same transistor set at a given dose. The relationship between the points demonstrate the effects of each of the anneal steps on the transistor gain degradation.

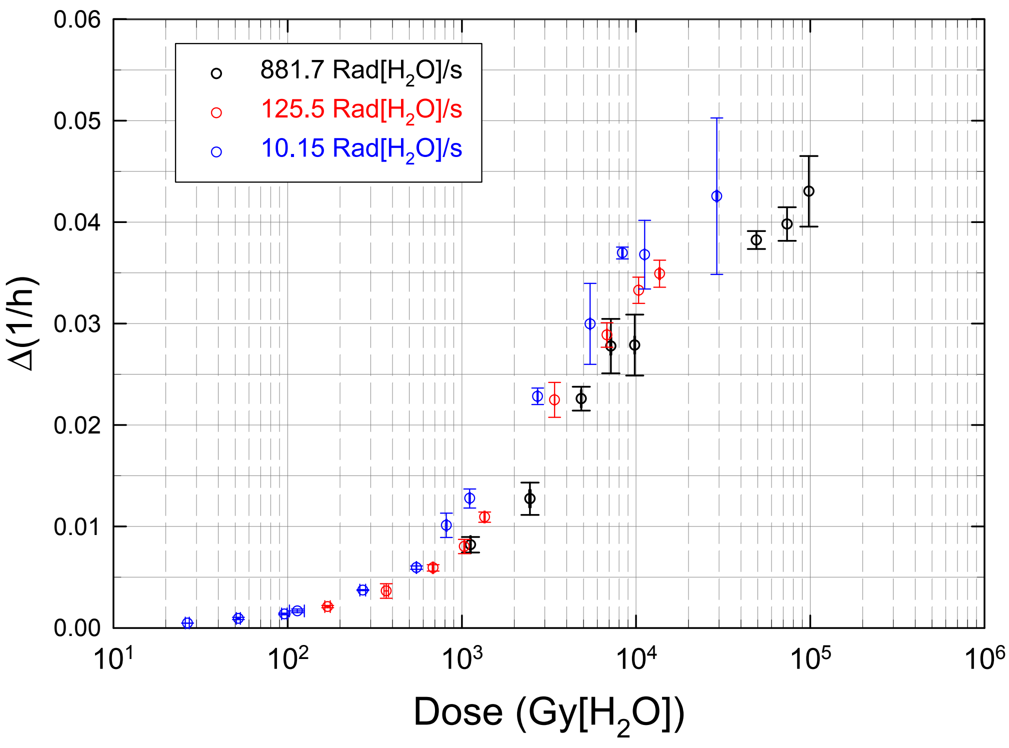

Figure 10. Post-Irradiation (No Anneal) Reciprocal Gain Calculations

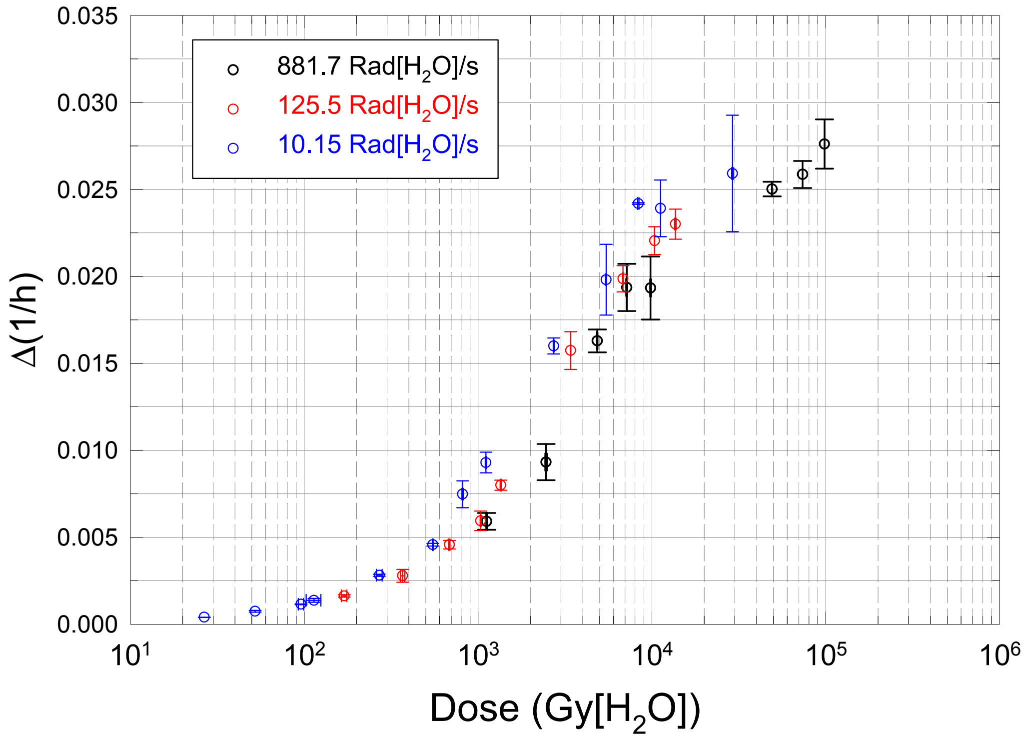

Figure 11. Post-Irradiation (Stabilization Anneal) Reciprocal Gain Calculations

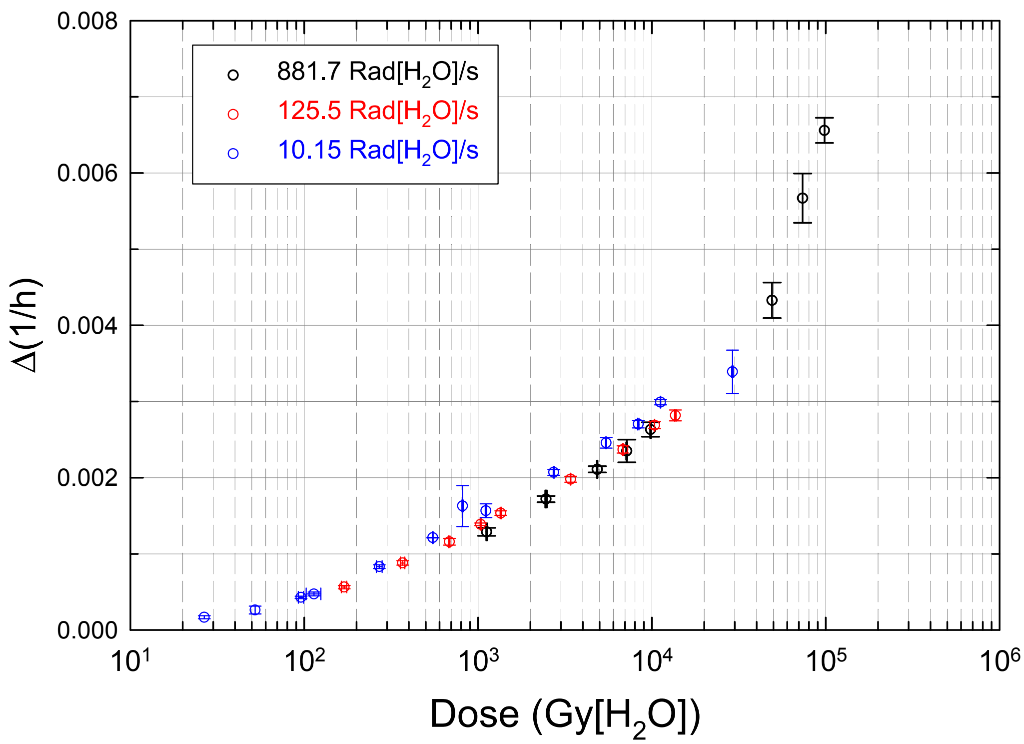

Figure 12. Post-Irradiation (Hard Anneal) Reciprocal Gain Calculations

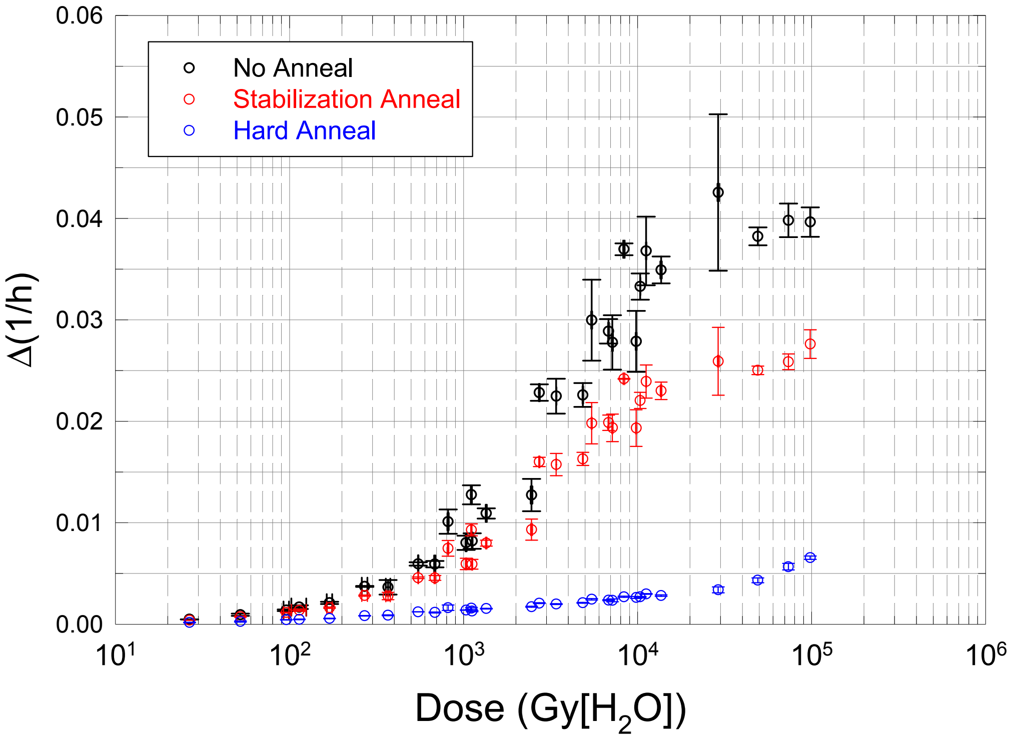

Figure 13. Reciprocal Gain Calculations for the Different Anneal States

2.6.2. Summary from Multiple GIF Irradiations

The additional irradiations at the 10.15 rad[H_2O]/s location were described above. The reciprocal gain calculations described above in the "Reciprocal Gain Calculations" section were performed for the transistors that received the additional irradiation. The data for the seven transistors exposed at each total dose were averaged to produce a single point. Table 13 contains the reciprocal gain calculations from the transistors that received the additional irradiations.

Table 13. Reciprocal Gains for Transistors Receiving Multiple Irradiations

Dose from 2nd Irradiation* (Gy[H_2O])	$\left(\Delta\frac{1}{h}\right)_{MULTIPLE}$ ^
9.02 (0.54)+	0.000170 (0.000019)
19.99 (1.34)+	0.000357 (0.000068)
46.31 (1.57)	0.000639 (0.000070)
68.27 (0.76)	0.000793 (0.000084)
102.17 (8.70)	0.001093 (0.000159)
218.61 (8.85)	0.002186 (0.000239)
430.74 (9.12)	0.003791 (0.000745)
640.37 (4.94)	0.005492 (0.001282)
848.21 (7.11)	0.006691 (0.002113)

***Value in parentheses is the uncertainty in Gy[H_2O].**
^Value in parentheses is the standard deviation in the reciprocal gain (7 transistors).
+CaF_2:Mn dose converted to H_2O dose.

Again, the reciprocal gains found in Table 13 can be plotted as a function of dose. The plot of the data in Table 13 is found in Figure 14. The data in the figure shows that the variation (as measured by the standard deviation) in the reciprocal gain increase with increasing dose. This increased variation in reciprocal gain will be investigated in the "Analysis" chapter that follows.

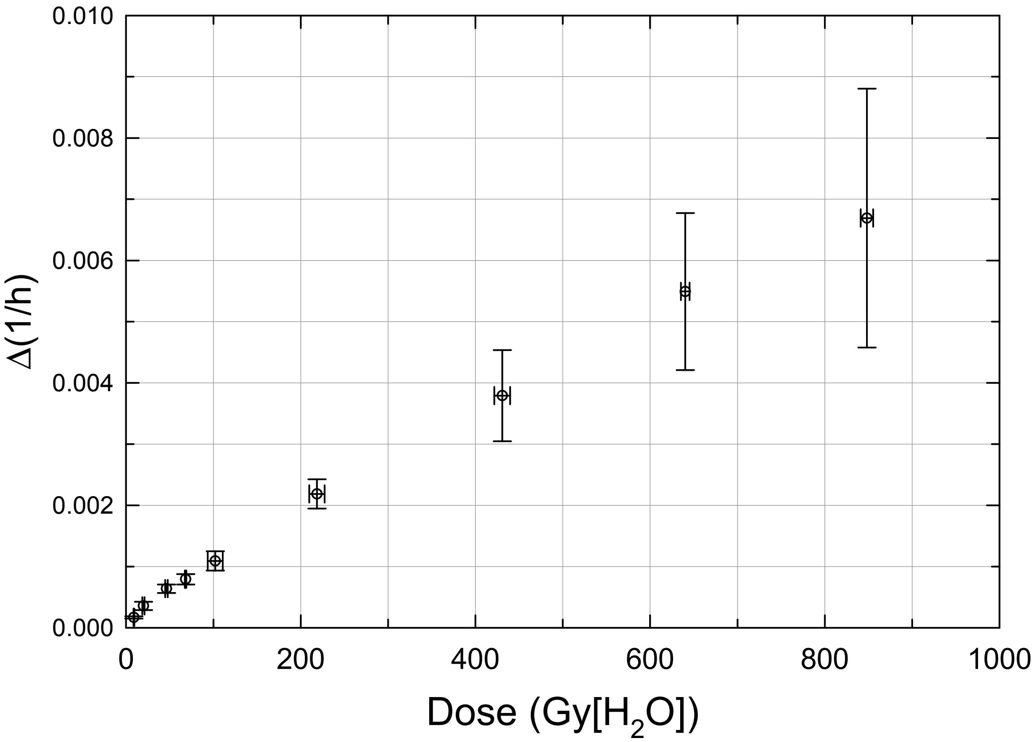

Figure 14. Post-Irradiation (Multiple Irradiations) Reciprocal Gain Calculations

3. ANALYSIS

3.1. γ-Ray Sensitivity as a Function of Total Ionizing Dose

3.1.1 Linear Relationship

Recall that transistor performance from radiation exposure is characterized by Equation (4) and that γ-ray sensitivity is a linear function [1]. The equation for γ-ray sensitivity is then given as:

$$\Delta\left(\frac{1}{h}\right) = b \cdot Dose \tag{6}$$

where b is a parameter to be estimated experimentally. To maintain an accurate linear relationship, Equation (6) needs to depend on dose rate as well as dose level [3]. This assumption breaks down at doses above 2000 Gy[H_2O] as seen in Figure 15. The breakdown occurs earlier for the higher dose rates; therefore, the higher doses also have an increased scatter in the reciprocal gain.

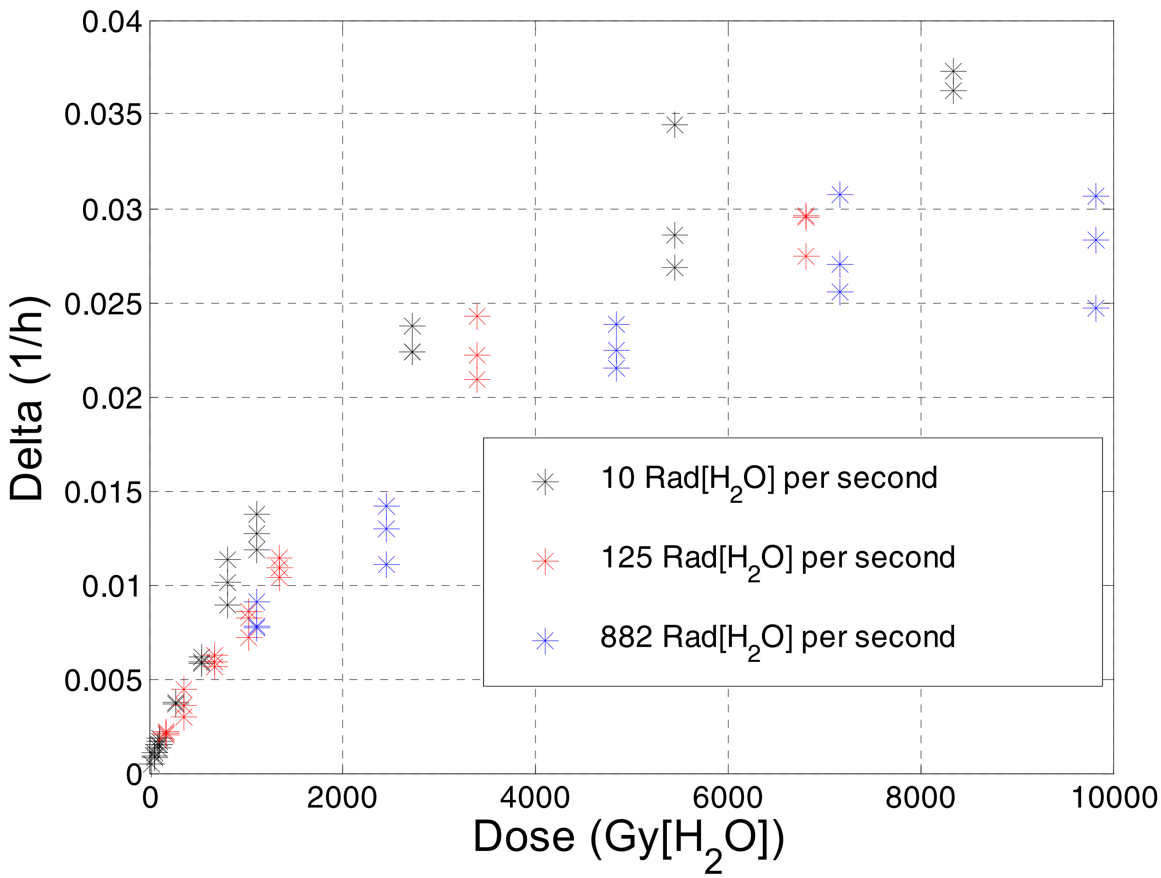

Figure 15. Delta (1/h) versus 1st Dose [Post Irradiation / Pre Anneal]

3.1.2 Non- Linearity in the Model

Due to the scattering and non-linearity in the proposed model between the dose and reciprocal gain, an alternative way to model the γ-ray sensitivity between $\Delta\left(\frac{1}{h}\right)$ and dose is through a different equation:

$$\log\left(\Delta\left(\frac{1}{h}\right)\right) = \beta_0 + \beta_1 \cdot \log\left(Dose\right) \tag{7}$$

implying that $\beta_1 = 1$ for a linear relationship. The graph of this data is seen in Figure 16, and follows a much more linear trend.

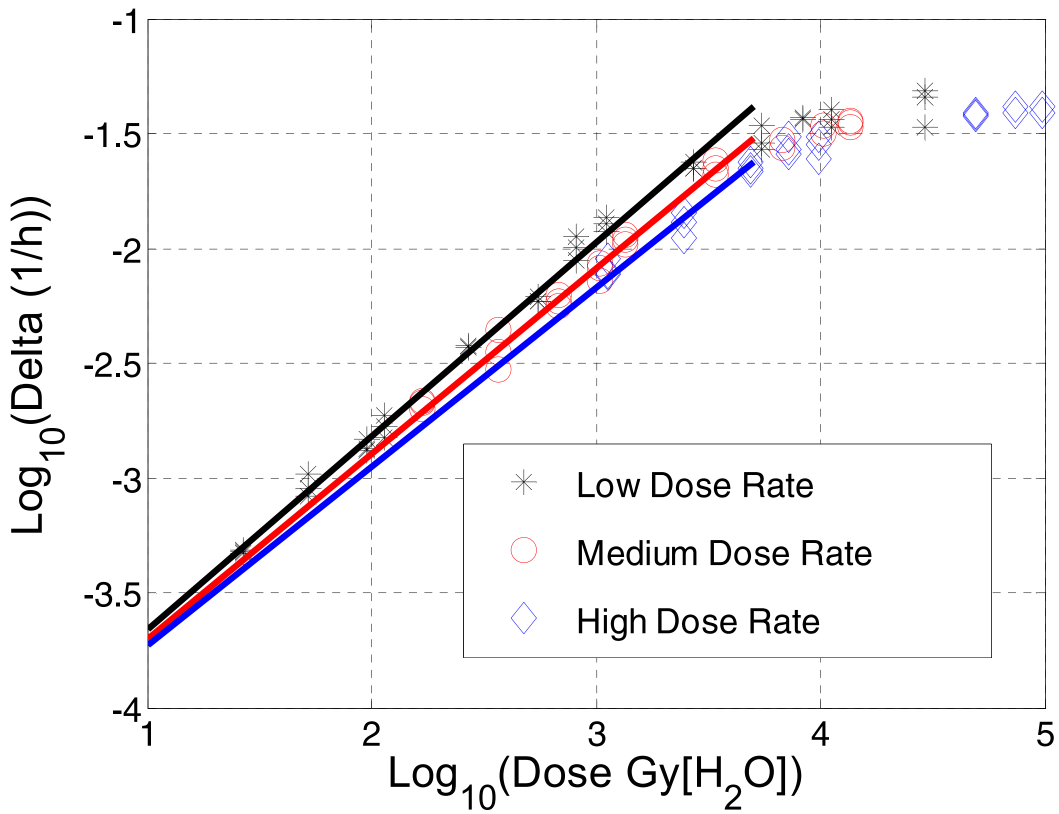

Figure 16. Log10(Delta (1/h)) versus Log10(1st Dose) [Post Irradiation / Pre Anneal]

3.1.3 Model Parameters and Associated Standard Errors

In order to find $\hat{\beta}_0$ and $\hat{\beta}_1$, only data consistent with the log-log linear model [3] was used. This data includes the transistors in the cases of post-irradiation/pre-anneal and post-irradiation/stabilization-anneal that were irradiated with a total dose less than 5000 Gy[H_2O], and the transistors in the case of post-irradiation/hard-anneal that received a total dose of less than 1200 Gy[H_2O]. Table 14 provides the estimates of model parameters and the associated standard errors for all cases (pre-anneal, stabilization anneal, hard anneal). The values of $\hat{\beta}_1$ are never equal to one in these cases, proving as evidence that the linear relationship between $\Delta\left(\frac{1}{h}\right)$ and dose stated above is an incorrect assumption.

Table 14. Estimates of Model Parameters and Associated Standard Errors

Transistor Status	**Dose Rate** Rad[H_2O] per second	$\hat{\beta}_0$	**Standard Error of** $\hat{\beta}_0$	$\hat{\beta}_1$	**Standard Error of** $\hat{\beta}_1$
Pre-anneal	All	-4.504	.029	-------	-------
Pre-anneal	10.15	-------	-------	.844	.011
Pre-anneal	125.48	-------	-------	.807	.012
Pre-anneal	881.7	-------	-------	.778	.012
Stabilization Anneal	All	-4.528	.024	-------	-------
Stabilization Anneal	10.15	-------	-------	.808	.010
Stabilization Anneal	125.48	-------	-------	.771	.009
Stabilization Anneal	881.7	-------	-------	.744	.010
Hard Anneal	All	-4.606	.039	-------	-------
Hard Anneal	10.15	-------	-------	.612	.016
Hard Anneal	125.48	-------	-------	.593	.015
Hard Anneal	881.7	-------	-------	.562	.019

3.2. Dose Rate Dependence of γ-Ray Sensitivity

3.2.1 Developing the Predictive Model

To formulate a predictive model involving the dose rate, the estimated parameters ($\hat{\beta}_0, \hat{\beta}_1(LowRate)$, $\hat{\beta}_1(MediumRate)$, and $\hat{\beta}_1(HighRate)$) were obtained using a least-squares regression, giving Equation (8):

$$\log_{10}\left(\Delta\left(\frac{1}{h}\right)\right) = \hat{\beta}_0 + \hat{\beta}_1\left(DoseRate\right)\cdot\log_{10}\left(Dose\right) \tag{8}$$

These predictive models are shown above in Figure 16 as solid lines. In this equation (8), $\hat{\beta}_1$ depends on the dose rate. Looking at Table 14, the values of $\hat{\beta}_1$ are significantly different across the levels of transistor status and different within a transistor status group for the three dose rate levels. Due to the fact that the step changes in $\hat{\beta}_1$ from low to medium to high dose rates is consistent across transistor status, and that the step changes in dose rate are roughly logarithmic, a possible, more generalized model would be in the form of:

$$\log\left(\Delta\left(\frac{1}{h}\right)\right) = \beta_0 + \left(\alpha + \gamma \cdot \log\left(DoseRate\right)\right) \cdot \log\left(Dose\right) \tag{9}$$

3.2.2 Testing the Predictive Model

To test this model (9), one can look at the effects of the 2[nd] irradiation and stabilization anneal. In that instance, the dose rate is fixed at 10.15 rad[H_2O] per second, causing the predictive model to be:

$$\hat{\log}_{10}\left(\Delta\left(\frac{1}{h}\right)\right) = \hat{\beta}_0 + \hat{\beta}_1 \cdot \log_{10}\left(2^{nd}\,Dose\right) \tag{10}$$

With $\hat{\beta}_0 = -4.529\,(.036)$ and $\hat{\beta}_1 = .796\,(.017)$, one can see from Figure 17 that this model is a fairly good linear approximation. To further test this newer model [Equation (10)], a plot of the difference between the observed values and the model prediction, using Equation 10, versus the $Log_{10}(1^{st}$ Dose) can be seen in Figure 18. From this plot it is observed that the change in reciprocal gain (due to the dose of the 2[nd] irradiation) depends somewhat on the level of the dose of the 1[st] irradiation [3]. This statement then furthers the development of the predictive model to:

$$\log_{10}\left(\Delta\left(\frac{1}{h}\right)\right) = \hat{\beta}_0 + \hat{\beta}_1 \cdot \log_{10}\left(2^{nd}\,Dose\right) + \hat{\beta}_2 \cdot \log_{10}\left(1^{st}\,Dose\right) \tag{11}$$

with $\hat{\beta}_0 = -4.452\,(.030)$, $\hat{\beta}_1 = .833\,(.011)$, and $\hat{\beta}_2 = -.045\,(.008)$. All data from transistors that received an initial dose greater than 20,000 Gy[H_2O] were not used in the model parameters because of their inconsistency with the other data.

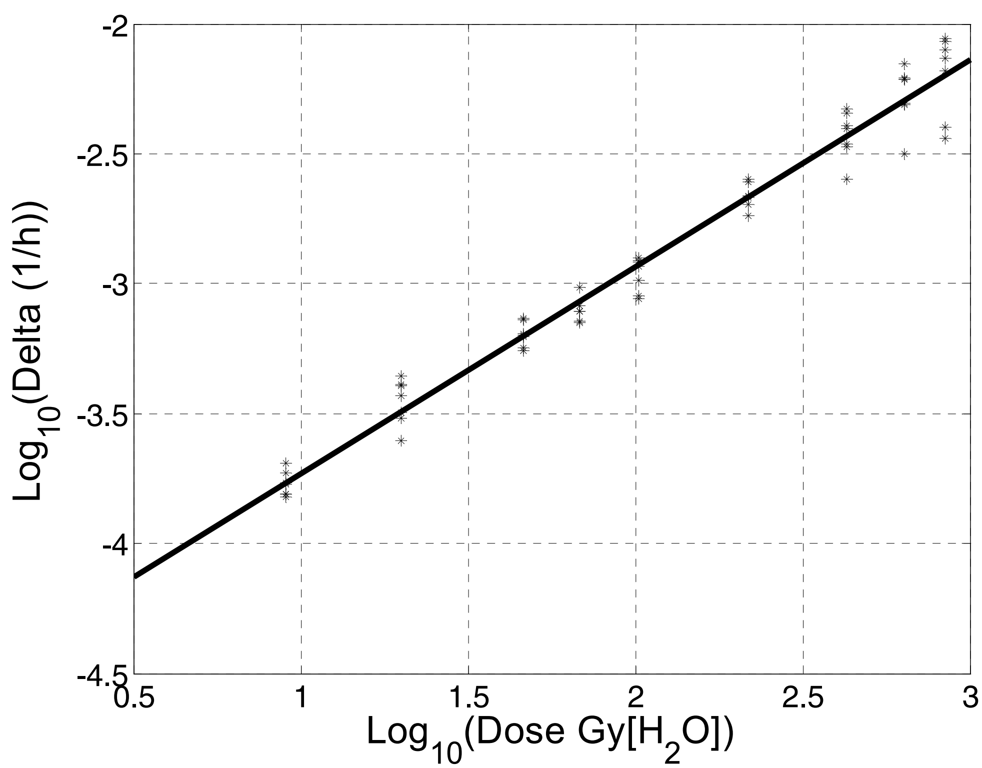

Figure 17. Log10(Delta (1/h)) versus Log10(2nd Dose)

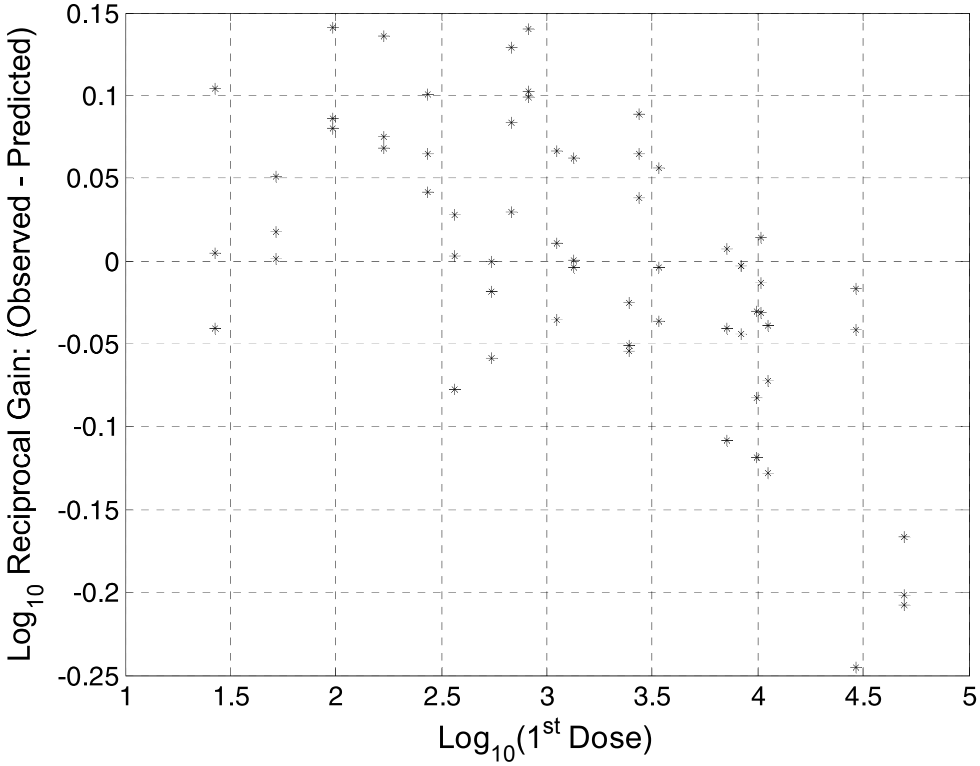

Figure 18. Difference between Observation and Model Prediction versus Log10(1st Dose)

3.3 Dose Range for Linear γ-Ray Sensitivity

The preceding section clearly emphasizes that there is not a range of ionizing doses that will best fit a linear model for γ-ray sensitivity. However, if a linear model is used for total doses less than 1000 Gy[H2O], the difference between the best fit and the linear model is small enough that the linear γ-ray sensitivity coefficient can be used for the correction factor. When comparing the effects of ionizing dose on reciprocal gain over the first and second irradiations, the most direct way is to look at the β_1 estimates. For the first irradiation, $\hat{\beta}_1 = .808\,(.010)$ and for the second, $\hat{\beta}_1 = .833\,(.011)$. By performing a statistical analysis, a conclusion can be drawn stating that the effect of dose on reciprocal gain is consistent across the two irradiations, because at a matched dose rate (10.15 rad[H_2O]/s) and annealing condition (stabilization anneal), the standardized difference is not statistically significant [3].

After analyzing the data for reciprocal gain, the model given by Equation 6 is revealed as not well supported. The best approximation for the data is given by:

$$\log_{10}\left(\Delta\left(\frac{1}{h}\right)\right) = \beta_0 + \beta_1 \cdot \log_{10}\left(Dose\right) \tag{12}$$

where β_1 depends on the gamma dose rate. This model can also be expressed as:

$$\Delta\left(\frac{1}{h}\right) = 10^{\beta_0} \cdot Dose^{\beta_1} = k \cdot Dose^{\beta_1} \tag{13}$$

where k is consistent across the experimental conditions that were considered. This model is applicable across a wide range of gamma doses and dose rates.

3.4. Gain Recovery as a Function of Total Ionizing Dose

As the dose received by the transistors increased, the percent of initial gain recovered during the hard anneal drops off. This phenomenon is shown in Figure 19. The "un-recovered" initial gain demonstrated in Figure 19 represents the permanent damage to the transistor caused by the total γ-ray ionizing dose.

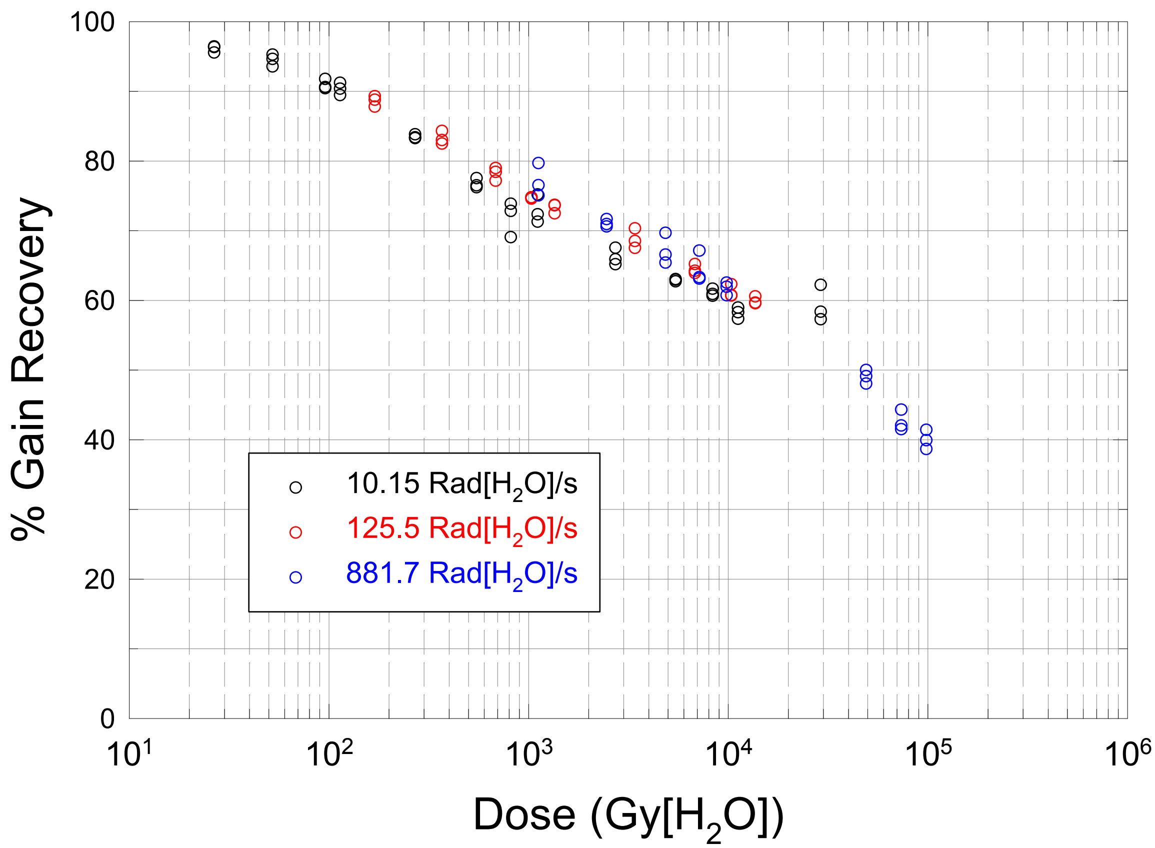

Figure 19. Gain Recovery After Hard Anneal as a Function of Total Dose

4. CONCLUSIONS

The primary purpose of the experiments was to determine the correlation between total ionizing γ-ray dose and the gain degradation for a single diffusion lot of 2N2222A transistors. This series of experiments allowed this purpose to be accomplished. Several notable conclusions can be made as a result of these experiments. Some are confirmations of expected results. The conclusions are as follows:

- The expected linear relationship between total γ-ray ionizing dose and reciprocal transistor gain was rejected. The linear model found in the ASTM standard test method [1] is appropriate for total dose levels less than 1000 Gy [H_2O]. However, experimenters that intend to use the linear model should be aware of the additional uncertainty that they introduce into the correction for γ-ray dose.

- The single diffusion lot of 2N2222A transistors showed a statistically significant dose rate effect for the approximately 3 orders of magnitude differences in dose rates studied. This result is consistent with other γ-ray sensitivity studies that have exhibited an "Enhanced Low-Dose Rate Sensitivity (ELDRS)" effect. When testing at a high dose rate facility such as LANSCE, SPR-III, or HERMES, experimenters should use the γ-sensitivity coefficients determined at GIF with caution and consider an additional term in the quantification of the uncertainty.

- The γ-ray sensitivity of the transistors tested in this study did not change statistically during multiple irradiations. This observation is consistent with one of the unstated assumptions in the ASTM standard test method [1].

- The experiments confirmed that there is a total dose dependence to the gain recovery after a hard anneal. The "un-recovered" initial gain represents permanent degradation of the transistors performance. The damage mechanism is believed to be trapped charge in the silicon oxide layer. Future experimentation will elucidate the actual damage mechanism.

5. REFERENCES

1. *E 1855–96: Standard Test Method for Use of 2N2222A Silicon Bipolar Transistors as Neutron Spectrum Sensors and Displacement Damage Monitors*, Annual Book of ASTM Standards, Volume 12.02, 2003.

2. *E 1249–00: Standard Practice for Minimizing Dosimetry Errors in Radiation Hardness Testing of Silicon Electronic Devices Using Co-60 Sources*, Annual Book of ASTM Standards, Volume 12.02, 2003.

3. Edward V. Thomas, *Personal communication (Electronic mail) with K. C. Kajder and K. R. DePriest*, August 7, 2005.

APPENDIX A: DOSE CONVERSION CALCULATIONS IN ^{60}CO FIELD

MCNP5 Input Deck for Dose Conversion in Pure ^{60}Co γ-field

```
Cross Section Fold for Virtual Materials in Co-60 free-field
C
C *********************************************************************
C *                            CELL CARDS                             *
C *********************************************************************
C
1     0   -1     imp:p=1
2     0    1     imp:p=0

C
C *********************************************************************
C *                          SURFACE CARDS                            *
C *********************************************************************
C
1     so   0.282094791        $Sphere with surface area of 1 cm^2

C
C *********************************************************************
C *                           DATA CARDS                              *
C *********************************************************************
C
MODE P
C
C *******************
C *  SOURCE CARDS    *
C *******************
C
C  Source is a point source of Co-60 photons
C
SDEF  ERG=D1
C
SC1   Cobalt-60
SI1   L  1.173  1.322
SP1   D  1.0    1.0
C
C *******************
C *  MATERIAL CARDS  *
C *******************
C
C
C  Water
C   Use unit density
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C   O-16       0.3325399          0.8857406          0.0333484
C   O-17       0.0001267          0.0003586          0.0000127
C   O-18       0.0006667          0.0019982          0.0000669
C   H-1        0.6665666          0.1118689          0.0668459
C   H-2        0.0001000          0.0000335          0.0000100
C
C  The total compound atom density (atom/b-cm):  0.10028395
C
M1       8000.04p  0.3333333     1000.04p  0.6666667
C
C  To convert a particle flux to rad[Material]
C  use FM  1.60664582E-09 1    -4 1 for neutrons
C   or FM  1.60664582E-09 1    -5 -6 for photons.
C
C
C   CaF2:Mn at a density of 3.10 g/cm3
C
C   Summary of MatMCNP Calculations:
C
```

```
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Ca-40       0.3204956          0.4877338          0.0227846
C  Ca-42       0.0021391          0.0034178          0.0001521
C  Ca-43       0.0004463          0.0007301          0.0000317
C  Ca-44       0.0069098          0.0115661          0.0004912
C  Ca-46       0.0000132          0.0000231          0.0000009
C  Ca-48       0.0006182          0.0011290          0.0000440
C   F-19       0.6612520          0.4784000          0.0470096
C  Mn-55       0.0081258          0.0170000          0.0005777
C
C  The total compound atom density (atom/b-cm):  0.07109178
C
M2      20000.04p  0.3306223   9019.04p  0.6612520   25000.04p  0.0081258
C
C  To convert a particle flux to rad[Material]
C  use FM  3.67941622E-10 2    -4 1 for neutrons
C   or FM  3.67941622E-10 2    -5 -6 for photons.
C
C
C
C  Silicon at a density of 2.33 g/cm3
C
C   Summary of MatMCNP Calculations:
C
C  Isotope  Number Fraction    Weight Fraction       Atoms/b-cm
C  Si-28       0.9223000          0.9187385          0.0460785
C  Si-29       0.0468300          0.0483159          0.0023396
C  Si-30       0.0308700          0.0329456          0.0015423
C
C  The total compound atom density (atom/b-cm):  0.04996044
C
C  MCNP Material 1800
C
M3      14000.04p  1.0000000
C
C  To convert a particle flux to rad[Material]
C  use FM  3.43525514E-10 3 -4 1 for neutrons
C   or FM  3.43525514E-10 3 -5 -6 for photons.
C
C ********************
C *  PHOTON TALLIES  *
C ********************
C
F2:P   1
E2     1.2000  1.4000
FC2    Photon fluence across surface 1 [(photon/cm2/source-photon)]
C
C
F12:P  1
FM12   1.60664582E-09 1    -5 -6
FC12   Co-60 Dose in Water (Rad[H2O]/(photon/cm2))
C
C
F22:P  1
FM22   3.67941622E-10 2    -5 -6
FC22   Co-60 Dose in TLD-400 (Rad[TLD]/(photon/cm2))
C
C
F32:P  1
FM32   3.43525514E-10 3    -5 -6
FC32   Co-60 Dose in Silicon (Rad[Si]/(photon/cm2))
C
NPS   100000000
```

Table 15. MCNP5 Output Table with Dose Conversion Constants

Material	^{60}Co Dose Rad[Mat]/(γ/cm^2)	Conversion for Rad[H_2O]	Conversion for Rad[TLD]	Conversion for Rad[Si]
Water	5.93930E-10	1.00000	0.87776	0.89748
CaF_2:Mn	5.21326E-10	1.13927	1.00000	1.02247
Silicon	5.33039E-10	1.11423	0.97803	1.00000

How to use this table:

1. Determine the units of the dosimetry. (Ex. – Alanine dosimetry results in Rad[H_2O].)

2. Find that entry in this table. (Ex. – Row 1 give the dose in Rad[H_2O].)

3. Find the appropriate conversion factor in table. (Ex. – I want to convert to Rad[TLD], so the conversion factor is 0.87776.)

4. Multiply to dosimetry results by the conversion factor.

CAUTION: These conversion factors are only valid in a ^{60}Co γ-field.

APPENDIX B: HISTOGRAMS OF INITIAL GAIN VALUES

Although not directly related to the gamma sensitivity, the initial gains of the single diffusion lot of 2N2222A transistors were evaluated. The distribution of the initial gain values was examined. In the ASTM standard test method [1], step 1 in the experimental procedure begins with an initial gain measurement and sorting of the transistors. The method does not strictly apply because it identifies initial gains between 50 and 200. The transistors in this investigation were high gain transistors, so none of them met the "gain less than 100" criteria for rejection. In addition, the top and bottom 5% gain transistors were not removed during this investigation as is suggested by the ASTM standard test method.

The minimum initial gain value in the transistor set is 198.13 while the maximum initial transistor gain is 259.07. The average initial gain for the transistors is 235.2 with a sample standard deviation of 11.8 (5%). Initially, the transistors gain values were sorted into a histogram. The histogram "edges" started 198 and ended at 261 (9 bins with a width of 7). The results of the histogram are found below in Figure 20. A quick inspection (i.e., without a rigorous statistical analysis) of the figure reveals that initial gain values of this transistor set is not normally distributed. There is obviously a long tail on the low gain side (to the left) of the mean of the transistor gain distribution.

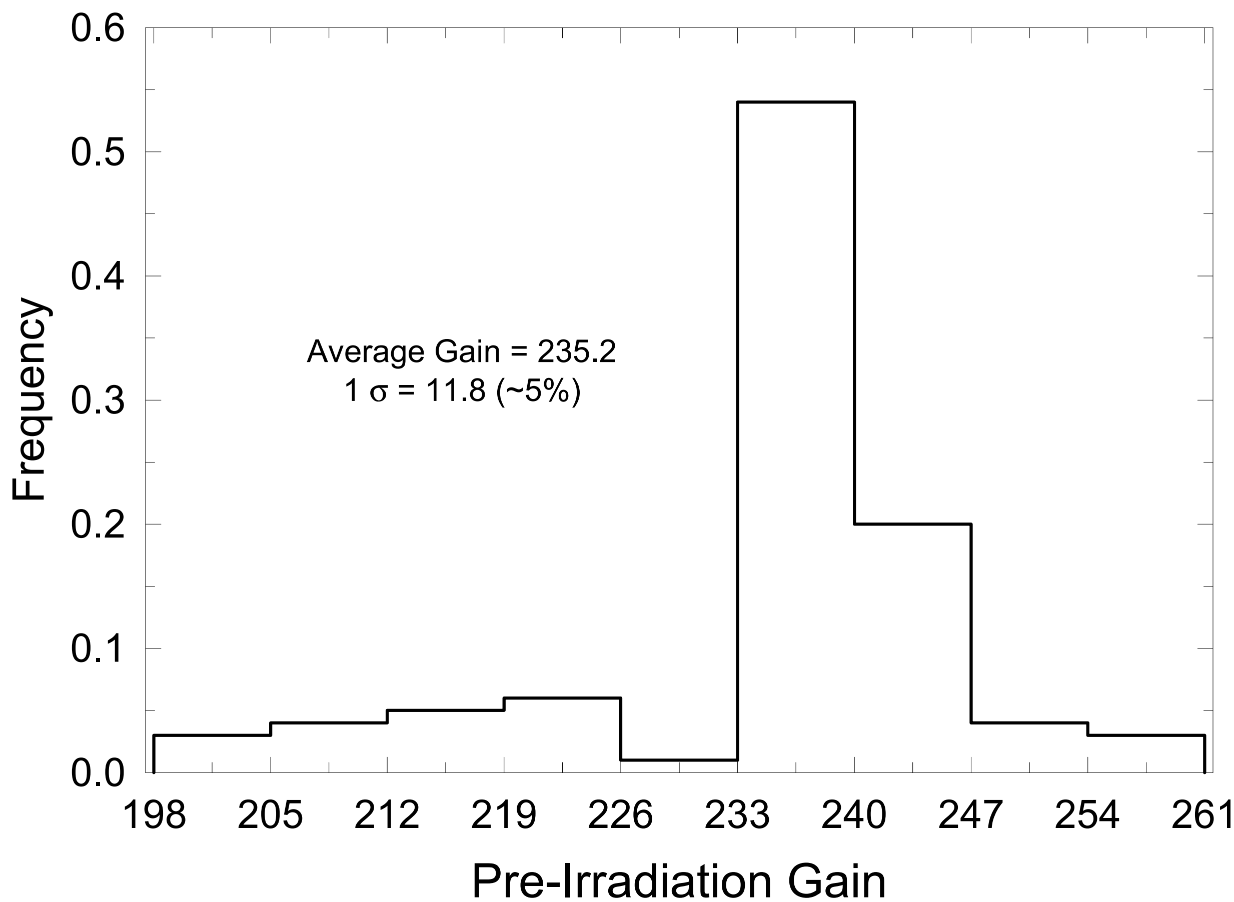

Figure 20. Nine Bin Histogram for Initial Transistor Gains

In summary, a rigorous statistical analysis was not performed on the distribution of initial transistor gains for this subset of the single diffusion lot of 2N2222A transistors. However, a histogram of the initial gain values was constructed. The histogram revealed that the transistor gains are not normally distributed and show a skew toward the higher portion of the distribution.

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