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Total Dose Effect of the ACTEL A1020 FPGA (2 micron size): AIRS Project

By

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TO: C. E. Barnes and distribution

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SUBJECT: AIRS project ACTEL A1020 (2.0µm size).

SUMMARY

- A single ACTEL A1020 (2.0µm feature size) FPGA from wafer lot JE-15 was irradiated under a low dose rate of 0.005 rad(Si) per second up to a total dose of 29 krad(Si).
- Results of the low dose rate experiment indicate that wafer JE-15 is potentially suitable for space application as long as the environment does not exceed a total dose of 29 krad(Si). **Please keep in mind that only one device from JE-15 was tested, thus we must recommend that at least two additional devices under go similar testing in order to ascertain lot characterization.**
- A second ACTEL A1020 device was irradiated under a high dose rate of 50 rad(Si) per second up to a total dose of 150 krad(Si).
- High dose rate results show that a rate of 50 rad(Si) per second will cause devices to fail somewhere between 60 and 100 krad(Si).

Introduction

In previous years, various laboratories have studied total dose effect on the ACTEL A1020 FPGA. As far as space radiation is concern, test data from older lots of the A1020 have worked up to levels of 100 krad(Si). However, because of process modifications, newer versions of the ACTEL A1020 have not faired as well. This report discusses results of two recent radiation experiments conducted at JPL.

Device background/description- The ACT 1 family of Field Programmable Gate Arrays (FPGA) is implemented on a 2.0 µm two-level metal CMOS process. ACTEL makes use of their PLICE antifuse science for this technology. Users can utilize up to 2000 gates per device. The salient feature of this device is the ability to program it on site, effectively reducing the turnaround time for implementation of new designs compared with conventional masked gate arrays.

The ACTEL A1020 is made on a commercial line (Matsushita, Uozo facility) and any radiation tolerance is strictly fortuitous in nature and in no way characterizes the process as "radiation-hardened". This is the reason why ACTEL A1020 (2.0 µm) FPGAs are frequently employed in several space applications, e.g., flight projects and or instruments.

Test Description

Devices- Two devices from wafer lot JE-15 were used in this experiment. These devices were programmed with four basic operational patterns, e.g., flip-flop, input/output, combinatorial logic, and shift register and counter.

Electrical bias- Bias was maintained at all times during the irradiation and annealing process except when the devices were transported to the test site.

Test equipment- Both test devices were measured with the ADVANTEST T3342 VLSI automatic tester at JPL. Additional tests were performed with the aid of Tektronix TM502A (current probe amplifier), Hewlett Packard 6629A (power supply), Lambda Electronics model LQ-521 (regulated power supply), Tektronix Oscilloscope 2440 (digital oscilloscope), and a 386 personal computer (Matrix).

By connecting the current probe to the regulated power supply, the startup current transient was captured on the oscilloscope (see figure 1). The maximum peak current and the time required for startup was obtained via the captured transient current. No current limit was placed on the power supply. Thus, the demand for startup current was always met, as long as the peak demand did not exceed 2 Amperes, which is the limit for the power supply.

In order to augment the startup current measurements, the HP6629A power supply was connected to the personal computer to capture the startup current of each DUT as a function of voltage. This was accomplished in two ways. The first method was done by a program called k9, which ramps the voltage supplied to the DUT in small increments and then measures the corresponding current (see figure 2). Once again, no current limit was placed on the HP6629A. The second technique, called k10, was performed by ramping the current while maintaining a constant voltage (5V) (see figure 3).

During each irradiation, the computer monitored the voltage and operational current supplied by the HP6629A power supply. From this data, a strip chart of current versus time was created for each DUT (see figure 4). Later this strip chart was converted to display current versus total dose (see figure 5).

All measurements were conducted at ambient temperature, with the exception of the additional temperature measurements performed at pre-radiation and at 6 krad (Si), for the low dose rate experiment. Those measurements were done at +75°C and -25 °C, in addition to the room temperature readings.

DUT test condition- Total dose tests were done using two Cobalt 60 sources. One source was utilized for the high dose rate (50 rad(Si) per second). The other source was used to emulate the dose rate found in space, approximately 0.003 rad(Si) per second. However, in order to expedite the experiment, while still retaining the near space dose rate, a rate of 0.005 rad(Si) per second was employed. Irradiation was performed at ambient temperature.

Both DUTs were irradiated under static condition with a voltage of 2.5 volts applied to the output pins and an operational voltage of 5.0 volts.

Testing procedure- For the high dose rate experiment, DUT serial number (S/N) 2573 was measured at 0, 6, 10, 15, 20, 30, 40, 60, 100, and 150 krad(Si). Following the 10 krad(Si) level, k9 and k10 measurements were performed before and after the VLSI testing. In the interest of monitoring any annealing effects that may have taken place between irradiation levels, redundancy in k9 and k10 measurements were necessary. At the completion of the last measurement (150 krad(Si)), the device was annealed for a total of 69 hours.

In the low dose rate experiment, DUT S/N 2561 was measured at 0, 6, 11, 21, and 29 krad(Si). As was stated previously, the VLSI testing was done at room temperature with the exception of the pre-irradiation and 6 krad(Si) levels, which were augmented with temperature measurements at +75°C and -25 °C. Following the last measurement, the DUT was annealed for a total of 144 hours. The redundancies in acquiring the additional set of k9 and k10 measurements were not necessary, because the DUT did not anneal noticeably between irradiation levels.

Results

High dose rate- DUT 2573, which was irradiated at the high dose rate, displayed rapid annealing between irradiation levels 6 k and 10 krad(Si) (see figure 6). This type of rapid anneal is a favorable quality (more about this in the conclusion section of this report). In order to monitor any annealing between irradiation levels, it was decided that a second set of k9 and k10 measurements had to be taken following each VLSI testing. Note that from 40 k to 60 krad(Si), the device was accidentally irradiated with two 10 krad(Si) levels separated by a 30 second interval, instead of the planned continuous 20 krad(Si) dose. During the period of no irradiation (30 seconds), the operational current dropped by 2.5mA. Between irradiation levels, other electrical parameters, besides the operational current, changed as well, i.e., minimum voltage, and startup conditions.

Prior to irradiation, the operational current of the DUT was 12mA. During the first radiation level, the current jumped to 19mA, an increase of 58%. Subsequent to each successive irradiation level, the operational current drop never exceeded 10mA.

An interesting phenomenon took place at 60 krad(Si), which is worth noting. The largest operational current of 34mA was observed there, that is an increase of 280%. From zero to 60 krad(Si), the operational current climbed in a near exponential fashion. But, from

60 to 150 krad(Si), the current *decreased* almost asymptotically to 30mA. This behavior can be attributed to competing radiation-induced effects. As the demand for operational current increases with increasing radiation level (up to 60 krad(Si)), annealing takes place due to the heat generated from the excess current. Therefore, the rapid drop of 2.5mA observed within the elapsed 30 seconds of no irradiation can be attributed to this current induced annealing.

Figure 7a shows the results of the pre and post-VLSI measurements based on k9 and k10 startup measurements. The electrical parameter called "minimum voltage", which we define as the smallest voltage needed for device operation, reached its largest value at ~3.1V, at 30 krad(Si). From this peak value of 3.1V, the minimum voltage decreases in a pseudo-quadratic fashion until the 150 krad(Si) level was reached, at which point the minimum voltage reached a value of about 1.2V. In figure 7a, the pre-VLSI measurement was at a higher voltage than post-VLSI measurement. This is (yet again) another manifestation of annealing process taking place. This minimum voltage is translated into a minimum operational current. Thus, any operational current in excess of the minimum operational current is effectively converted into heat. It is this heat that produces the annealing. From 60 to 150 krad(Si), the favorable rapid annealing property of the device exceeds the rate of accumulating radiation damage. Thus, effectively lowering the operational current.

Figure 7b displays the minimum voltage as a function of time, post irradiation anneal. During the first hour of anneal (done at 125 °C), the minimum voltage parameter jumped from 1.2V to 4.2V, an increase of 250%. This DUT is a relatively fast annealing device, but under the high dose rate of 50 rad(Si) per second it is not fast enough. This is the reason why the minimum voltage parameter jumps from 1.2V to 4.2V. Under the ideal radiation dose rate, the device should anneal during the exposure to irradiation. Thus, the voltage jump would not have taken place. In fact, a no change in voltage would be have been observed during any part of the high temperature anneal.

Figures 8a (irradiation) and 8b (annealing) follow the transient startup conditions of the DUT as captured by the current probe and oscilloscope (see figure 1). During the irradiation, the device drew its maximum startup current of 86mA at 6 krad(Si). The startup current continued to decrease with successive radiation levels. At 30 krad(Si) a second hump (or spike) was observed. Following this hump, the startup current continued to decrease with additional radiation. The largest startup time was also observed at 30 krad(Si). At pre-radiation, the DUT startup time was 13.9msec. The startup time parameter increased as a function of radiation level. At 30 krad(Si) the time parameter reached its highest value of 16.7msec, an increase of 20%. Following the 30 krad(Si) level, the startup time decreased with increasing irradiation levels. At 150 krad(Si) the startup current was too small to be detected via the current probe technique. However, based on the current probe measurements obtained at 150 krad(Si), it was apparent that the current startup had to be smaller to or equal to the current at 100 krad(Si). Thus, the values at 100 krad(Si) were used in place of the missing 150 krad(Si) data (see appendix).

During the anneal process (see figure 8b), the first hour of high temperature (125°C) brought an increase in startup current from 10.6mA to 151mA. Startup time went from 8.8msec to 30.9msec, that is an increase of 250%. In just this initial hour there was a rapid increase in both startup time and current. The following 25 hours, at ambient temperature, the device behaved as if had been subjected to radiation. There was a decrease in current (down to 89mA) and in startup time (down to 23.2msec). The next 25 hours, which were done at 125°C, brought a rapid increase in current (up to 185mA) and a small increase in the startup time (up to 25.8msec). The final 17 hours, at room temperature, the device again displayed the characteristics to radiation exposure. However, the startup parameters did not change by significant amounts.

Based on the results of the high dose rate experiment, it is apparent that the device can not maintain its electrical functionality within a high dose rate environment. It is equally apparent, that a total dose of 150 krad(Si) is excessive radiation for this device to recover from. Since only one device was irradiated, there is no way of telling if this behavior is a characteristic of wafer lot JE-15 or simply a characteristic of the single irradiated device.

Low dose rate- Device 2561 was irradiated at a low dose rate of 0.005 rad(Si) per second. Figure 9 shows the operational current for the DUT as a function of total dose. Note that neither the operational current nor the net load current changed. From pre-radiation to 29 krad(Si), the observed current change was very small, less than 2% of the initial value. The device showed no signs of annealing between irradiation levels. This type of near "flat" response serves as an indicator that the device can maintain its electrical integrity (functionality) under this low dose rate.

Figure 10a shows how the minimum voltage parameter changed with increasing total dose. Note that the minimum voltage changed very slightly. At pre-radiation, the DUT required a minimum of 2.56V to maintain functionality. The maximum value of the minimum voltage parameter of 2.64V, occurred at 21 krad(Si), that is an increase of 3.1%. Finally, when the device was removed from the irradiation room (29 krad(Si)), the value of the minimum voltage decreased slightly to 2.62V.

Figure 10b tracks the minimum voltage parameter as a function of time, following the end of irradiation. The first four hours, which were done at high temperature (125°C), showed the most rapid anneal. Within these four hours, this voltage parameter went from 2.62V to 2.98V, an increase of 13.8%. The next interval of anneal (24 hours at 125°C) brought an additional amount of annealing. The minimum voltage increased to 3.12V, a 19% increase from pre-anneal value. After an additional 72 hours of high temperature anneal, the minimum voltage parameter increased by a small amount (0.019V). The last 48 hours, which were done at room temperature, brought an additional increase in minimum voltage (0.039V). A typical pattern observed during the anneal process is one where the minimum voltage increases with elapsed time following the end of irradiation but reaches an asymptotic value. In the case of DUT 2561, that value is about 3.2 volts.

Figures 11a and 11b show the startup characteristics of DUT 2561 as a function of irradiation (11a) or post irradiation (11b). During the irradiation, the device reaches its maximum startup current of 92mA at pre-radiation. With increasing radiation levels, the startup current decreases. However, the startup *time* (or peak width) reached its maximum value at 6 krad(Si), then settled to values between 15.4 to 15.7msec. In the first four hours of high temperature (125°C) anneal, the device show the most rapid annealing. The startup current went from 54.3 to 113.2mA, an increase of 108%. The startup time increased from 15.7 to 19.9msec, an increase of 26%. The following 24 hours (125°C), brought a small increase in both startup parameters. However, during the next 72 hours of high temperature anneal, the startup current decreased from 117.7 to 108.2mA. This decrease in current was also observed in the minimum operational current under startup condition (see Raw Data in appendix) as well as in the operational current (also under startup condition). This anomalous behavior could be due to human error, e.g., not making certain a proper contact was made between device and startup board tester. It appears that a pin or more then one may have been floating. The last 48 hours were done at ambient temperature. Startup current increased from 108.2 to 124.7mA. While, the startup time went from 21.3 to 22.1msec.

Finally, figure 12 shows the operational and net load current during annealing. Each output pin was connected in series to a 2.2kΩ resistor. In turn, the resistors were all connected a constant 2.5V (relative to ground). Thus, we defined the net load current, as the aggregate current needed to maintain the 2.5V potential (relative to ground) on all resistors. At pre-anneal, the operational current was at 16.5mA. As soon as the device was exposed to the high temperature (125°C), the operational current dropped to 16mA. This current drop is thermally induced. When thermal equilibrium was reached, the operational current rose in an exponential fashion. Note the spikes on both the operational and net load current curves. These spikes are due to thermal effects induced by the sudden rise (or drop) in temperature, which coincided with the turning on and turning off of the oven. Recall that the all measurements were performed at room temperature. Eventually, during the high temperature anneal, the operational current reached the value of 16.4mA (asymptotically). When the device was allowed to cool down to ambient temperature, the operational current reached 17.1mA. This value was reproduced every time the device was allowed to reach thermal equilibrium at room temperature. The net load current is essentially a mirror image of the operational current except that the heights of two of the spikes are greater. Asymptotically, the net load current reached a value of 7.9mA. With each successive measurement, the thermal spikes observed in the net load current decreased.

Based on the low dose rate experiment, the DUT (2561) was able to maintain its electrical functionality during the entire irradiation process. This implies that the device will work under the low dose rate conditions in space without any of the startup current anomalies that occur in laboratory tests at high dose rate. But again, it must be understood that only a single device was irradiated under this low dose rate and therefore there is no way of telling if the observed behavior is a characteristic of wafer lot JE-15 or simply a characteristic of the specific unit that was tested.

Conclusion/recommendations

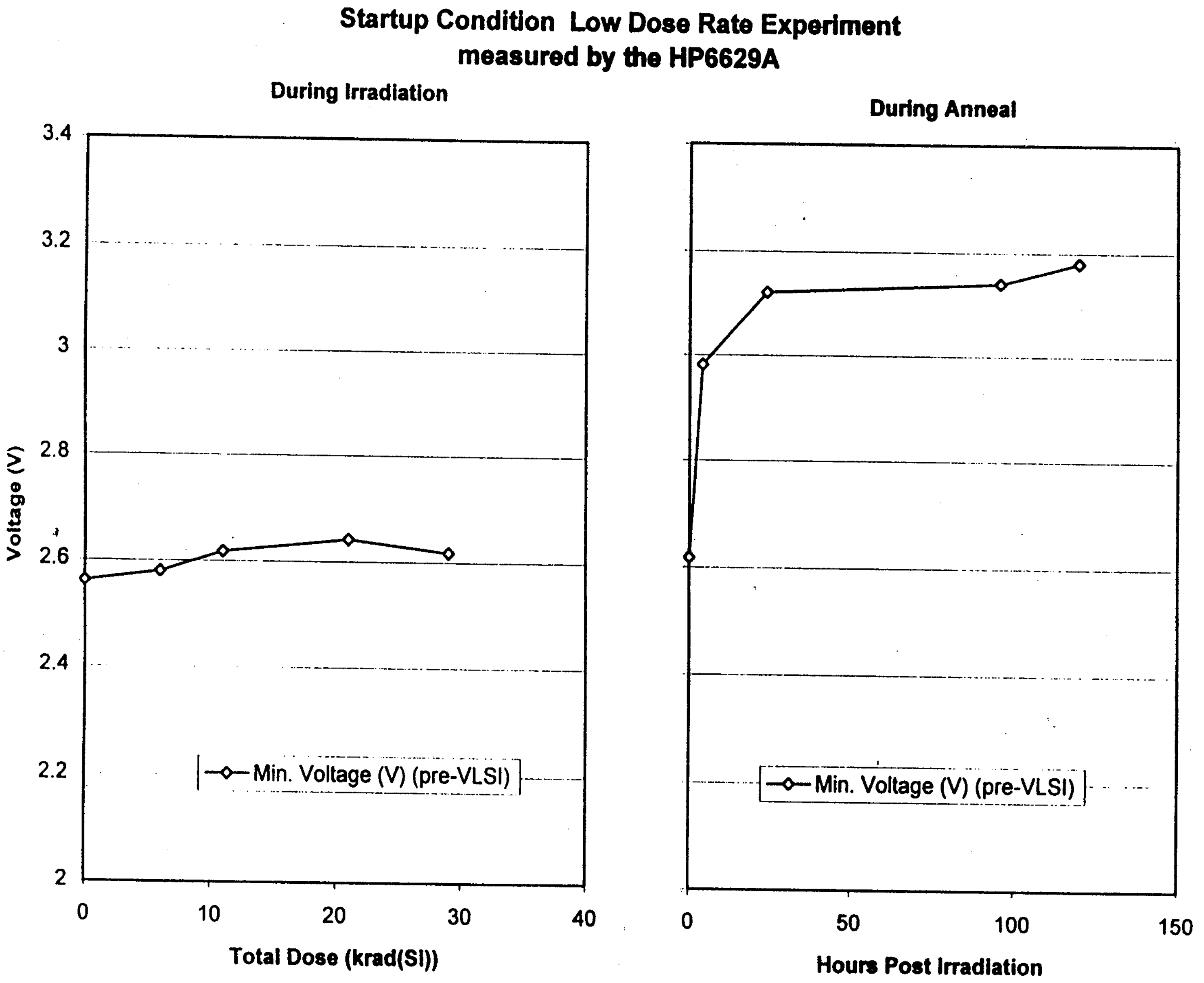
In order to ascertain the radiation effect characteristics of wafer lot JE-15, further testing of devices from this lot is necessary. While, some useful information was gathered from the high dose rate experiment, it was the low dose rate experiment that yielded more useful information of device characterization.

The high dose rate experiment of 50 rad(Si) per second, showed that although a fast annealing device, the DUT was incapable of maintaining its electrical functionality. This point was made evident in at least two places, between irradiation levels and during the high temperature anneal.

Between irradiation levels, it was observed that the operational current decreased from 2.5mA to 10mA. This rapid anneal, as was pointed out in the result section of this report, is a favorable quality. However, a rapid anneal in operational current forewarns of the possibility that other electrical parameters may likewise be changing. And indeed, this was shown to be the case. The minimum voltage parameter, as an example, changed as a function of time between irradiation levels. A clear indication that the device was not maintaining electrical integrity.

During the first hour of high temperature anneal, the minimum voltage parameter showed an increase of 250%. A clear indications that the device had problems retaining functionality. Following the one-hour of high temperature anneal, the minimum voltage decreased do a value of approximately 4V.

The low dose rate experiment of 0.005 rad(Si) per second, indicated that the device was able to retain functionality between and during irradiation levels. Within the entire process of high temperature anneal, the minimum voltage parameter never increased by over 22% of pre-anneal value. Startup current demand, however, increased by nearly 125%. Thus, it is recommended that a power supply with a current limit exceeding 125% of pre-radiation startup current be employed.



(a)

(b)

Figure 10. Irradiation and anneal measurements for DUT 2561 (minimum voltage).

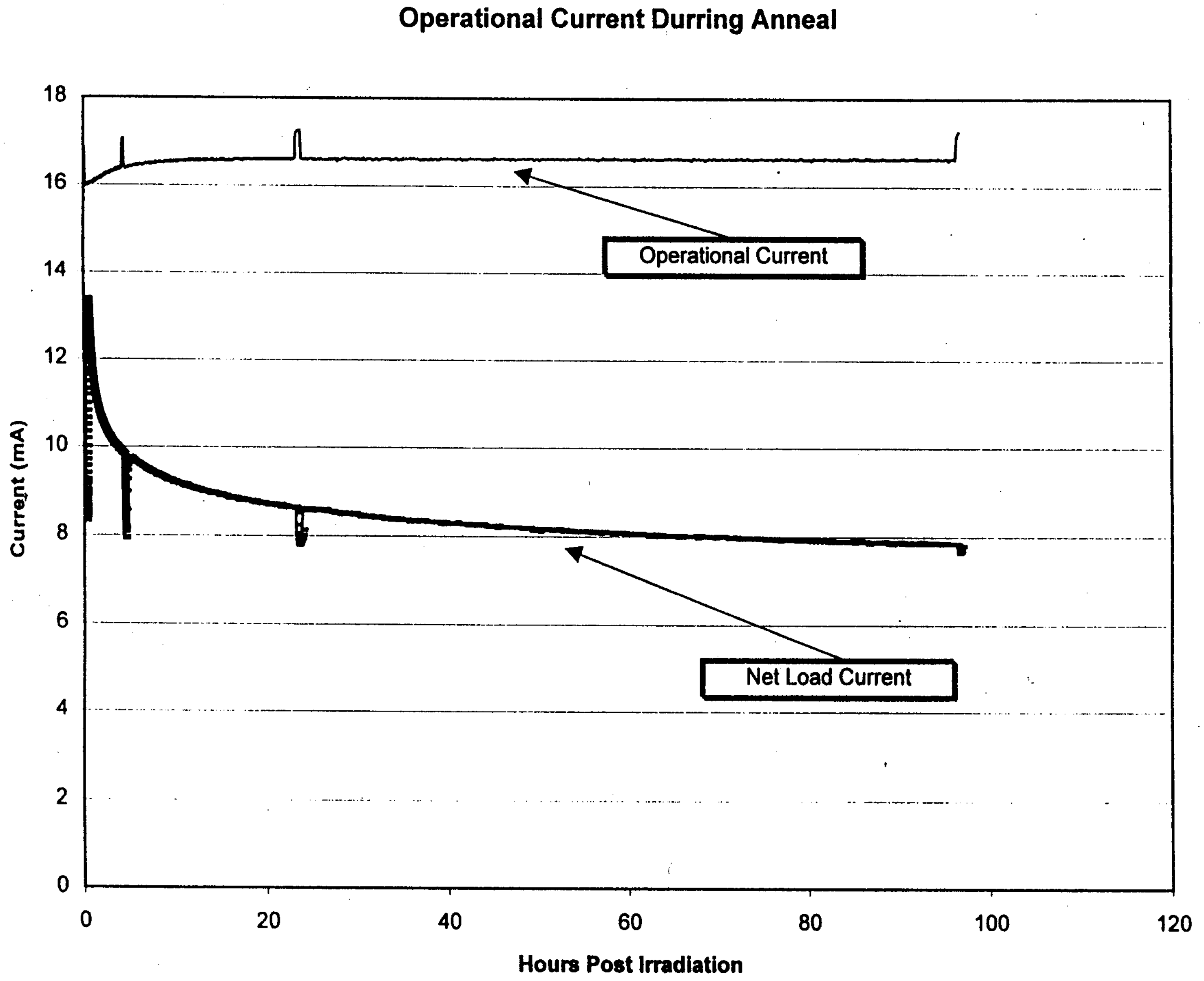


Figure 12. Operational and net load current versus elapsed time post irradiation (DUT 2561).

Appendix

- Raw data for high dose rate experiment (DUT 2573). Includes irradiation and anneal data.
- Raw data for low dose rate experiment (DUT 2561). Includes irradiation and anneal data.
- Current probe picture of DUT 2573, pre-VLSI measurement, at 100 krad(Si).
- Current probe picture of DUT 2573, pre-VLSI measurement, at 150 krad(Si).

Raw Data:

Irradiation sequence

Results from the AIRs Low Dose Rate (0.005 rad(Si) per second): DUT 2561					
Rad Lvl krad(Si)	Pre-VLSI Measurements			Current Probe Measurements	
	Min. Voltage (V)	Min. Current (mA)	Operational Current (mA)	Time (msec)	Peak Current (mA)
0	2.561	4.870	11.470	15.7	92
6	2.580	4.890	11.500	16.7	82.3
11	2.618	4.980	11.510	15.4	71
21	2.642	5.020	11.490	15.5	63.4
29	2.618	4.940	11.500	15.7	54.3

Annealing sequence

Anneal Hrs	Total Hours (Hrs)	Pre-VLSI Measurements			Current Probe Measurements	
		Min. Voltage (V)	Min. Current (mA)	Operational Current (mA)	Time (msec)	Peak Current (mA)
0	0	2.618	4.940	11.500	15.7	54.3
4*	4	2.981	5.770	11.350	19.9	113.2
24*	24	3.122	6.220	11.430	20	117.7
72*	96	3.141	6.210	11.290	21.3	108.2
48**	144	3.180	6.370	11.410	22.1	124.7

* Annealed at 125°C

** Annealed at room Temp.

Total Dose of 150 krad(Si)
DUT 2573
Measured on 5/19/97
6:15 PM
scale: 10mA/div

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CH1    10mV50OHM         A    5ms   2.50mV   VERT
CH2     1V
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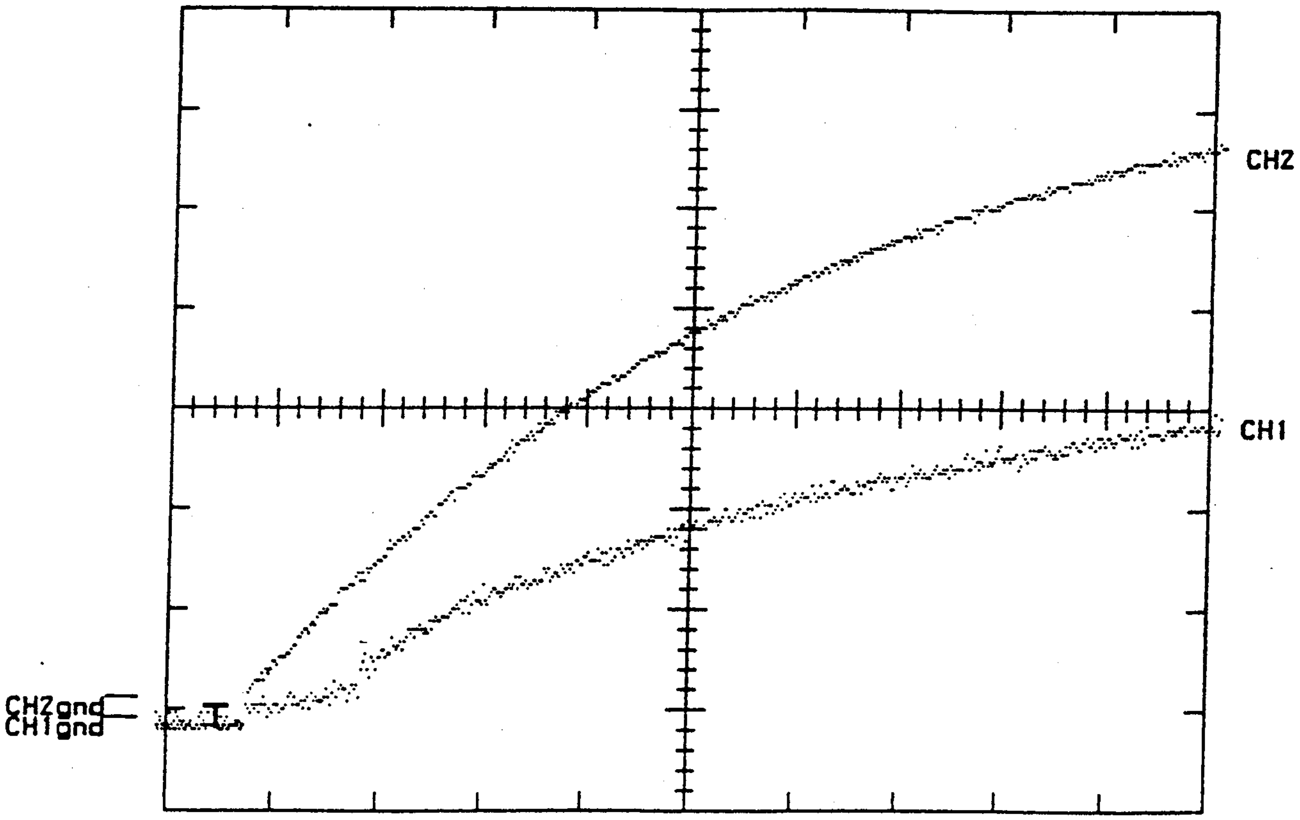

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