ANALYSIS OF THE BEHAVIOR OF INTEGRATED SCHOTTKY LOGIC
IN NEUTRON, TOTAL DOSE AND DOSE RATE ENVIRONMENTS*Richard D. Blice and James H. Collins
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ISL devices were irradiated in neutron, total dose and dose rate environments and their response was explained in terms of (1) circuit configurations, (2) SPICE (nonlinear circuit simulation program) transistor models fitted through experimental data, and (3) physical parameter transistor models based on nominal doping profiles. Three new modelling techniques were developed: (1) determination of SPICE transistor model parameters by a method which allows both low and high injection effects to be present over the current range of interest and does not require graphical analysis; (2) determination of the minority carrier lifetime which characterizes a dose rate upset mechanism and the corresponding lowest steady state dose rate at which upset would occur; and (3) prediction of the primary photocurrent of a transistor neutral region from its saturation current, which can be obtained either from physical model calculations or from properly determined SPICE parameters.

Introduction

Integrated Schottky Logic (1), ISL, is basically low power Schottky logic with the buried layer shortened to create a parasitic vertical PNP transistor between the base of the down NPN and ground (Figure 1(b)). When the NPN goes into saturation, the vertical and lateral PNP transistors turn on and shunt enough drive current to ground to keep the NPN out of deep saturation (Figure 1(a)). This allows drive current to be heavy enough to insure operation after high neutron fluences without degrading prerad propagation delay when gains are high.

ISL has an exceptional tolerance for neutron and total dose radiation, but is susceptible to upset at dose rates much lower than many other technologies. This paper analytically investigates these characteristics.

Experimental and Analytical Procedures

The test vehicle for this modelling effort was the Signetics 8A1200, an ISL Configurable Gate Array containing MSI functions for technology evaluation. The following functions were available:

- (1) 4-bit Binary Adder
- (2) 4-bit Bidirectional Shift Register
- (3) 8-to-1 Multiplexer
- (4) 3 separate Ring Oscillators

A TI 990/100 microcomputer was used to exercise the MSI functions, with the 8A1200 input buffers driven by 74125 buffer gates and with the 8A1200 output buffers driving a 74LS373 8-bit latch.

Twelve devices were tested and irradiated, the first six having a 12 ohm-cm substrate and the second six having a 2 ohm-cm substrate. The 2 ohm-cm samples came from two different processing lots. Table I gives the handling details, but briefly, out

of the first group two samples each were subjected to neutron, total dose and dose rate irradiations. The entire second group was tested for dose rate upset with one unit given a neutron fluence of 5×10^{13} n/cm² to determine its effect on dose rate upset.

Neutron irradiations were performed on the Fast Burst Reactor at White Sands Missile Range (WSMR), dose rate upset was performed on the WSMR Linac, and total dose work was performed on the Cobalt 60 source at Indiana State University.

The goal was to find the level in each of the radiation environments at which the MSI functions failed and then relate that level to degraded transistor and ISL cell characteristics and circuit considerations. Failure was considered to have occurred when any of the six MSI structures did not operate after a neutron or total dose irradiation. Dose rate upset levels reported were performed on the shift register by setting the output buffers high and increasing the dose rate until an output changed state. When the output buffers were set low, upset occurred at a much higher dose rate or not at all.

Neutron and total dose degradation of transistors and ISL cells was modelled by measuring h_{FE} vs. I_C of two test structures, a buffer output transistor and an ISL gate. SPICE parameters were determined after each irradiation by the method in Appendix I so that damage constants could be determined at any collector current of interest. Figures 2(a) and 2(b) show the measurements and curves for neutron degradation of S/N 1 and Figure 2(c) shows the measurements and curves for S/N 3 after total dose irradiation.

Table I

Handling of Signetics ISL CGA 8A1200 Units12 ohm-cm Substrate

- S/N 1 Neutron ($\phi = 3 \times 10^{15}$ n/cm²)
- 2 Neutron ($\phi = 3 \times 10^{15}$ n/cm²)
- 3 Total dose ($\gamma = 1 \times 10^7$ rads(Si))
- 4 Dose rate upset
- 5 Dose rate upset
- 6 Total dose ($\gamma = 1 \times 10^7$ rads(Si))
- Angle lap

2 ohm-cm Substrate - Lot 1

- S/N 7 Dose rate upset ($\phi = 0$)
- 8 Dose rate upset ($\phi = 5 \times 10^{13}$ n/cm²)

2 ohm-cm Substrate - Lot 2

- S/N 9 Dose rate upset
- 10 Dose rate upset
- 11 Dose rate upset
- 12 Dose rate upset

The primary photocurrent generated by each neutral region was then calculated by dividing the saturation current for that region (3) by the thermal

Neutron Degradation

The MSI structures on the 8A1200 failed between the fluences of 1×10^{15} and 3×10^{15} n/cm², which indicated that the input buffers, output buffers, or ISL gates contained transistors whose gains had fallen below some minimum value dependent on circuit configuration. To determine which element failed at the lowest fluence, all transistors were assumed to be out of saturation with emitter-base voltages of 0.75 volt. With the resulting mode voltages and nominal resistor values, shown in Figures 3(a), 3(b) and 3(c), collector currents and the minimum gains at those currents could be determined.

FIGURE 2(a)

GAIN OF THE ISL GATE VS. COLLECTOR CURRENT BEFORE AND AFTER NEUTRON IRRADIATION. WITH A FAN OUT OF FOUR THE GATE WOULD FAIL AT A FLUENCE OF 2.3×10^{15} n/cm². THE GAIN MEASUREMENTS ARE INDICATED ON EACH CURVE, AND EACH CURVE WAS GENERATED WITH A SET OF BIPOLAR TRANSISTOR PARAMETERS WHICH FORCES THE CHARACTERISTIC THROUGH THE MEASURED VALUES. THE TRANSISTOR GAIN MODEL IS THE ONE INCORPORATED INTO THE SPICE NONLINEAR CIRCUIT SIMULATION PROGRAM (SEE APPENDIX I).

To find the fluence at which the gain of a particular transistor dropped to the minimum value, its gain at the specified collector current was calculated by means of the SPICE parameters generated after each neutron irradiation. The damage constant K was determined by a least squares fit of Δh_{FE}^{-1} vs. ϕ and the fluence of failure ϕ_F was found from initial gain, minimum gain and the damage constant:

$$\phi_F = \frac{1/h_{FE}(\min) - 1/h_{FE0}}{K} \quad (1)$$

Table III shows the calculated fluences of failure for all the elements, and the ISL gates had the lowest values, 2×10^{15} n/cm².

FIGURE 2(b)

GAIN OF THE BUFFER OUTPUT TRANSISTOR BEFORE AND AFTER NEUTRON IRRADIATION. THE INPUT TRANSISTOR OF THE INPUT BUFFER FAILED AT THE LOWEST NEUTRON FLUENCE, 2.6×10^{15} n/cm². DATA POINTS ARE INDICATED, AND EACH CURVE WAS GENERATED BY THE SET OF SPICE TRANSISTOR PARAMETERS WHICH MAKES IT PASS THROUGH THOSE POINTS (SEE APPENDIX I).

Table III
Calculated Neutron Fluences of Failure

Input Buffer	S/N	IC	Interpolated h_{FE}	$h_{FE}(\min)$	Calculated ϕ_F
Input Transistor	1	538 μA	64.11	2.94	2.61×10^{15} n/cm ²
	2	538 μA	84.82	2.94	2.42×10^{15}
Output Transistor	1	1.5 mA	56.82	2.81	3.15×10^{15}
	2	1.5 mA	75.18	2.81	3.13×10^{15}
ISL Gate	1	600 μA	51.36	4.00	2.32×10^{15}
	2	600 μA	58.07	4.00	2.06×10^{15}
Output Buffer					
Input Transistor	1	423 μA	65.02	1.82	4.07×10^{15}
	2	423 μA	86.03	1.82	3.71×10^{15}
Output Transistor	1	400 μA	65.20	0.853	8.71×10^{15}
	2	400 μA	86.26	0.853	7.89×10^{15}

Total Dose Degradation

The minimum gains determined in the preceding section did not come into play after total dose irradiation because gains were not degraded enough by a dose of 1×10^7 rads(Si) as shown by Table IV and Figure 2(c). The prerad slope constants for the nonideal base current component, determined as described in Appendix I, had values of 1.45, which indicates a good surface (nominal value is 1.5). The postrad slope constants were 1.6, indicating that very little surface degradation had occurred (a value of 2 indicates severe damage).

FIGURE 2(c)

GAINS OF ISL GATE AND BUFFER OUTPUT TRANSISTOR AFTER A TOTAL DOSE OF 1×10^7 RADS (Si). THE MINIMUM GAINS AT THE CORRESPONDING COLLECTOR CURRENTS ARE ABOUT AN ORDER OF MAGNITUDE LOWER THAN THE MEASURED GAINS.

Dose Rate Upset

ISL parts upset at dose rates ten or more times lower than other technologies (4), as summarized in Tables V and VI, but the variation of minority carrier lifetime in the different technologies and among units of a single technology prevented a direct comparison of measured upset levels. To overcome this problem a method was devised to infer the minority carrier lifetime and the steady state upset dose rate from upset dose rates at two radiation pulse widths. Appendix III and Figure 4 describe the method.

Figure 5 shows the calculated steady state upset dose rates plotted against calculated minority carrier lifetimes, and there is an inverse relationship. Units 4 and 5 had a 12 ohm-cm substrate and the long lifetime gave a low upset dose rate. Units 7 through 12 had a 2 ohm-cm substrate and a lower prerad lifetime, and S/N 8 was given a neutron fluence of 5×10^{13} n/cm² to determine the effect on upset of a reduced lifetime. The result was that compared to S/N 7 lifetime was lower by a factor of 8 and upset dose rate was higher by the same factor.

The calculated lifetimes of the 2 ohm-cm parts were comparable to those of the other technologies, but the calculated upset dose rates were three to 30 times lower at a given lifetime. This is a result of the generation of photocurrent over the entire area of the ISL cell, which is much larger than the junction areas of individual transistors.

FIGURE 3(a)

INPUT BUFFER OF THE SIGNETICS 8A1200. THE CURRENTS AND NODE VOLTAGES INDICATED ARE THOSE WHICH WOULD RESULT FROM DEGRADATION OF TRANSISTOR GAINS TO THE POINT WHERE COLLECTOR-BASE VOLTAGES ARE ZERO. THE COLLECTOR AND BASE CURRENTS FLOWING UNDER THIS CONDITION DEFINE THE MINIMUM GAIN OF EACH TRANSISTOR.

FIGURE 3(b)

ISL GATE WITH A FAN OUT OF FOUR. THE MINIMUM GAIN OF THE DOWN npn IS 4.00 AT 600 uA.

FIGURE 3(c)

THREE-STATE OUTPUT BUFFER IN THE LOW STATE WITH THE CONTROL CIRCUITRY OMITTED. WHEN Q_8 GOES OUT OF SATURATION ITS COLLECTOR VOLTAGE RISES TURNING ON Q_9 AND Q_{10} , WHICH SUPPLIES EMITTER CURRENT TO Q_{11} AND BRINGS IT FURTHER OUT OF SATURATION.

The upset mechanism in ISL is the primary photocurrent of an "off" gate shunting to ground current which otherwise would flow through the bias resistor of the next gate and saturate its NPN. At the upset dose rate only enough current flows into the NPN transistor base to support the required collector current in the active state and the collector voltage goes high. Upset occurs at higher dose rates when V_{BB} is raised because photocurrent must shunt a proportionally higher current to ground. Figure 6 shows experimental data for upset dose rate vs. V_{BB} at three different radiation pulse widths.

Figure 6 also shows upset dose rates vs. V_{BB} calculated by the physical parameter models generated for the 12 and 2 ohm-cm parts. Tables VII and VIII tabulate the figures used to generate these curves.

As mentioned previously, the primary photocurrent of a single neutral transistor region can be related to its saturation current, which can be obtained from a physical parameter model or SPICE parameters fitted to data as described in Appendix I:

$$I_{pp}(\dot{\gamma}) = \frac{q \phi \dot{\gamma}}{n_i^2/N} I_s \quad (2)$$

Table IV
Gains Degraded by Total Dose (1×10^7 rads(Si))

Input Buffer	S/N	IC	$h_{FE}(\text{min})$	Interpolated Postrad h_{FE}
Input Transistor	3	538 μ A	2.94	31.53
	6	538 μ A	2.94	33.13
Output Transistor	3	1.5mA	2.81	38.16
	6	1.5mA	2.81	38.55
ISL Gate	3	600 μ A	4.00	26.51
	6	600 μ A	4.00	27.78
<u>Output Buffer</u>				
Input Transistor	3	423 μ A	1.82	29.86
	6	423 μ A	1.82	31.37
Output Transistor	3	400 μ A	0.853	29.47
	6	400 μ A	0.853	30.95

Table V
Dose Rates at Which ISL Upset Occurred (rads(Si)/sec)

	100ns P.W.	1 μ s P.W.	Steady State	Effective Lifetime
<u>12 ohm-cm Substrate</u>	$\dot{\gamma}_1$ (meas.)	$\dot{\gamma}_2$ (meas.)	$\dot{\gamma}_0$ (calc.)	τ (calc.)
S/N 4	1.16×10^7	1.82×10^6	1.22×10^6	898ns
5	3.08×10^7	6.48×10^6	5.61×10^6	497
<u>2 ohm-cm Substrate - Lot 1</u>				
S/N 7 ($\phi=0$)	3.49×10^7	1.12×10^7	1.09×10^7	266
8 ($\phi=5 \times 10^{13}$ n/cm ²)	8.41×10^7	7.97×10^7	7.97×10^7	34
<u>2 ohm-cm Substrate - Lot 2</u>				
S/N 9	2.07×10^7	5.91×10^6	5.67×10^6	312
10	2.04×10^7	5.90×10^6	5.67×10^6	307
11	1.82×10^7	5.45×10^6	5.27×10^6	292
12	1.84×10^7	6.07×10^6	5.95×10^6	256

Table VI
Upset Dose Rates for Other Technologies (rads(Si)/sec)

	100ns P.W.	1 μ s P.W.	Steady State	Effective Lifetime
<u>3D</u>	$\dot{\gamma}_1$ (meas.)	$\dot{\gamma}_2$ (meas.)	$\dot{\gamma}_0$ (calc.)	τ (calc.)
TDC 1005J	2×10^8	5×10^7	4.64×10^7	378ns
<u>I²L</u>				
SBP9900	4×10^8	8.5×10^7	7.40×10^7	489
SBP9960	3×10^9	7.5×10^8	6.97×10^8	378
SBP9900A	1.5×10^9	1×10^9	1.00×10^9	91

FIGURE 4

THE CARRIERS GENERATED IN A REGION BY IONIZING RADIATION APPROACH AN EQUILIBRIUM CONCENTRATION AT A RATE CONTROLLED BY THE MINORITY CARRIER LIFETIME. PHOTOCURRENT GENERATED BY THAT REGION INCREASES IN STEP WITH THE CARRIER CONCENTRATION, AND UPSET OCCURS WHEN THE SUM OF THE PHOTOCURRENTS FROM ALL REGIONS OF A DEVICE REACHES A CRITICAL VALUE. IF THE DOSE RATE IS INCREASED, THE CARRIER CONCENTRATION EXPONENTIALLY APPROACHES A HIGHER EQUILIBRIUM VALUE AND THE CRITICAL LEVEL IS REACHED SOONER. TWO IONIZING RADIATION PULSE WIDTHS AND THE CORRESPONDING UPSET DOSE RATES DETERMINE THE EFFECTIVE LIFETIME OF THE CARRIERS (τ) AND THE LOWEST STEADY STATE DOSE RATE AT WHICH UPSET WOULD OCCUR ($\dot{\gamma}_0$) (SEE APPENDIX III).

FIGURE 5

STEADY STATE UPSET DOSE RATE AS A FUNCTION OF THE CARRIER LIFETIME FOR ISL AND OTHER TECHNOLOGIES. THE THREE GROUPS OF ISL PARTS SHOW A SIMILAR LIFETIME-DOSE RATE PRODUCT WHICH IS SIGNIFICANTLY LOWER THAN \$I^2L\$ AND 3D PARTS.

where I_S is the saturation current, $(g_0 \tau \dot{\gamma})$ is the carrier concentration generated by radiation, and (n_i^2/N) is the thermal equilibrium carrier concentration.

The expressions for I_S are given below for the emitter, base (normal orientation), base (inverse orientation), and collector regions in terms of the physical parameters defined in Appendix II (collector terms are defined analogously):

$$I_{SE} = qA_E D_E (n_i^2/N_{EE}) [e_2 \coth(e_2 W_E) - e_1] \quad (3)$$

$$I_{SEB} = qA_E D_B (n_i^2/N_{EB}) [b_2 \exp(b_1 W_B) / \sinh(b_2 W_B)] \quad (4)$$

$$I_{SCB} = qA_C D_B (n_i^2/N_{CB}) [b_2 \exp(-b_1 W_B) / \sinh(b_2 W_B)] \quad (5)$$

$$I_{SC} = qA_C D_C (n_i^2/N_{CC}) [c_2 \coth(c_2 W_C) - c_1] \quad (6)$$

The I_S expressions in terms of SPICE parameters are the following:

$$I_{SE} = I_S / B_F \quad (7)$$

$$I_{SEB} = I_S \quad (8)$$

FIGURE 6

THE UPSET DOSE RATE FOR AN ISL CELL IS A FUNCTION OF V_{BB} BECAUSE THE CURRENT WHICH MUST BE SHUNTED TO GROUND BY THE PRECEDING STAGE TO UPSET THE ISL CELL DEPENDS ON $(V_{BB} - V_{BE})$. THE THREE LOWER CURVES ARE EXPERIMENTAL DATA TAKEN ON UNITS 9 THROUGH 12 AT DIFFERENT RADIATION PULSE WIDTHS, AND THE UPPER CURVES ARE STEADY STATE UPSET CURVES CALCULATED FOR 12 & 2 ohm-cm ISL MODELS WHICH WERE NOT BASED ON THE EXPERIMENTAL PARTS TESTED.

Results

Failure in the neutron environment occurred between 1×10^{15} and 3×10^{15} n/cm² and the calculated fluence of failure was 2×10^{15} n/cm². After a total dose of 1×10^7 rads(Si) failure had not occurred because postrad gains ranged from 25 to 40. The calculated steady state dose rate upset of ISL parts which did not receive neutron irradiation ranged from 1.22×10^6 to 1.09×10^7 rads(Si)/sec, and the upset level of a part which received a fluence of 5×10^{13} n/cm² rose to 7.97×10^7 rads(Si)/sec. For comparison, the steady state upset level was 4.64×10^7 rads(Si)/sec for 3D devices and 7.40×10^7 to 1.00×10^9 rads(Si)/sec for I²L devices.

Conclusions

The hardness of ISL parts to neutron radiation was attributed to a narrow base in the down NPN and to small resistor ratios in the input and output buffers.

These factors did not account for total dose hardness, however, because gains did not degrade enough to bring them into play. The small increase in base current was due to the minimal damage done to the oxide-silicon interface; the slope constants determined as described in Appendix I did not increase above 1.65. The nominal slope constant is 1.5 or less for a good interface and 2 for a severely damaged one.

The sensitivity to dose rate upset involves the substrate under the ISL cell. Photocurrent generated by the entire substrate junction of a cell is drawn through the bias resistor of the following cell tending to turn it off, and the long lifetime in the high resistivity substrate contributes to the magnitude of the photocurrent.

References

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1. Jan Lohstroh and Jan D. P. van den Crommenacker, "Performance, Temperature Behavior, and First-Order Modeling of ISL," IEEE J. Solid State Circuits, vol. SC-15, pp. 269-276, June 1980.
2. R. D. Blice, J. A. Munarin and R. L. Pease, "Bipolar Screening Methods for Neutron Hardness Assurance," IEEE Trans. Nuclear Science, vol. NS-19, pp. 115-120, December 1972.
3. R. D. Blice and J. A. Munarin, "Neutron Hardness Assurance for Bipolar Transistors Through Determination of Physical Parameters," AFWL-74-327, October 1975.
4. R. L. Pease and T. Ellis, "Radiation Response of Bipolar LSI Circuits and Test Structures," 1980 Government Microcircuit Applications Conference (GOMAC), Dig. Papers, pp. 312-315.

Table VII

Calculated Primary Photocurrents at 1×10^7 rads(Si)/sec

	Down NPN	Vert. PNP (12 ohm-cm)	Vert. PNP (2 ohm-cm)	Lat. PNP
Emitter Region	(373pA)*	2.89nA	2.89nA	2.97nA
E-B Depletion Region	(288pA)*	5.94nA	5.94nA	1.58nA
Base Region (normal)	(251nA)*	733nA	733nA	79.6nA
Base Region (inverse)	75.6nA	737nA	733nA	79.6nA
C-B Depletion Region	5.94nA	14.5nA	8.18nA	1.58nA
Collector Region	321pA	846nA	309nA	2.97nA
<u>Substrate Region</u>				
Buried Layer Area	-	3.10μA	1.13μA	-
Rest of Cell (except PNP)	-	9.46μA	3.45μA	-
<u>Substrate Depletion Region</u>				
Buried Layer Area	-	52.8nA	20.0nA	-
Rest of Cell (except PNP)	-	162nA	91.4nA	-
Totals	81.9nA	15.1μA	6.48μA	168nA

$$I_{pp} (12 \text{ ohm-cm}) = 81.9\text{nA} + 15.1\mu\text{A} + 168\text{nA} = 15.3\mu\text{A}$$

$$I_{pp} (2 \text{ ohm-cm}) = 81.9\text{nA} + 6.48\mu\text{A} + 168\text{nA} = 6.73\mu\text{A}$$

*These photocurrents were calculated for completeness but were not included in the totals.

Table VIII

Calculated ISL Upset Dose Rates for $V_{BB} = 1.5\text{V}$

$$\dot{\gamma}_{\text{upset}} = \left(\frac{I_C - I_B}{I_{pp}(\dot{\gamma}_1)} \right) \dot{\gamma}_1$$

Substrate	I_C (NPN)	I_B (NPN)	$\dot{\gamma}_1$	$I_{pp}(\dot{\gamma}_1)$	$\dot{\gamma}_{\text{upset}}$
12 ohm-cm	153μA	1.82μA	1×10^7 rads(Si)/sec	15.3μA	9.88×10^7 rads(Si)/sec
2 ohm-cm	153μA	1.82μA	1×10^7 rads(Si)/sec	6.73μA	2.25×10^8 rads(Si)/sec

Appendix I Determination of Forward SPICE Parameters from

η_{FE} and V_{BE} vs. I_C

The transistor gain model utilized in the SPICE nonlinear circuit simulation program has independent factors for modeling gain fall off at low and high currents; as a result, if the parameters are selected so that the curve passes through the data points then even gains calculated at collector currents outside the range of measurements are fairly accurate.

The following forward parameters are determined in this procedure:

- I_S Saturation current
- B_F Emitter efficiency
- I_K Knee current for high I_C gain fall off
- η_{EL} Slope constant for nonideal I_B component
- C_2 Coefficient for nonideal I_B component
- R_B Series base resistance

These six parameters are determined from four η_{FE} measurements and two V_{BE} measurements as indicated in the table below.

V_{BE1} determines I_S , V_{BE4} determines R_B , and B_2 through B_4 define the peak of the η_{FE} vs. I_C curve, or the beginning of high injection gain degradation of the measurements do not include a peak.

Operating Point	Measurements	Comments
1	$\frac{\eta_{FE}}{B_1}$ @ I_{C1}	$\frac{V_{BE}}{V_{BE1}}$ Lowest I_C of interest
2	B_2 I_{C2}	$B_2 > B_1$; $I_{C2} = \sqrt{I_{C1} I_{C3}}$
3	B_3 I_{C3}	Peak η_{FE} if $B_4 < B_3$
4	B_4 I_{C4}	V_{BE4} $2B_4 > B_3$

As successive passes are made through the set of equations below, parameters η_{EL} , C_2 , B_F and I_K approach the values which make the curve pass through the data points. R_B is then calculated from the difference between measured and calculated values of V_{BE} at operating point 4. All parameters usually have reached stable values when the fourth significant digit of I_K stabilizes unless the η_{FE} vs. I_C curve is very flat.

Equations

$$I_S = \frac{I_{C1}}{1 + \exp(V_{BE1}/V_T)} \quad (1-1)$$

$$\begin{aligned} \text{Initial } B_F &= 2 B_4 \\ \text{Initial } I_K &= 2 I_{C4} \end{aligned}$$

$$f_n = \frac{1}{2} \left\{ 1 + \sqrt{1 + 4 \left(I_{Cn}/I_K \right) (1 + I_{Cn}/I_K)} \right\} \quad \text{for } n = 1, 2 \text{ and } 3 \quad (1-2)$$

$$m = \ln \left\{ \frac{1/f_1 B_1 - 1/B_F}{1/f_2 B_2 - 1/B_F} \right\} \quad (1-3)$$

$$\ln \left\{ \frac{I_{C1} (I_{C1} + I_K)}{I_{C2} (I_{C2} + I_K)} \right\}$$

$$\eta_{EL} = 1/(1 + m) \quad (1-4)$$

$$C_2 = \frac{1/f_1 B_1 - 1/B_F}{\left\{ (I_{C1}/I_S) (1 + I_{C1}/I_K) \right\}^m} \quad (1-5)$$

$$B_F = \frac{\left\{ \frac{I_{C1} (1 + I_{C1}/I_K)}{I_{C3} (1 + I_{C3}/I_K)} \right\}^m - 1}{\frac{1}{f_3 B_3} \left\{ \frac{I_{C1} (1 + I_{C1}/I_K)}{I_{C3} (1 + I_{C3}/I_K)} \right\}^m - \frac{1}{f_1 B_1}} \quad (1-6)$$

$$I_K = \frac{4 I_{C4} (1 + I_{C4}/I_K)}{\frac{2/B_4}{(1/B_F + C_2 [(I_{C4}/I_S) (1 + I_{C4}/I_K)]^m - 1)} - 1} \quad (1-7)$$

Return to Eq. (1-2) if 4th significant digit of I_K changed

$$R_B = \frac{V_{BE4} - V_T \ln[(I_{C4}/I_S) (1 + I_{C4}/I_K)]}{I_{C4}/B_4} \quad (1-8)$$

$$\eta_{FE}(I_C) = \frac{1}{2} \frac{B_F}{1 + \sqrt{1 + 4(I_C/I_K)(1 + I_C/I_K)}} \left[\frac{1 + B_F C_2 [(I_C/I_S) (1 + I_C/I_K)]^m (1/\eta_{EL} - 1)}{1 + B_F C_2 [(I_C/I_S) (1 + I_C/I_K)]^m (1/\eta_{EL} - 1)} \right] \quad (1-9)$$

Appendix II

Physical Parameter Equations for IB Components and hFE

The equations applying to the active region of transistor operation were taken from Reference 3 for the purpose of calculating gains, junction voltages and saturation currents of the three transistors which make up the ISL cell. These quantities were utilized in the dose rate upset modelling.

Parameters

A_E	Emitter area (cm ²)
W_E, W_B	Emitter, base widths (cm)
τ_E, τ_B	Emitter, base minority carrier lifetimes (sec)
D_E, D_B	Emitter, base diffusion constants (cm ² /sec)
E_E, E_B	Emitter, base electric fields (V/cm) ($E_E > 0$ retarding; $E_B > 0$ aiding)
N_{EE}, N_{EB}	Doping concentrations on emitter and base sides of emitter junction (cm ⁻³)
a	Grading constant at emitter junction (cm ⁻⁴)
R_i	Recombination rate per carrier in emitter-base junction (sec ⁻¹)
I_{SO}	Extrapolated surface current at zero applied voltage (A)
V_T	Thermal voltage (0.0259V)
n_i	Thermal equilibrium intrinsic carrier concentration (1.45X10 ¹⁰ cm ⁻³)

Equations

$$b_1 = EB/2V_T \quad (11-1)$$

$$b_2 = \sqrt{b_1^2 + 1/D_B \tau_B} \quad (11-2)$$

$$I_{RB} = I_C \left[\frac{b_1 \sinh(b_2 W_B) + b_2 \cosh(b_2 W_B)}{b_2 \exp(b_1 W_B)} - 1 \right] \quad (11-3)$$

$$n_{B0} = n_i^2 / N_{EB} \quad (11-4)$$

$$n_B = \frac{I_C}{qA_E D_B} \left[\frac{\sinh(b_2 W_B)}{b_2 \exp(b_1 W_B)} \right] \quad (11-5)$$

$$U_E = \frac{\sqrt{(N_{EF}/2)^2 + (N_{EB} + n_B + n_{B0})(n_B + n_{B0})} - N_{EF}/2}{N_{EB} + n_B + n_{B0}} \quad (11-6)$$

$$V_{BE} = V_T \ln \left[(N_{EE} N_{EB} / n_i^2) U_E \right] \quad (11-7)$$

$$n_{EO} = n_i^2 / N_{EE} \quad (11-8)$$

$$n_E = \frac{N_{EB} U_E + N_{EF} U_E^2}{1 - U_E} - n_{EO} \quad (11-9)$$

$$e_1 = E_E / 2V_T \quad (11-10)$$

$$e_2 = \sqrt{e_1^2 + 1/D_E \tau_E} \quad (11-11)$$

$$I'_{DE} = qA_E D_E \left[e_2 \coth(e_2 W_E) - e_1 \right] n_E \quad (11-12)$$

$$I_{RG} = \frac{qA_E n_i \pi R_i}{\ln(N_{EE} N_{EB} / n_i^2)} \left[\frac{12\varepsilon}{q a} V_T \ln(1/U_E) \right]^{1/3} \left[\exp(V_{BE}/1.5V_T) - 1 \right] \quad (11-13)$$

$$I_S = I_{SO} \left[\exp(V_{BE}/2V_T) - 1 \right] \quad (11-14)$$

$$h_{FE} = I_C / [I_{RB} + I'_{DE} + I_{RG} + I_S] \quad (11-15)$$

Appendix III

Determination of Effective Lifetime (τ) and Steady State Upset Dose Rate ($\dot{Y}_0$)

Under the condition of a constant ionizing dose rate $\dot{Y}$, the concentration of radiation-generated carriers increases exponentially as dictated by the minority carrier lifetime in that neutral region:

$$n(\text{cm}^{-3}) = g_0 \tau \left[1 - \exp(-t/\tau) \right] \quad (\text{III-1})$$

where g_0 is the radiation carrier generation constant (4×10^{13} carriers/cm³-rad(Si)) and τ is the lifetime. The resulting photocurrent depends on this carrier concentration just as the saturation current of a single neutral region depends on its thermal equilibrium extrinsic carrier concentration, n_i^2/N .

At two different dose rates ($\dot{Y}_1$ and $\dot{Y}_2$), radiation-generated carriers reach the upset level after different periods of time ($P.W.1$ and $P.W.2$) because one is approaching a higher final value. This is expressed by the following relation:

$$\begin{aligned} n(\text{upset}) &= g_0 \tau_1 \left[1 - \exp(-P.W.1/\tau) \right] \\ &= g_0 \tau_2 \left[1 - \exp(-P.W.2/\tau) \right] \end{aligned} \quad (\text{III-2})$$

Rearranging the terms puts a single τ on one side of the equation, but another remains on the other side so the value must be obtained by successive approximations:

$$\tau = \frac{-P.W.2}{\ln \left\{ 1 - \left[1 - \exp(-P.W.1/\tau) \right] \frac{\dot{Y}_1/\tau_2}{\dot{Y}_2/\tau_1} \right\}} \quad (\text{III-3})$$

where $\left[P.W.1 (\dot{Y}_1/\tau_2) \right]$ is used as an initial estimate for τ . This lifetime is referred to as "effective" because it is characteristic of the dominant upset mechanism of a particular part.

The steady state upset dose rate $\dot{Y}_0$ can be obtained from the converged τ value by letting $P.W.2$ in Eq. III-2 approach infinity:

$$\dot{Y}_0 = \dot{Y}_1 \left[1 - \exp(-P.W.1/\tau) \right] \quad (\text{III-4})$$

This is the lowest steady state dose rate at which upset would occur and is an indication of upset susceptibility not dependent on the duration of the radiation pulse width.

Figure 4 illustrates these calculations.