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RADIATION EFFECTS ON ELECTRONICS

PRELIMINARY GUIDELINES FOR DESIGNING ELECTRONICS
FOR OPERATION IN A RADIATION ENVIRONMENT

NERVA Program, Contract SNP-1

September 1970

MASTER

AEROJET NUCLEAR SYSTEMS COMPANY

A DIVISION OF AEROJET-GENERAL

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I. INTRODUCTION TO SYSTEM HARDENING

A. DETERMINATION OF FAILURE BUDGET FOR RADIATION EFFECTS

1. Scoping Relative to Desired System Failure Budget
2. Typical System Failure Budget Requirement (see Figure 1)
 - a. One failure or less for 10 systems operating for two years
 - b. System contains 5,000 electronic components
 - c. Resulting required device failure rate $\leq 2 \times 10^{-9}/\text{hr}$
 - d. MTBF $\approx 5 \times 10^8$ hr; 0.0002%/1,000 hr
 - e. System achievements at present time
 - (1) Minuteman II, less than 0.003%/1,000 hr
 - (2) Apollo Saturn II computer, less than 0.003%/1,000 hr
 - (3) Apollo program; less than 0.001%/1,000 hr
 - f. Requires highly developed reliability and quality-control technology
 - (1) Material and process control
 - (2) Baseline control or captive line
 - (3) Flight specification procurement
 - (4) Line certification
 - (5) Physics of control
 - (6) Failure analysis
 - (7) Burn-in at part and system level
 - (8) Build-up screening
 - (9) 100% screens to truncate failure distribution curves

Apportionment of Failure Budget to Neutrons and Gamma Effects Consistent with an Overall System Failure Budget of 2×10^{-9} /hr.

Figure 1 - Typical System Failure Budget (In Terms of Device Failure Rate/hr)

3. Device Failure Probability for Radiation Effects

- a. 10^{-9} /hr degrades overall system to approximately 2×10^{-9} /hr
- b. 10^{-10} /hr will not substantially degrade system
- c. Choose 10^{-9} /hr if radiation levels are relatively high
Choose 10^{-10} /hr if radiation levels are relatively benign

4. Assuming a Choice of 10^{-9} /hr for Typical System for Radiation Effects

- a. Neutron induced failure mechanism - principally β degradation
 - (1) Failure mechanism well understood - no mavericks
 - (2) 100% electrical screen available - probably F_t
 - (3) Neutron failure budget 2×10^{-10} /hr
- b. Gamma induced failure mechanisms - principally surface effects
 - (1) Degradation of current gain at low bias current levels $< 10 \text{ A/cm}^2$
 - (2) Increased leakage currents
 - (3) Device short circuits caused by surface inversion or excessive accumulation
 - (4) Mechanism not well understood - mavericks suspected
 - (5) Statistical data base at levels $> 10^6$ rads (Si) is insufficient
 - (6) Gamma failure budget 8×10^{-10} /hr

5. Confidence

- a. Concept useful for large production runs
- b. Concept not adaptable to small production runs (i.e., < 10 items)

- c. Concept difficult to apply when design changes are frequently made during a production run
- d. Nomograph (see Figure 2)

	80% probability of survival, 80% confidence
(1) Zero failures in eight trials	90% probability of survival, 58% confidence
	70% probability of survival, 92% confidence

	80% probability of survival, 50% confidence
(2) One failure in eight trials	70% probability of survival, 75% confidence
	60% probability of survival, 90% confidence

- e. Confidence requires implementation of quality-assurance program backed-up by sample testing on production run

B. BUILD-UP SCREENING

1. Device Failure Probability Undergoes Continuing Reduction Over Entire Manufacturing Cycle as a Result of Consecutive Screening Processes

a. Typical progression

	Finished Device	Device Test Electrical Screen	Device Burn-In
Failure Rate (per hr)	0.5	10^{-2}	10^{-4}

	Board Mount Electrical Screen	Black-Box Electrical Screen	Black-Box Overstress Screen	Black-Box or System Burn-In
Failure Rate (per hr)	10^{-6}	10^{-7}	10^{-8}	10^{-9}

b. Minuteman computer example (see Figure 3)

Example: Sampling Plan

Required: A Sampling Plan Having
 $P = 0.95$ at $p = 0.02$
 $P = 0.10$ at $p = 0.08$

Solution: Make Alignments and Read
Sample Size (n) and
Acceptance Number (c)
as in Diagram Below:

Example: Reliability

Reliability at 90% Confidence
Demonstrated by 50 Tests With
One Failure

$$\text{Set } P = \frac{(100-90)\%}{100\%} = .10$$

Locate Point $n = 50, c = 1$
Draw Line Through the Two Points
to p Scale. Read $p = .075$.
Reliability = $1 - .075 = .925$

NOTE: If p_1 (The Smallest p in a Problem) is Less Than .01, Set kx_p on the p Scale and Multiply the Values on the n Scale by k , Where $k = 0.01/p_1$ (Taking k to the Next Higher Integer)

Figure 2 - Nomograph Based on Cumulative Binomial Distribution

Figure 3 - Example of Build-Up Screening

SYSTEM OR SUBSYSTEM	TEST	DEVICE FAILURE RATE	
		ALL MODES	INTERCONNECTS
MULTILAYER BOARD (30-150 DEVICES)	COMPLETE ELECTRICAL	1 %	0.1
COMPUTER (4000 DEVICES)	ELECTRICAL CONFIDENCE TEST	.081	
COMPUTER (4000 DEVICES)	VIBRATION TEST 3g, 3 AXES, 7.5 MIN EACH AXIS, 5-1000 CPS	.038	
COMPUTER (4000 DEVICES)	COMPLETE FUNCTIONAL TEST		
	BURN IN APPROX 30 HR	.002	
	TEMPERATURE CYCLE (40-120°F)	.016	
	ELECTRICAL STRESS (VOLTAGE STEPS)	.002	
NS-17 SYSTEM (7000 DEVICES)	BURN IN 300 HR WITH FUNCTIONAL TEST		
MINUTEMAN (7000 DEVICES)	PACKING, SHIPPING, INSTALLATION, AVERAGE OF 2 YR ON ACTIVE STANDBY	0.03%	0.001%

2. Partition of Failure Rate Responsibility

a. Device manufacturer

- (1) Current technology $\sim 10^{-4}/\text{hr}$
- (2) Target $\sim 10^{-5}/\text{hr}$

b. System manufacturer

- (1) Current technology $\sim 10^{-4}/\text{hr}$
- (2) Target $\sim 10^{-5}/\text{hr}$

c. Resulting system

- (1) Current technology $\sim 10^{-8}/\text{hr}$
- (2) Target $\sim 10^{-10}/\text{hr}$
- (3) Concept can be extended to radiation effects

C. OVER-DESIGN FACTORS

1. Power Dissipation

- a. Ordinary systems (television sets) use devices up to rated power
- b. High reliability systems use devices at one-tenth rated power
 - (1) Rule of thumb
 - (2) Violations are strictly controlled and reliability impact separately assessed

2. Other Normal Environmental or Electrical Limits

- a. Temperature derating $\sim$ one-fifth maximum rated ΔT
- b. Voltage derating $\sim$ one-third maximum rated voltage
- c. Current derating $\sim$ one-third maximum rated current

3. Radiation Over-Design Factors

- a. Components to be used at one-tenth rated radiation tolerance where possible.
- b. Violations strictly controlled and reliability impact separately assessed.

4. Theory of Overdesign Factors

- a. Originated as experimentally determined reliable design practices
- b. Imply relationship between failure rate and stress, usually through Arrhenius equation for rate of degradation process
- c. F_t example for neutron degradation (see Figure 4)
- d. Overdesign factors should be set as high as practical
 - (1) Usually a large over-design factor ($>10X$) is practical in electron devices within current technology without significantly increased cost (e.g., at 10^{12} n/cm²/10⁴ rads total dose)
 - (2) Sometimes over-design factors must be compromised (e.g., power transistor circuits) because of state of the art limitations (e.g., at 5×10^{14} n/cm²/5x10⁶ rads a compromise over-design factor of two might be used)
 - (3) Exceptions to over-design factors should be rigidly controlled and their reliability impact carefully evaluated

D. WORST CASE DESIGN AND ANALYSIS

1. Degradation Failure Rate and Catastrophic Failure Rates Add Directly to Give Total Failure Rates

- a. No good formal theoretical basis for degradation failure modes
 - (1) Some work combining distribution functions at simple circuit level

Figure 4 - Example of Truncation by 100% Screening of F_t

- (2) No closed form mathematical analysis available for circuit of average complexity
- (3) Computer codes usually employ Monte Carlo subroutines

b. Catastrophic failures

- (1) Device failure rate directly extrapolates to system failure rate
- (2) Device failure rate X No. of devices = system failure rate

c. Rules of thumb, degradation failure modes

- (1) Based on past experience with Minuteman, Polaris, Poseidon and USAEL communication equipment
- (2) Work with limited worst case device parameters in the $1/1,000$ to $1/10,000$ range
- (3) For typical circuits containing ≈ 100 devices, this results in 10^{-6} to 10^{-7} typical failure probability range for significant functional parameters
- (4) For subsystem containing ≈ 10 typical circuits this results in 10^{-7} to 10^{-8} probability range for functional interface requirements
- (5) For system containing ≈ 10 subsystems, this results in 10^{-8} to 10^{-9} system failure probability range

d. Prediction and verification procedure

- (1) Parts level prediction for gamma and neutron response
- (2) Based on Ebers and Moll radiation inclusive model
- (3) Experimental verification of prediction on small sample (≈ 25) devices
- (4) Comparison of predicted and experimentally measured results
 - (a) Congruence - acceptable
 - (b) Disagreement

- 1 Check experiment
- 2 Check dosimetry
- 3 Modify model
- 4 Repeat prediction and verification procedure until congruence results

- (5) Circuit level prediction and experimental verification
- (6) Based on use of Ebers and Moll model using SCAN computer code
- (7) Check for congruence between predicted and measured results
- (8) If congruence does not occur, modify model and repeat procedure until congruence is obtained
- (9) System level prediction and experimental verification
- (10) Based on SECURE computer code
- (11) Check for congruence between predicted and measured results
- (12) If congruence does not occur, modify model and repeat until congruence results
- (13) Final result is verified engineering model describing system response to gamma and neutron radiation

E. TENTATIVE GUIDELINES AND SUGGESTIONS FOR EPIC DESIGN FOR CURRENT TECHNOLOGY

1. Use Proven High-Reliability Suppliers Exclusively
2. Use Proven High-Reliability Hardened Parts Wherever Possible
 - a. Parts used in Minuteman
 - b. Parts used in Apollo
 - c. Parts used in Polaris and Poseidon
 - d. Other parts with proven reliability history
3. Maintain a Qualified Suppliers List Under Cognizance of Quality-Assurance Manager

- a. Establish periodic vendor audits
- b. Utilize resident government inspectors

4. Maintain a Parts Monitoring Activity

- a. Base line documentation
- b. Qualification program
- c. Failure analysis program
- d. Continuing parts audit program
- e. Controlled specification documents

5. Reliability and Hardness Assurance Program

- a. Controlled over-design factors
- b. Maintain and periodically update system hardness and reliability estimates

6. Hardness Activities

a. Neutron activities

- (1) Specification control using F_t
- (2) Circuit analysis program to eliminate or control marginal design
- (3) Very limited experimental verification program

b. Gamma activities

- (1) Specification control using leakage currents or low current level common emitter current gain
- (2) Process control demanding passivated silicon devices
- (3) Substantial experimental verification program
- (4) Circuit analysis program to eliminate or control marginal design (e.g., do not use devices at $<100 \text{ A/cm}^2$).

7. Controlled Environments in Electronic Black Boxes

- a. Temperature $25^{\circ}\text{C} \pm 20^{\circ}\text{C}$
- b. Vacuum or inert gas fill*

8. Shield Design

- a. Source of 10X over-design minimum for radiation
- b. Interaction of EMI, temperature and radiation requirements

9. Operating Current Levels

- a. Less than one-third rated current maximum
- b. Greater than $100\text{A}/\text{cm}^2$
- c. When either a. or b. must be violated use rigid control and separately evaluate hardness and reliability impact

10. Do Not Use MOS Devices

- a. No hardened devices available
- b. At 5000 rads characteristics start changing, undergoing great changes in turn on voltage

11. Power Transistors

- a. Major hardness problem because of neutron susceptibilities
- b. Consider replacement by hardened SCRs (disadvantage - no high-reliability sources presently available)
- c. Consider replacement by magnetic circuits in power supply application (disadvantage - increased weight and frequency limitations)

*Leakage rate should be specified.

12. Emphasize Miniaturization

- a. Reliability improvement
- b. Reduced shield weight
- c. Increase use of bipolar ICs vs hybrid ICs

II. EFFECTS OF NEUTRONS ON SEMICONDUCTOR ELECTRICAL PROPERTIES

A. PRODUCTION OF DEFECTS

$$1. \quad N_D = N_A \int_{E_T}^{E_N} \int_{E_D}^{E_{PMAX}} \Phi(E) \sigma(E, E_p) N_s(E_p) dE_p dE$$

a. E_D is threshold energy required to displace semiconductor atom

(1) Direction dependent because of semiconductor lattice properties

10 ev < E_D < 35 ev for silicon

(2) Average value $\bar{E}_D \approx 25$ ev for silicon

b. E_T is threshold energy for neutron, assuming head on collision to deliver E_D to semiconductor atom

(1) Conservation of energy and momentum

(2) Hard sphere interaction

$$(3) \quad E_T = \frac{\bar{E}_D (M+m)^2}{4 m M} \approx \frac{A \bar{E}_D}{4}$$

(a) m = mass of neutron

(b) M = mass of target atom

(c) A = atomic weight of target atom

(d) A = 28 for Si

(e) $E_T \approx 200$ ev for Si

- c. E_N is maximum energy of incident neutron
- (1) $E_N \approx 8$ Mev for reactor spectrum
 - (2) $E_N \approx 14$ Mev for fusion neutrons
- d. E_{PMAX} = highest primary recoil energy
- (1) $E_{\text{PMAX}} = \frac{4E_N}{A}$
 - (2) $E_{\text{PMAX}} \approx 2\bar{E}_p$ for reactor neutrons
- e. $\Phi(E)$ = differential neutron flux spectrum (see Figure 5)
- (1) For reactors below 0.1 Mev $\Phi(E) \propto \frac{1}{E}$
 - (2) Theoretical fission spectrum
 - (3) Hump at ≈ 1 Mev due to moderator effect and fission spectrum
- f. $\sigma(E, E_p) dE_p$: This is the differential cross section per target atom for producing a primary recoil in the energy range from E_p to $E_p + dE_p$ with an incident neutron of energy E .
- g. N_A is the density of target atoms
- $$N_A \approx 5 \times 10^{22} / \text{cm}^3 \text{ for silicon}$$
- h. N_D = the initial density of displaced target atoms
- (1) No annealing - clusters with large vacancy concentration and Frenkel defects along primary tracks
 - (2) Room-temperature annealing reduces N_D by about a factor of ten
 - (3) Quasi-equilibrium established at room temperature and composed of stable defect complexes such as A, E, and divacancy centers (further defined in Paragraph 6 of this Section).

Figure 5 - Neutron Flux Spectrum in Horizontal Beam Hole (HB-2)
of the LITR Reactor

2. Approximate Integral Solution for Reactor Spectrum

- a. $N_D = N_A \sigma_D \bar{\phi} \bar{n}$
- b. $\bar{n}$ = average number of defects produced by a recoil primary
- c. $\bar{n} \approx 500$ for a 1 Mev incident neutron
 $\bar{n} \approx 1500$ for a 14 Mev incident neutron
- d. $\sigma_D = \sigma_s \left(1 - \frac{A\bar{E}_D}{4E_N}\right) \approx \sigma_s \approx 3 \times 10^{-24} \text{ cm}^2$
- e. $\bar{n} = E_{\text{PMAX}}/4\bar{E}_D$
- f. $N_c \approx N_p = N_A \sigma_D \bar{\phi} = 0.15/n/\text{cm}^2$ for Si
- g. $\text{Range} = (N_A \sigma_D)^{-1} = 7 \text{ cm}$ for Si

3. Functional Dependence of N_D on Incident Neutron Energy

- a. E_p above ≈ 50 kev, energy loss is primarily by ionization
- b. $E_p < 50$ kev, energy loss is primarily by production of displacements
- c. $A(E) + I(E) = E$
 - (1) $A(E)$ is energy lost by displacement production
 - (2) $I(E)$ is energy lost by ionization
 - (3) E is total energy lost
- d. Plot of $\frac{I(E)}{E}$ and $\frac{A(E)}{E}$ vs energy of incident neutron (see Figure 6)
- e. $\bar{n} = \frac{E_{\text{PMAX}}}{4\bar{E}_D} \frac{A(E)}{E}$
- f. Plot of $N_D \propto \frac{1}{K}$ vs energy of incident neutron (see Figure 7).

Figure 6 - Fractional Energy Lost in Ionization and Atomic Processes as a Function of Energy of Recoil Silicon Atom (Lindhards Calculated Value)

Figure 7 a - Energy Going into Atomic Processes and Normalized Reciprocal Lifetime Damage Constant as a Function of Incident Neutron Energy

Figure 7 b - Energy Going into Ionization as a Function of Incident Neutron Energy

- (1) $N_D \propto E (1 - e^{-\frac{3.1}{E}})$ with E in Mev*
- (2) Importance of resonance structure

g. Indirect Ionization

4. Formation of Clusters

- a. Plot of Monte Carlo calculation of stopping of primary recoil in silicon
- b. Displacement cross section in primary recoil increases with decreasing energy
- c. Primary loses energy by ionization over a relatively long path length
- d. After first major collision, primary divides energy with target atom roughly equally
- e. Both primary atom and target atom now have larger displacement cross sections and cascade collision process immediately leads to a damage cluster
- f. Reactor radiation leads to a uniform distribution of cluster defects in semiconductor devices.

- (1) Semiconductor devices have critical dimensions $\ll 6$ cm neutron range
- (2) Damage is nonuniform if critical semiconductor device dimensions ≥ 6 cm

5. Secondary Processes

- a. Start with nonequilibrium cluster - Frenkel defects
- b. Relaxation to quasi-equilibrium

*Present data indicate that a better fit for spectra containing a high percentage of 14 Mev neutrons is obtained from:

$$N_D \propto 1.1 E (1 - e^{-\frac{2.4}{E}})$$

(1) Diffusion of interstitials

- (a) Move at $\approx 4^\circ\text{K}$
- (b) No electrical damage results
- (c) Acceptor interaction

(2) Diffusion of vacancies

- (a) Move at 160°K in N type Si, 60°K in P type Si
- (b) Forms divacancies, E centers and A centers
- (c) Stable at room temperature

c. Quasi-equilibrium defect structure

- (1) Defects largely within cluster
- (2) Some stable defects external to cluster
- (3) "Ordered disorder" within cluster

6. Characteristics of Room-Temperature Stable Defects

- a. A center - oxygen vacancy defect $E_c - E = 0.18 \text{ ev}$
- b. E center - donor vacancy defect $E_c - E = 0.40 \text{ ev}$
- c. J center - divacancy defect $E - E_v = 0.3 \text{ ev}$
- d. Complex defect level picture results from level splitting and other defects introduced at lower rates

B. ANNEALING

- 1. Germanium example (see Figure 8)
- 2. Silicon example (see Figure 9a, b, and c)
- 3. Stages caused by formation of defects stable at successively higher temperatures (see Figures 8 and 9a)
- 4. Rapid annealing - not significant for reactor problem

Figure 8 - Annealing Characteristics of Germanium

Isochronal annealing curves for base-current recovery ($I_C - 1 \text{ ma}$) of 2N2102 n-p-n and 2N1132 p-n-p transistors damaged with 125 keV electrons followed by 1 MeV electrons. Curves compared with data from annealing of A and K-centers in bulk silicon from references 25 and 26.

Isochronal annealing curves for base-current recovery ($I_C - 1 \text{ ma}$) of 2N2102 n-p-n and 2N1132 p-n-p silicon transistors damaged with 125 keV electrons followed by either 16.8 MeV protons or reactor neutrons.

Isothermal annealing curves for base-current recovery ($I_C - 1 \text{ ma}$) of 2N1132 p-n-p transistors damaged with 125 keV electrons followed by either 16.8 MeV protons or reactor neutrons.

Figure 9 - Annealing Characteristics of Silicon

C. RECOMBINATION STATISTICS

1. Shockley-Read Model

- a. Recombination center charge changes by one unit
- b. Centers located near center of band

$$c. \quad \tau = \frac{\tau_{no} (P_o + P_1 + \delta_n) + \tau_{po} (n_o + n_1 + \delta_n)}{P_o + n_o + \delta_n}$$

- (1) τ is lifetime in seconds
- (2) τ_{no} is lifetime at low injection level in highly doped P material
- (3) τ_{po} is lifetime at low injection level in highly doped N material
- (4) P_o, n_o - equilibrium carries concentrations
- (5) P_1, n_1 - carrier concentrations if Fermi level is coincident with recombination center level
- (6) δ_n = injected carrier concentration - source; light - bias current, etc.

$$d. \quad \Delta \frac{1}{\tau} = \frac{\Phi}{K}$$

$$e. \quad \text{Two independent recombination centers } \frac{1}{\tau} = \frac{1}{\tau_1} + \frac{1}{\tau_2}$$

f. K has properties of "radiation lifetime"

$$g. \quad K^{-1} = (\tau\Phi)^{-1} = \frac{1}{\frac{1}{C_{P1}R_1} \frac{n_o + n_1 + \delta_n}{n_o + p_o + \delta_n} + \frac{1}{C_{n1}R_1} \frac{p_o + p_1 + \delta_n}{n_o + p_o + \delta_n}} + \frac{1}{\frac{1}{C_{p2}R_2} \frac{n_o + n_2 + \delta_n}{n_o + p_o + \delta_n} + \frac{1}{C_{n2}R_2} \frac{p_o + p_2 + \delta_n}{n_o + p_o + \delta_n}}$$

- (1) $\tau_{no} = \frac{1}{C_n R \Phi}$; $\tau_{po} = \frac{1}{C_p R \Phi}$; subscripts 1, 2 for two recombination centers
- (2) R is relative introduction rate of recombination centers
- (3) C_n, C_p are cross sections of recombination center for electrons and hole
- (4) $K_{\infty}^{-1} = \frac{C_{n1} R_1}{1 + \frac{C_{n1}}{C_{p1}}} + \frac{C_{p2} R_2}{1 + \frac{C_{p2}}{C_{n2}}}$; High injection level damage constant
- (5) $K_{Ln}^{-1} = \frac{C_{p1} R_1}{1 + \frac{n_1}{n_o}} + \frac{C_{p2} R_2}{1 + \frac{C_{p2}}{C_{n2}} \frac{p_2}{n_o}}$; Low injection level damage control for N type material
- (6) General graph (see Figure 10)

D. CARRIER REMOVAL (see Figure 11)

1. Defects with energy levels near band edges
2. $n = n_o - \frac{dn}{d\Phi} \Phi$
3. Linear from threshold to values of $n \approx 0.1 n_o$
4. About two orders of magnitude less important than lifetime reduction in devices

E. MOBILITY REDUCTION

1. $\frac{1}{\mu} = \frac{1}{\mu_i} + \frac{1}{\mu_I}$
2. $\mu = \mu_i - \frac{d\mu}{d\Phi} \Phi$
3. Carrier removal creates ionized scattering centers
4. Threshold for changes in $\mu \approx$ threshold for changes in carrier concentration for devices
5. About two orders of magnitude less significant than lifetime reduction in devices

Figure 10 - Lifetime Damage Constant K_N , K_P vs Resistivity
for Various Injection Ratios, $X = \frac{\delta N}{N_0}$, $\frac{\delta P}{P_0}$

Figure 11 - Effects of Radiation on Conductivity of Germanium and Silicon

F. CLUSTER DEFECTS (see Figures 12 and 13)

- a. Central core containing several hundred atoms
- b. Depleted region around core for a radius of several hundred atoms; radius determined by doping of silicon according to Poisson's equation
- c. Some material removed from normal conduction process
- d. $\rho \equiv \rho_0 \left(1 + \frac{F_v}{V}\right)$

(1) F_v = volume of depletion regions and is proportional to ϕ

(2) V = total volume

(3) ρ = resistivity in Ω cm

G. NEUTRON FLUENCE STANDARDIZATION

- 1. For convenience and standardization, only neutrons above 10kev are counted for calculating damage in silicon
- 2. One Mev equivalent silicon damage
- 3. Average energy is approximately one Mev in reactor

Figure 12 - Typical Recoil-Atom Track

Figure 13 - Typical Cluster

III. EFFECTS OF GAMMA RADIATION ON SEMICONDUCTOR ELECTRICAL PROPERTIES

A. INTRODUCTION

1. Basically a surface ionization effect
2. Bulk damage possible through Compton process
3. In reactor environment bulk gamma damage usually <1% of neutron damage
4. Obviously selective shielding can be used to change neutron to gamma ratio

B. BULK DAMAGE

1. Gamma Spectrum 0.2 - 8.0 Mev; $E_{AV} \approx 1.0$ Mev

- a. Primary interaction is Compton scattering (see Figures 14 and 15)

$$b. N_D = N_A \sigma_{C,D}^{\gamma} \Phi_{\gamma} \bar{\eta}$$

$$(1) \bar{\eta} \approx 1.0$$

$$(2) \sigma_{C,D}^{\gamma} \approx 10^{-25} \text{ cm}^2 \text{ for Si} \quad \text{(Displacement cross section for damage produced through Compton Process)*}$$

$$(3) \sigma_{C,D}^{\gamma} = \int_0^{E_c} K_c^{\gamma} dE_c \int_0^{E_c} -1/dE/dx dE \int_{E_D}^{E_{pmax}} K(E_e, E_p) dE_p$$

Integration
over gamma
spectrum

Integration
over electron
range start-
ing from γ
of energy E_c

Integration over
energy range of
recoil primaries

* $\sigma_{C,D}^{\gamma}$ is the curve labeled "Compton Times Avg Fractional Energy Loss in Figure 14.

Figure 14 - Photoelectric Effect, Compton Effect, and Pair-Production Cross Sections

Figure 15 - Relative Density of Defects as a Function of Electron Energy

- (4) $1 \text{ rad} \approx 2 \times 10^9 \text{ Mev/cm}^2$ 0.2 to 8 Mev range
- (5) $K_\gamma \approx 10^9 \text{ photon sec/cm}^2$
- (6) $\Delta \frac{1}{\tau} = \frac{\Phi_\gamma}{K_\gamma} = \frac{R_\gamma (\text{Si})}{K_{R_\gamma}}$ where $K_{R_\gamma} \approx 2$
- (7) $2 \times 10^7 \text{ rads } \gamma$ is like $10^{13} \text{ neutrons/cm}^2$ for bulk damage

C. SURFACE DAMAGE

1. Basic Effects (see Figure 16)

- a. Accumulation of positive charge density in SiO_2 near $\text{Si} - \text{SiO}_2$ interface
- b. Creation of interface states
 - (1) Usually relatively small effect
 - (2) Fast states
 - (3) Slow states - absorption of gas ions on outside of SiO_2

Figure 16 - Basic Effects of Radiation on Silicon Surface

2. Surface Physics

a. Surface recombination velocity, S , cm/sec

b.
$$S = \frac{1}{2} \sqrt{\sigma_n \sigma_p} \bar{v} \pi kT N_R$$

(1) σ_n and σ_p are electron and hole capture cross sections, respectively

(2) $\bar{v}$ is carrier velocity

(3) kT is Boltzmann's constant times temperature

(4) N_R is density of recombination centers

c. S is a function of surface potential, ϕ_s (see Figure 17)

d. Surface conductance, σ

e. σ is a function of surface potential, ϕ_s

3. Total Ionizing Dose (see Figure 18)

a. Increases charge density, Q_{ss} at $Si - SiO_2$ interface

b. Changes surface potential ϕ_s by inducing $-Q_{ss}$ in semiconductor to maintain charge neutrality, function of surface trap density and level (see Figure 19)

(1) Drastically changes S through dependence of S on ϕ_s (see Figure 20)

(a) Changes effectivity of N_R through Fermi occupational statistics

(b) Some increase in N_R also caused by radiation

(2) Effect saturates with increasing dose (at ≈ 1 Mega rad)

c. Changes surface conductance σ_s by inducing $-Q_{ss}$

(1) Depletion, inversion and accumulation of semiconductor surfaces (see Figure 21)

Figure 17 - Normalized Surface Recombination Velocity as a Function of Surface Potential

Figure 18 - Variation of Space Charge Density in the Semiconductor as a Function of the Surface Potential ψ_s for p-Type Silicon

Figure 19 - Change of Trapped-Carrier Density in Fast States on Germanium and Silicon Surfaces vs Surface Potential

Figure 20 - Surface Recombination Velocity of a Silicon Surface as a Function of Radiation Dose

Figure 21 - Depletion, Inversion, and Accumulation Surface Layers for n- and p-type Semiconductors

- (2) Inversion of P type surfaces
 - (3) Accumulation of N type surfaces
 - (4) Surface conductivity increases exponentially with Φ_s beyond a threshold determined by doping of semiconductor
 - (5) Highly doped semiconductors less susceptible than low doped semiconductors. (Excludes tunneling in extremely high doping cases.)
- d. Changes threshold voltage, V_T , in MOS devices (see Figure 22)

4. Bias Effects

- a. Application of forward bias reduces S to a very low value
- b. Devices should be operated at $>10 \text{ A/cm}^2$ to eliminate effects of S and the increase of S with total ionizing dose
 - (1) Relationship between surface charge density, Q_{ss} and gate voltage as a fraction of trap density (see Figure 23)
 - (2) Change in channel conductance usually negligible.
- c. Positive voltage bias retards accumulation of positive charge
- d. Negative voltage enhances accumulation of positive charge
- e. Voltage bias can produce an order of magnitude difference in rate of damage accumulation

5. Surface Conductance Effects

- a. Of negligible importance unit or unless strong inversion or accumulation region is entered
- b. Effect of surface channel (see Figure 24)
- c. Some decrease in low current level current gain
- d. Some increase in leakage currents (see Figure 25)
- e. Strong accumulation or inversion causes device shorting

Figure 22 - Turn-On Voltage vs Neutron Flux for a p-Type MOS Transistor

Figure 23 - Dependence of the Saturation Value of the Excess Charge Induced in the Silicon on the Gate Bias Applied During Irradiation

Figure 24 - Forward Emitter Characteristics for a Surface Channel ($V_{GB} = 20V$) and for No Surface Channel ($V_{GB} = 20V$)

Figure 25 - Typical Results for I_{CBO} Degradation of Several Transistor Types

6. Passivating Layer - SiO₂

- a. Thick ($>10,000\text{\AA}$) passivating layer nearly eliminates gamma dose sensitivity at bias currents $>10\text{A}/\text{cm}^2$
- b. Unpassivated devices can short circuit in gamma environment

IV. EFFECTS OF RADIATION ON DEVICE OPERATION

A. INTRODUCTION

1. Lifetime Reduction of Dominant Importance

- a. Current gain reduction
- b. Changes in other parameters related to current gain
 - (1) Storage time
 - (2) Saturation voltage

2. Secondary Radiation Effects

- a. Surface potential and surface recombination velocity changes
- b. Carrier removal or addition
- c. Reduction of carrier mobility

3. Establishment of Transistor Equations in Terms of Radiation Dependent Parameters

- a. General admittance matrix
- b. Low injection level effects
- c. High injection level modifications

4. Functional Dependence of Lifetime, Carrier Density, Carrier Mobility, and Surface Recombination Velocity on Radiation Fluence

5. Transistor Equations as a Function of Radiation Fluence

- a. Admittance matrix
- b. Current gain

6. Various Radiation Environments

7. Microcircuits

B. ESTABLISHMENT OF GENERAL ADMITTANCE MATRIX

1. Basic One-Dimensional Structure (see Figure 26)

One Dimensional Structure and Boundary Conditions
For Transistor Discussion

Typical Doping Profile in the Transistor Base Region

Figure 26 - Geometry and Doping Profile in the Base Region

a. Discussion of general applicability

(1) Constant field in base (see Figure 27)

(a) Graded base

(b) Homogeneous base

(2) Other base distributions such as error function (Reference 1)

(3) Two-dimensional effects

(4) Emitter area often smaller than collector area

b. Basic differential equations (Reference 2)

$$(1) \quad \frac{\partial n}{\partial t} = g - R + \frac{1}{q} \frac{\partial J_n}{\partial x}$$

$$\frac{\partial p}{\partial t} = g - R - \frac{1}{q} \frac{\partial J_p}{\partial x}$$

$$(2) \quad J_p = q\mu_p pE - qD_p \frac{\partial p}{\partial x}; \quad E = \frac{KT}{q} \frac{1}{p} \frac{dp}{dx}$$

$$J_n = q\mu_n nE + qD_n \frac{\partial n}{\partial x}; \quad \frac{1}{p} \frac{dp}{dx} = - \frac{1}{N} \frac{dN}{dx}$$

$$E = - \frac{KT}{q} \frac{1}{N} \frac{dN}{dx}$$

$$(3) \quad \nabla^2 \phi = - \frac{p-n + N_D - N_A}{\kappa \epsilon_0}$$

c. Discussion of required assumptions

(1) τ_p, τ_n Shockley-Read functions of resistivity. Assumed constant for solving equations and the solution subsequently multiplied by Shockley-Read function (Reference 3).

Figure 27 - Base Doping Profile Resulting from a Fixed Supply of Diffusion Atoms

(2) μ_n, μ_p, D_n, D_p assumed constant. They are actually related to impurity density by the Conwell-Weisskoff or Brooks-Herring functions (see Figure 28).

(3) Effect of transition from low-level to high-level conditions modifies diffusion constants by a factor of 2 (see Figure 29) This is taken into account by the factor

$$f'(Z) = \frac{1 + \frac{Z}{2}}{1 + Z} \quad \text{applied after the integration}$$

(4) Space charge neutrality assumed

(5) $n_b = N_D$ assumed

d. Discussion of boundary conditions (Reference 4)

(1) Lifetime τ_E, τ_B, τ_C

(2) Finite emitter region

(3) $N_B = N_B^W e^{(1 - \frac{X}{W}) \ln k}$;

$$\frac{1}{N} \frac{dN}{dx} = - \frac{\ln k}{W} \quad \frac{dN}{dx} = - \frac{\ln k}{W} N_B^W e^{(1 - \frac{X}{W}) \ln k}$$

(4) $P_E = p_n^o e^{\frac{qV_E}{kT}}$; $P_C = p_n^W e^{\frac{qV_C}{kT}}$

e. Low frequency admittance matrix

$$I_e = a_{11} \psi_E - a_{12} \psi_C$$

$$I_c = a_{21} \psi_E + a_{22} \psi_C,$$

$$\psi_E, C = e^{\frac{qV_{E,C}}{kt}} - 1,$$

Figure 28 - Variation of Mobility with Impurity Concentration for n- and p-Type Silicon

Figure 29 - Field Factor as a Function of the Parameter Z

Matrix Element Function	Exact Form	Approximate Form
$\frac{a_{11}}{AD_p q p_n^o}$	$\sigma \coth \sigma W + \frac{n}{2W}$	$\frac{1 + \frac{W^2}{2L_p^2} + \frac{n}{2} + \frac{n^2}{8}}{W}$
$\frac{a_{12}}{AD_p q p_n^W}$	$\frac{\sigma \operatorname{csch} \sigma W}{\sqrt{k}}$	$\frac{1}{W \sqrt{k}} \left(1 + \frac{W^2}{6L_p^2} + \frac{n^2}{24} \right)$
$\frac{a_{21}}{AD_p q p_n^o}$	$\sqrt{k} \sigma \operatorname{csch} \sigma W$	$\frac{\sqrt{k}}{W} \left(1 + \frac{W^2}{6L_p^2} + \frac{n^2}{24} \right)$
$\frac{a_{22}}{AD_p q p_n^W}$	$\sigma \coth \sigma W - \frac{n}{2W}$	$\frac{1 + \frac{W^2}{2L_p^2} - \frac{n}{2} + \frac{n^2}{8}}{W}$

$$\sigma = \frac{1}{2} \sqrt{\left(\frac{n}{W}\right)^2 + \left(\frac{4}{L_p}\right)^2}, \quad k = \frac{N_{DE}}{N_{DC}}, \quad n = \ln k, \quad L_p = \sqrt{D_p \tau},$$

$$k = p_n^W / p_n^o; \quad p_n^o = \frac{n_i^2}{N_B^o} = \rho_b^o \quad q \mu \sigma n_i^2; \quad p_n^W = \frac{n_i^2}{N_B^W} = \rho_b^W \quad q \mu \sigma n_i^2$$

$$\gamma_{E, C} = 1/1 + \frac{j_{n E, C}}{j_{p E, C}}$$

$$\frac{1}{2} \sigma^2 W^2 = \frac{n^2}{8} + \frac{W^2}{2L_p^2}$$

C. DEPENDENCE OF CURRENT GAIN ON FLUENCE

1. Contributions to Current Gain and Minority Carrier Loss

a. Description of recombination processes

- (1) Finite emitter current due to majority carriers
- (2) Recombination in emitter field region
- (3) Recombination on peripheral emitter surface
- (4) Bulk recombination
- (5) Collector multiplication

$$b. \quad \alpha = \gamma \alpha_S \alpha_T \alpha^*$$

$$\gamma = 1 - \epsilon_1$$

$$\alpha_S = 1 - \epsilon_2$$

$$\alpha_T = 1 - \epsilon_3$$

$$\alpha^* = 1 + \epsilon_4$$

$$c. \quad \frac{1}{\beta} = \frac{1 - \alpha}{\alpha} = \epsilon_1 + \epsilon_2 + \epsilon_3 - \epsilon_4$$

$$d. \quad \frac{1}{\beta} = \frac{S A_S}{D_p A (\sigma \coth \sigma W + \ln k/2W)} \quad F'(Z) \quad \text{Surface term}$$

$$+ \frac{\sigma W \coth \sigma W + \frac{n}{2}}{\sigma W e^{\frac{n}{2}} \operatorname{csch} \sigma W} - 1 \quad \text{Bulk recombination}$$

$$+ \frac{J_{neo}}{J_{peo}} (1 + b I_E) \quad \text{Emitter efficiency and bulk conductivity modulation}$$

+ A/I_E Recombination in base emitter field region

2. Low Injection Level Case (Silicon only)

a. Recombination in base emitter field region (Reference 5)

$$j_{RG} = \frac{2W_S q n_i}{2\tau_o} \frac{kT}{q(\psi_o - V)} e^{qV/kTm} \quad m \approx 2$$

$$b. \quad \gamma_E = 1/(1 + \frac{I_{RG}}{a_{11}}) = 1/(1 + \frac{A}{I_E^{1/2}}) \quad I_E \neq 0$$

c. Homogeneous base

$$\gamma_E = 1/(1 + \frac{W_S kT}{q(\psi_D - V)} \frac{n_1}{p_n} \frac{W}{L^2} e^{-\frac{qV_E}{2kT}})$$

3. High Injection Level Case

a. Built-in field slowly disappears as injection increases

$$b. \quad \gamma_E = 1/ \left(1 + \frac{n_p^o D_n (\sigma_E \coth \sigma_E W_E + \frac{\ln k_E}{2 W_E})}{p_n^o D_p (\sigma \coth \sigma W + \ln K/2W)} \right)$$

c. Effect of emitter lifetime, $W_E \gg L_E$

$$n_p^o D_n (\sigma_E \coth \sigma_E W_E + \ln k_E/2W_E) \approx \frac{n_p^o D_n}{L_n}$$

d. Homogeneous base conductivity modulation

$$\gamma_E = 1 / \left(1 + \frac{j_{neo} W (1 + \frac{Z}{2})}{q n_1^2 D_p} \right), Z = \frac{j_E W}{q D_p N_D}$$

e. Graded base conductivity modulation

- (1) Modification to differential equation for determining a_{11} (Reference 6)

$$\frac{dp}{dx} N_D + 2p \frac{dp}{dx} + p \left(\frac{J_p}{q D_p} - N_{DE} W e^{-\eta x/W} \right) + N_{DE} e^{-\eta x/W} \frac{J_p}{q D_p} = 0$$

$$(2) \gamma_E = \frac{1}{1 + A(1 + bI_E)}$$

f. Emitter crowding

4. Surface Recombination Effects

$$j_S = q S p_B^o$$

$$\gamma_S = 1/l + \frac{I_S}{a_{11}}$$

5. Dependence of Lifetime and Other Parameters on Fluence

a. Lifetime (Reference 7, 8, and 9)

$$\frac{1}{\tau} = \frac{1}{\tau_i} + \frac{\phi}{K(p_b, E_n)}$$

$\tau \approx K/\phi$ when $K/\phi \ll \tau_1$ Defines Lifetime Damage
Constant "Radiation Lifetime"

b. Carrier density (Reference 10)

$$(1) \quad n = n_o \pm \phi \frac{dn}{d\phi}$$

$$(2) \quad \frac{dn}{d\phi} \text{ is a function of } \phi$$

(Reference 11)

(3) Silicon approaches intrinsic; germanium approaches
low resistivity p-type

c. Surface recombination velocity and surface potential
(Reference 12)

(1) S versus ϕ

(2) ϕ versus R

d. Other Effects

6. Homogeneous Base Transistor (Reference 8)

$$\frac{1}{\beta} = \frac{SWA_s}{D A_e} g(Z) + \frac{\sigma_b W}{\sigma_e L_e} \left(1 + \frac{Z}{2}\right) + \frac{1}{2} \frac{W^2}{L_b^2} h(Z) + \frac{dI_{RE}}{dI_E}$$

7. Volume Recombination Dominant (Reference 4)

$$a. \quad \frac{1}{\beta} = \frac{\sigma W \coth \sigma W + \frac{n}{2}}{\sigma W e^{\frac{n}{2}} \operatorname{csch} \sigma W} - 1 \quad (\text{see Figure 30})$$

b. $\tau = K/\phi$

c.
$$\frac{\partial \frac{1}{B}}{\partial \phi} = \frac{W^2}{2DK} \frac{e^{-n/2}}{\sigma W} \left[\sinh \sigma W - \frac{\eta \sinh \sigma W}{2(\sigma W)^2} + \frac{\eta \cosh \sigma W}{2 \sigma W} \right]$$

d.
$$\frac{W^2}{2D_p} = \frac{1}{4\eta ft} \frac{n^2}{e^{-\eta} + n - 1}$$

e.
$$K = \frac{0.16\phi}{ft \Delta \frac{1}{B}}$$

f.
$$\Delta \frac{1}{\beta} = \frac{0.16\phi}{Ft K}$$

8. Surface Recombination Dominant (see Figure 31)

a.
$$\frac{1}{\beta} = \frac{1}{\beta_1} + \frac{A_S S(\phi)}{D_p A (\sigma \coth \sigma W + \ln K/2W)}$$

Figure 30 - Variation of $\frac{1}{\omega_T}$ with $\frac{1}{I_E}$

Figure 31 - Variation of Reciprocal Current with Electron Fluence
Showing the Combination of Bulk and Surface Effects

$$b. \quad \Delta \frac{1}{\beta} = \frac{W A_S}{D A_p} \quad \frac{\partial S}{\partial \phi} \quad \phi \quad (\text{Homogeneous Base})$$

D. DEPENDENCE OF DAMAGE CONSTANT ON RESISTIVITY, INJECTION LEVEL AND TEMPERATURE (REFERENCE 13)

$$\text{Return to } \Delta \frac{1}{\beta} = \frac{0.16}{f_{\alpha} K} \quad \text{where } K = K(\rho, \frac{\delta n}{n}, T)$$

1. Recombination through a Center in the Forbidden Band

$$a. \quad \tau = \frac{K}{\phi} = \frac{\tau_{no} (p_o + p_1 + \Delta n) + \tau_{po} (n_o + n_1 + \Delta n)}{(p_o + n_o + \Delta n)}$$

$$b. \quad \text{Let } \tau_{no} = \frac{1}{C_n R \phi} \quad \text{and } \tau_{po} = \frac{1}{C_p R \phi}$$

$$c. \quad K = \frac{1}{C_n R} \frac{p_o + p_1 + \delta_n}{p_o + n_o + \delta_n} + \frac{1}{C_p R} \frac{n_o + n_1 + \delta_n}{p_o + n_o + \delta_n}$$

2. Two-Level Model

$$a. \quad \frac{1}{\tau} = \frac{\phi}{K} = \frac{1}{\tau_1} + \frac{1}{\tau_2}$$

$$\begin{aligned}
 \text{b. } \frac{1}{K} &= \frac{1}{\frac{C_{p1} R_1}{\frac{n_o + n_1 + \delta_n}{n_o + p_o + \delta_n}} + \frac{1}{\frac{C_{n1} R_1}{(p_o + p_1 + \delta_n)(n_o + p_o + \delta_n)}}} \\
 &+ \frac{1}{\frac{1}{\frac{C_{p2} R_2}{\frac{n_o + n_2 + \delta_n}{n_o + p_o + \delta_n}} + \frac{1}{\frac{C_{n2} R_2}{(p_o + p_2 + \delta_n)(n_o + p_o + \delta_n)}}}
 \end{aligned}$$

$$\text{c. } \frac{1}{K_H} = \frac{\frac{C_{n1} R_1}{\frac{C_{n1}}{C_{p1}} + 1}}{\frac{C_{p2} R_2}{\frac{C_{p2}}{C_{n2}} + 1}} + \frac{C_{p2} R_2}{\frac{C_{p2}}{C_{n2}} + 1}$$

$$\text{d. } \frac{1}{K_{LN}} = \frac{\frac{C_{p1} R_1}{1 + \frac{n_1}{n_o}}}{1 + \frac{C_{p2}}{C_{n2}} \frac{p_2}{n_o}} + \frac{C_{p2} R_2}{1 + \frac{C_{p2}}{C_{n2}} \frac{p_2}{n_o}}$$

$$\text{e. } \frac{1}{K_{LP}} = \frac{\frac{C_{n1} R_1}{1 + \frac{C_{n1}}{C_{p1}} \frac{n_1}{p_o}}}{1 + \frac{C_{n2} R_2}{1 + \frac{C_{n2}}{C_{p2}} \frac{p_2}{p_o}}} + \frac{C_{n2} R_2}{1 + \frac{C_{n2}}{C_{p2}} \frac{p_2}{p_o}}$$

f. Dependence on injection level

$$\begin{aligned}
 \frac{1}{K_p} &= \frac{\frac{C_{n1} R_1}{1 + \frac{C_{n1}}{C_{p1}} \frac{n_1 + \delta_n}{p_o + \delta_n}}}{\frac{\delta_n}{p_o + \delta_n} + \frac{C_{p2}}{C_{n2}} \left(\frac{p_o + p_2 + \delta_n}{p_o + \delta_n} \right)} \\
 &+ \frac{C_{p2} R_2}{\frac{\delta_n}{p_o + \delta_n} + \frac{C_{p2}}{C_{n2}} \left(\frac{p_o + p_2 + \delta_n}{p_o + \delta_n} \right)}
 \end{aligned}$$

g. Temperature dependence

$$(1) \quad n_1 = AT^{3/2} \exp(-(E_c - E_1)/kT)$$

$$P_2 = BT^{3/2} \exp-(E_2 - E_v)/kT$$

$$(2) \frac{1}{K_N} = \frac{C_{p1} R_1}{\frac{C_{p1}}{C_{n1}} \left(\frac{n}{n_o + \delta_n} \right) + 1 + \left(\frac{n_1}{n_o + \delta_n} \right) \left(\frac{n_1}{n_o} \right) T_1 \left(\frac{T}{T_1} \right)^{3/2} \exp[38.6 \left(1 - \frac{T_1}{T} \right) \Delta E_1]} + \frac{C_{n2} R_2}{\frac{C_{n2}}{C_{p2}} + \frac{\delta_n}{n_o + \delta_n} + \left(\frac{n_o}{n_o + \delta_n} \right) \left(\frac{p_2}{n_o} \right) T_1 \left(\frac{T}{T_1} \right)^{3/2} \exp[38.6 \left(1 - \frac{T_1}{T} \right) E_2]}$$

h. Low temperature asymptote

$$\frac{1}{K_{n^{**}}} = \frac{C_{p1} R_1}{\frac{C_{p1}}{C_{n1}} \left(\frac{\delta_n}{n_o + \delta_n} \right) + 1} + \frac{C_{n2} R_2}{\frac{C_{n2}}{C_{p2}} + \frac{\delta_n}{n_o + \delta_n}}$$

i. Calculated Curves

(a) Kn vs 1000/T°K (see Figure 32)

(b) Kn, Kp vs Injection Ratio $\frac{\delta_n}{\delta_{no}}, \frac{\delta_p}{p_o}$. (see Figure 33)

j. Silicon constants

$$R_1 C_{p1} = 0.37 \times 10^{-6} (\text{sec-n/cm}^2)^{-1}$$

$$R_1 C_{n1} = 0.40 \times 10^{-5} (\text{sec-n/cm}^2)^{-1}$$

Figure 32 - Variation of Electron Damage Constant with Reciprocal Temperature for Silicon for Various Values of Injection Ratio X

Figure 33 - Variation of Silicon Damage Constant with Injection Ratio

$$R_2 C_{p2} = 0.68 \times 10^{-5} (\text{sec-n/cm}^2)^{-1}$$

$$R_2 C_{n2} = 0.76 \times 10^{-6} (\text{sec-n/cm}^2)^{-1}$$

$$n_1 = 2.0 \times 10^{14} \text{ cm}^{-3}$$

$$p_2 = 1.3 \times 10^{13} \text{ cm}^{-3}$$

$$K_{LN} = \frac{1.4 + 8.6 \cdot 10^{-2} \rho + 1.2 \cdot 10^{-3} \rho^2}{1 + 3.8 \cdot 10^{-2} \rho}$$

$$K_{LP} = \frac{2.0 + 0.18 \rho + 9.0 \cdot 10^{-5} \rho^2}{1 + 1.4 \cdot 10^{-2} \rho}$$

k. Germanium Constants

$$R_1 C_{p1} = 4.4 \times 10^{-8}$$

$$R_2 C_{p2} = 92 \times 10^{-8}$$

$$R_1 C_{N1} = 35 \times 10^{-8}$$

$$R_2 C_{N2} = 0.9 \times 10^{-8}$$

$$E_1 = 0.28 \text{ ev}$$

$$E_2 = 0.32 \text{ ev}$$

1. K_{∞} histogram for silicon (see Figure 34)

E. DEPENDENCE OF DAMAGE PROCESS ON RADIATION PARTICLE ENERGY

(References 8 and 9)

1. Neutrons

a. Threshold Energy E_d 10 to 30 ev

Figure 34 - Histogram for High-Level Damage Constant for Silicon

$$b. \quad \text{Let } E_d = E_{p(\text{MAX})} = \frac{4E_n Mm}{(M+m)^2} \approx \frac{4E_n}{A}$$

$$E_N \sim 200 \text{ ev for silicon}$$

c. Above 200 ev $N_D \propto E_n$ up to ~ 1 Mev then slowly saturates

d. As E_N increases, point defects give way to clusters.

$$\bar{E}_p = E_{p(\text{MAX})}/2$$

$$e. \quad \text{First order theory } N_d = \frac{N_A \sigma_d \phi E_{p(\text{MAX})}}{4E_d} \quad E_p < E_i$$

$$N_d = \frac{N_A \sigma_d \phi E_i}{2E_d} \quad E_p \geq E_i$$

$$N_d = N_A \sigma_d \phi \bar{v}$$

$$f. \quad \bar{n}(E) + \bar{\eta}(E) = E$$

$$a) \quad \bar{n}(E)/E \text{ versus } E_n$$

$$b) \quad \bar{\eta}(E)/E \text{ versus } E_n$$

$$g. \quad \text{Assume } N_R \propto \bar{n}(E)$$

h. Neutron Spectra

$$K^{-1} = \frac{\int_{0.01 \text{ Mev}}^{\infty} \sigma(E) N(E) dE}{\int_{0.01 \text{ Mev}}^{\infty} N(E) dE}$$

$$\sigma = a E_n (1 - e^{-A/E_n})$$

$$a = 1.02/\text{MeV} \text{ and } A = 3.6 \text{ MeV}$$

F. TRANSISTORS

1. Common Emitter Current Gain Degradation (see Figure 35)
2. Dependence on Bias Current

G. MICROCIRCUITS (REFERENCE 9)

1. Classification Scheme
 - a. Monolithic
 - (1) p-n junction isolated
 - (2) SiO_2 isolated
 - b. Multiple chip
 - c. Compatible
 - d. Hybrid
2. Permanent Damage Effects
 - a. General
 - b. Gates
 - c. Flip-flops
 - d. Amplifiers
3. Ionization Effects
 - a. General
 - (1) p-n junction isolation
 - (2) Dielectric isolation
 - (3) Other

Figure 35 - Common Emitter Current Gain Degradation as a Function of Collector Current for Various Values of Neutron Fluence

- b. Gates
- c. Flip-flops
- d. Amplifier

H. EBERS-MOLL MODEL

- 1. General Model
- 2. Inclusion of Radiation Effects

a. Current Gain

$$(1) \quad \Delta \frac{1}{\alpha_{N,I}} = \frac{0.16\phi}{Ft K} \quad (\text{Neutrons})$$

$$(2) \quad \Delta \frac{1}{\alpha_{N,I}} = F (\gamma \text{ Dose})$$

b. Leakage Currents

$$(1) \quad R_C = F (\gamma \text{ Dose})$$

$$(2) \quad R_E = F (\gamma \text{ Dose})$$

c. Other Effects

- (1) Breakdown Voltage
- (2) Carrier Removal
- (3) Conductivity Modulation of Resistors

V. CIRCUIT ANALYSIS

A. COMPONENT MODELS

1. Charge control (see Figure 36)
2. Ebers - Moll (see Figure 37)
3. Modified Ebers - Moll (see Figure 38)
4. Equivalence

Both models represent the same degree of approximation relevant to a completely rigorous approach. Charge control parameters are associated with CIRCUS. Ebers and Moll parameters were associated with SCAN, TRAC, and SECURE computer programs.

Measured device data exist in TREE community literature for both the charge control model and the Ebers and Moll model. It is desirable to be able to determine Ebers and Moll model parameters from charge control parameters. Table 1 presents the transform relationships among the parameters. Auxiliary formulas for the models are presented in Table 2.

B. CIRCUIT LEVEL COMPUTER CODES

1. NET
2. CIRCUS
3. SCEPTRE
4. TRAC
5. SCAN

C. CAPABILITIES

1. Automatic generation of circuit equations
2. Built-in or user models

Figure 36 - Charge Control Model

Figure 37 - Ebers and Moll Model

INCLUSION OF PRIMARY
PHOTOCURRENT GENERATORS

$$\alpha_N \triangleq = \frac{B_N}{1 + B_N} \quad \frac{B_N(\phi)}{B_N(0)} = \frac{1}{1 + K_D B_N(0)\phi}$$

$$K_D = \frac{.6}{K \cdot f_t}$$

Figure 38 - Modification for Ionization and Degradation Effects

TABLE 1

Parameter Transforms for Charge Control
and Ebers and Moll Models

Ebers and Moll Parameters in Terms
of Charge Control Parameters

$$I_{ES} = Q_{BN} \frac{1}{T_{BN}} + \frac{1}{T_{CN}}$$

$$C_E = C_{ib}$$

$$C_C = C_{ob}$$

$$\alpha_N = \frac{T_{BN}}{T_{CN} + T_{BN}}$$

$$I_{CS} = Q_{BI} \left(\frac{1}{T_{BN}} + \frac{1}{T_{CI}} \right)$$

$$\alpha_I = \frac{T_{BI}}{T_{BI} + T_{CI}}$$

$$T_N = \frac{T_{BN} T_{CN}}{T_{BN} + T_{CN}}$$

$$T_I = \frac{T_{BI} T_{CI}}{T_{BI} + T_{CI}}$$

$$r_b = r_b$$

$$r_c = r_c$$

$$I_{EPH} = I_{PP}^*$$

$$I_{CPH} = I_{PP}$$

$$\theta_N = \theta_N$$

$$\theta_I = \theta_I$$

Charge Control Parameters in Terms
of Ebers and Moll Parameters

$$Q_{BN} = T_N I_{ES}$$

$$C_{ib} = C_E$$

$$C_{ob} = C_C$$

$$T_{CN} = \frac{T_N}{\alpha_N}$$

$$T_{BN} = \frac{T_N}{1 - \alpha_N}$$

$$T_{CI} = \frac{T_I}{\alpha_I}$$

$$T_{BI} = \frac{T_I}{1 - \alpha_I}$$

$$Q_{BI} = T_I I_{CS}$$

$$r_b = r_b$$

$$r_c = r_c$$

$$I_{PP}^* = I_{EPH}$$

$$I_{PP} = I_{CPH}$$

$$\theta_N = \theta_N$$

$$\theta_I = \theta_I$$

TABLE 2

Auxiliary Formulas for Models

$$q_{BN} = Q_{BN} \left(e^{\theta_N v_{be-1}} \right)$$

$$q_{BI} = Q_{BI} \left(e^{\theta_I v_{bc-1}} \right)$$

$$I_{EF} = I_{ES} \left(e^{\theta_N v_{be-1}} \right)$$

$$I_{CF} = I_{CS} \left(e^{\theta_I v_{bc-1}} \right)$$

$$T_N = \frac{1}{F_{tN}}$$

$$T_I = \frac{1}{F_{tI}}$$

3. Automatic initial conditions
4. Transient solution
5. Restart capability
6. Tabular or graphic output

D. SYSTEM LEVEL CODES, SECURE

1. Block function
2. Detailed circuit functions
3. Example: neutron effects simulation of platform stabilization loop.
 - a. Block diagram (see Figure 39)
 - b. Network amp output response (see Figure 40)
 - c. Gyro error (see Figure 41)

E. COMBINATION OF MANUAL AND COMPUTER ANALYSIS

F. COMPUTER AIDED CIRCUIT DESIGN

G. STATISTICS

H. TYPICAL GATE CIRCUIT (See Figure 42)

Figure 42 - Typical Gate Circuit

Figure 39 - Neutron Effects Simulation; Platform Stabilization Loop

Figure 40 - Network Amplifier Response ($\gamma + N$)

Figure 41 - Gyro Response ($\gamma + N$)

1. Critical Parameters

$$a. \quad t_{on} = \tau_{BF}(\phi) \ln \left\{ 1 - \frac{I_c}{I_B h_{FE}(\phi)} \right\}$$

This will not charge more than an acceptable 50% before the IC fails by coming out of saturation

$$b. \quad V_{CESAT} = \pm 0.026 \ln \left[\frac{\alpha_I \left\{ 1 - \frac{I_c}{h_{FEN} I_B} \right\}}{1 + (I_c/I_B)(1 - \alpha_I)} \right]$$

Not strongly dependent on α_I

$$\text{Mainly determined by } h_{FEN} \rightarrow h_{FEN} = \frac{1}{\frac{1}{h_{FENO}} + \frac{0.2\phi}{F_{TN} K}}$$

2. Limited Worst Case Values

h_{FEN}	85	30
h_{FEI}	1.5	1.1
F_{TN}	1.5×10^8	1.1×10^8
F_{TI}	4.0×10^6	1.0×10^6
K	3×10^6	1.5×10^6

3. Prediction and Experimental Confirmation (see Figure 43)

Figure 43 - Worst Case Analysis for $V_{CE(SAT)}$ vs Fluence for Typical Gate Circuit (Data points are experimentally measured values which confirm the analysis)

4. Special Problems

a. Low-level switch, demodulator, etc.

Dynamic output impedance

$$r_d = \frac{dV_{out}}{dI_E}$$

$$V_{out} = I_C R_{sc} + \frac{kT}{q} \ln \left[\frac{\beta_I (\beta_N + \beta_F + 1)}{\beta_N (\beta_I - \beta_F)} \right]$$

$$r_d = R_{sc} + \frac{kT}{q} \left(\frac{1}{I_B (\beta_N + \beta_F + 1)} \right) \frac{(\beta_N + \beta_I + 1)}{(\beta_I - \beta_F)}$$

$$r_d \approx R_{sc} + \frac{kT}{qI} \frac{1}{\beta} \frac{1}{\beta_I}$$

b. Device specifications (see Figure 44)

- (1) Must insure margin
- (2) Problem of operator circuits

Figure 44 - Variation of V_{CE} with the Ratio of Transistor Gain to Forced Circuit Gain

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