RIVISTA TECNICA SELENIA

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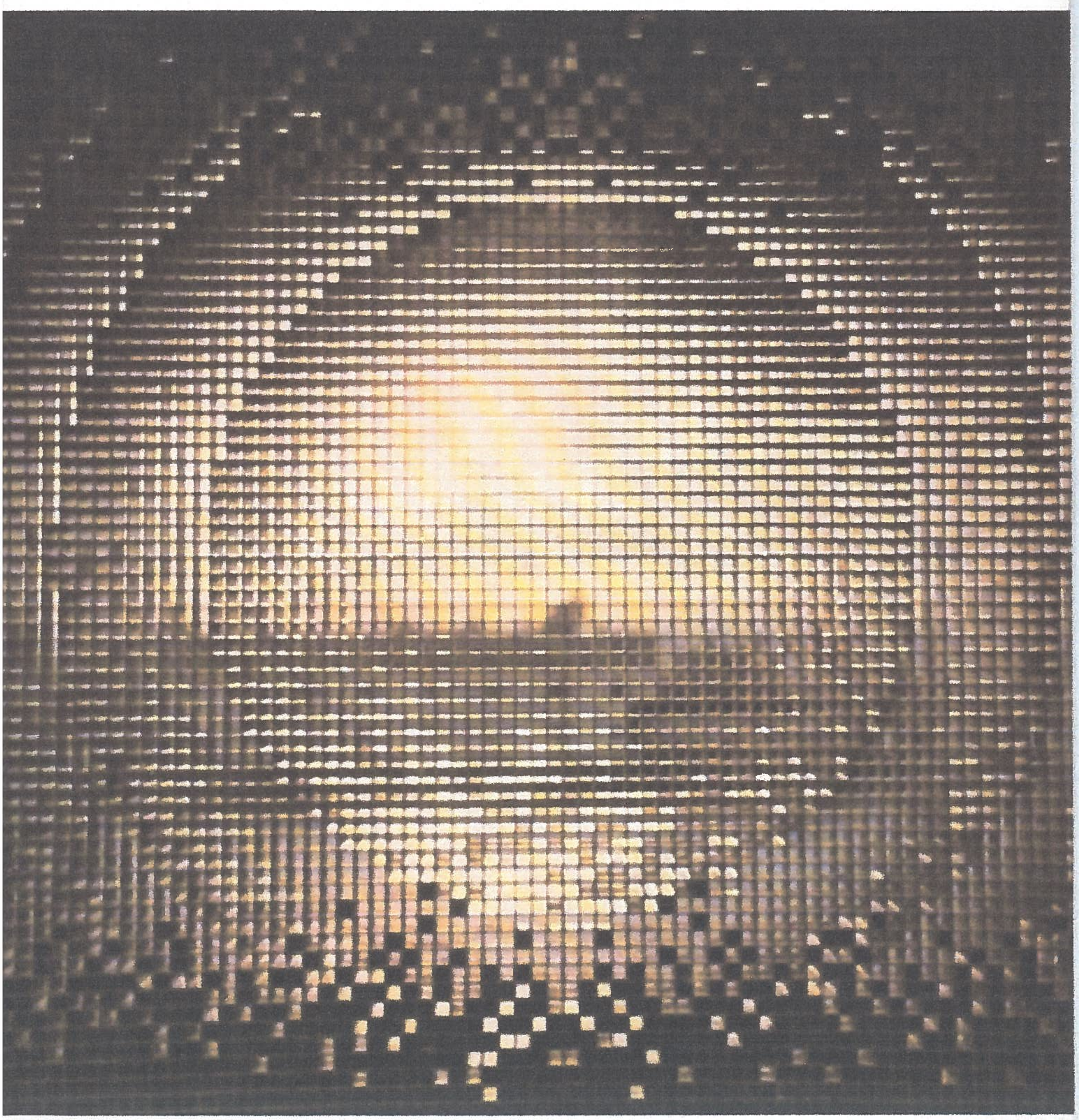

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SUMMARY

Edited by Selenia,
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Via Tiburtina Km. 12.400 – 00131 Rome, Italy

EFFECTS OF SPACE RADIATION ON LOGICAL INTEGRATED CIRCUITS

ROBERTO SOMMA
Reliability Department

SUMMARY

This article gives a review of the available information on the effects of space radiation on digital integrated circuits, the introduction is followed by a brief description of the space environment relevant to radiation.

Next, improvements obtained through shielding of the integrated circuits are examined, in order to acquire a feeling for the amount of radiation incident on the junctions.

The effects of radiation on semiconductors are then discussed. Both the intrinsic parameters of the devices themselves, and the external ones are taken into consideration. Finally, the behaviour of digital integrated circuits subjected to these effects is discussed.

1. Introduction

Their characteristics of weight, small dimensions, reliability and resistance to mechanical stress, make integrated circuits ideally suitable for on-board equipment applications for satellites.

The semiconductor materials of which integrated circuits are built, are however easily damaged by radiation present in the space surrounding the Earth. A study of the main effects induced by this radiation is therefore necessary, in order to help designers choose the components most suitable to the specific task.

This paper describes information gathered from a feasibility study, for the on-board Computer, carried out by Selenia on ESTEC's behalf.

2. Brief description on space environment

1) Our knowledge of space, surrounding this planet, is continuously being improved by measurements carried out by artificial satellites and space probes. A deeper understanding of the physical quantities characterizing space radiation therefore is being gained.

Electromagnetic radiation is ignored since it does not damage integrated circuits (1). The corpuscular component is, however, examined in detail. Corpuscular radiation is characterized by its flux, measured in units of particles/cm^2 sec, and by the energy of the single particle, measured in MeV.

The main source of corpuscular radiation are: the Van Allen belts, solar wind, high energy solar protons, and galactic radiation.

2) The Van Allen belts were discovered in 1958 by means of particle detectors installed on-board Explorer I and Explorer III satellites. They are two concentric belts, at different altitudes, consisting of a large number of high energy protons and electrons trapped in the earth magnetic field. As a first approximation this magnetic field yelds the same effect of a dipole field. The particle energy lies in the range of one KeV to several MeV for electrons, and in the range of 1 KeV to ~700 MeV for protons.

A more detailed description of these belts can be found in specialized literature, and we will only recall that: the first belt extends from 400 to 10,000 Km., while the second one extends from 10,000 to 60 ÷ 80,000 Km (3).

They are usually represented by means of maps showing, for different values of energy, the constant flux lines as a function of altitude.

The radiation reaches its maximum intensity at a distance of 3,300 Km from Earth giving a daily exposure dose of $\sim 1.8 \times 10^{13}$ el./cm^2 for electrons of energy higher than 1.2 MeV, and of 3.3×10^{10} pr./cm^2 for protons of energy higher than 14 MeV (4). These values have been quoted to give an idea of the amount of the integrated fluxes, or daily incident doses, in order to be able to better evaluate the results hereafter reported.

3) The Sun continuously emits a plasma flux in the radial direction. This plasma mainly consists of protons and electrons originating from ionized hydrogen. This solar wind has a velocity of 300 Km/sec during the quiescent solar periods, but can attain 800 Km/sec during periods of turbulence. The plasma density lies in between 0.5 p/cm^3 and 30 p/cm^3, corresponding to a proton flux in between 1.5×10^7 p/cm^2 sec and 2×10^9 p/cm^2 sec, and to energies in the range of 0.5 to 3.5 KeV. The electrons energy is approximately 1eV and its contribution to radiation damage is therefore negligible. On the other hand the solar wind protons can only produce superficial damage due to their very short range in matter (1).

4) Solar explosions, occurring with a periodicity of approximately 11 years, cause emission of electromagnetic radiation and of charged particles. Such emissions enormously increase the proton density in the solar wind. The integrated flux, over six years of activity (1956-1961), has been of 2.1×10^{10} particles/cm^2 with energies higher than 30 MeV.

5) In addition to the above, a radiation consisting of particles coming in from outer space is also present. The flux of this radiation is not constant and varies in accordance with periods of solar activity. The total integrated flux over six years (1956-1961) has been of 4.7×10^8 particles/cm^2 with energies higher than 30 MeV.

6) So far, corpuscular radiation, present in space, has been described and its intensity roughly evaluated. The following investigation on radiation damage to integrated circuits, will show that the threshold above which substantial damage occurs is such that only the Van Allen belts need be taken into account.

3. Shielding

1) A large fraction of the radiation in the space region, covered by the satellite's orbit is absorbed in the material shielding its circuits from space. Therefore, in order to evaluate the actual dose, incident on the circuits, it is necessary to take this shielding effect into account.

2) The shielding efficiency depends on the density of the shielding material, i.e. the shielding efficiency is proportional to the material density. The appropriate unit to measure shielding is g/cm^2 since the necessary thickness is determined by the material used.

In order to be able to compare radiations differing in nature and energy, it is necessary to reduce them to a single kind of equivalent radiation. This reduction is accomplished on the basis of the effects produced by the radiation flux, i.e. two different radiation fluxes are considered equivalent if they produce the same damage. The flux of normally incident 1 MeV electrons is taken as the reference radiation flux.

3) As shown later, exposure of a semi-conductor to radiation causes:

a) Damage due to the volume dislocations. This is related to the flux incident on the junction.

b) Damage due to superficial ionization effects. This in related to the absorbed energy dose, measured in rads (1 rad = 100 ergs/g).

Reduction of radiation to equivalent fluxes of 1 MeV electrons for bulk damage and to superficial ionization for surface damage is carried out by means of graphs. These graphs give the equivalent flux of 1 MeV electrons or deionization dose in Rads/cm^2 versus the proton or electron energy in MeV, for different values of shielding thickness.

4. Effect of radiation on semiconductors

1) Bulk damage – It is well known, that the characteristics of a semiconductor depend upon its crystalline structure. Conductivity, in particular, depends on the irregularities of this structure, whether of chemical (doping) or of physical (external energy supply) nature.

The reticular defects produced within the semiconductor volume by radiation speed up the process of re-combination of the free charges. The process can occur directly when a conduction band electron combines with a valence band hole (but direct re-combination is a rare process due to the large difference in energy of the two carriers) or, more frequently, it occurs because either the electron or the hole have an energy lying in the forbidden energy gap of the crystal and are therefore nearer to each other, making re-combination easier.

Such intermediate energy levels can be produced by several kinds of imperfections, and radiation is very efficient in producing lattice imperfections that act as recombination centers.

A number of re-combination centers caused by lattice imperfections and chemical impurities is present even in crystals that have not been irradiated.

A physical parameter called "minority carriers life-time" (τ), is used to describe the above mentioned recombination process, τ is defined as the time constant in the exponential decay law of the injected charges which, under equilibrium conditions, are minority carriers, i.e. electrons for p-type or holes for n-type semiconductors.

Two other important physical parameters, the diffusion constant D, describing the diffusion process of a given charge, and mobility μ describing the drift velocity of free charges subject to an electric field, are also affected, like τ, by radiation.

D and μ are connected through the following relationship:

$$\frac{D}{\mu} = \frac{KT}{q}$$

where

T is the absolute temperature

K is the Boltzmann constant

q is the eletron charge.

Another parameter, related to the previous ones, is the diffusion lenght L, which is the mean free path of a particle before re-combination. It is related to D and τ by $L^2 = D\tau$.

2) Surface damage – The surface of a semiconductor consists of a complex series of interfaces, whose properties often affect the characteristics of the component.

Semiconductor components get very rapidly covered by an oxide film. At the oxide-semiconductor interface a perfect interfacing of crystal structures is practically impossible. This gives rise to the occurrence, in the forbidden energy band, of other electronic levels, besides those due to impurities. These levels, acting as donors and acceptors, take part in the re-combination process, according to their charge and energy values.

The presence of a large number of donors or acceptors on the surface of a semiconductor, can lead to a value or type of superficial conductivity different from that of volume conductivity. An electric charge on the surface, or inside the oxide volume, induces variations in the free charge density.

A positive surface charge will push holes away from the surface and attract electrons. If such an effect becomes large enough, a material that was originally of the p-type can acquire electron surface conductivity (inverted surface). This creates below a region of minimum conductivity followed by normal conductivity (p-type).

If majority carriers accumulate near the surface (accumulation region), the inverse situation occurs.

Radiation will produce positive trapped charges inside the oxide layer, near the oxide-semiconductor interface. This effect is due to low energy radiation, which is unable to produce bulk effects, and is noticeable for doses larger than $10^4 \div 10^5$ rads, this is not dependent on radiation nature but only on the total absorbed dose.

Variations in the oxide charge density will produce variations of the surface potential and, possibly, inversion in p-type semiconductors, and accumulation states in n-type semiconductors.

5. Alterations in the parameters of semiconductor elements

1) Changes in the intrinsic parameters are caused by the creation of new centers of re-combination. These are produced in a semiconductor subjected to radiation, and τ will therefore be decreased according to the following law (3):

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_\tau \phi$$

where:

τ_0 = initial minority carriers lifetime

ϕ = charged particle flux

K_τ = degrading constant of τ ; it dependes on particle nature, on energy and on type of material.

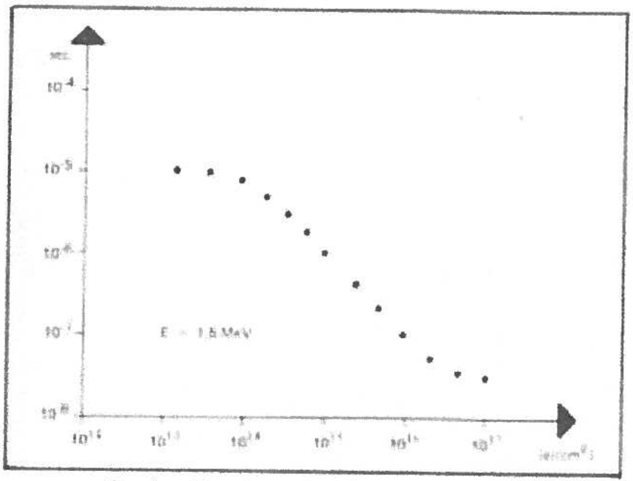

Fig. 1 Minority carrier lifetime degradation
Experimental results

Fig. 1 (8) shows some experimental results on the decrease of τ under bombardament, by 1.5 MeV electrons, on n-type Silicon.

Other effects of radiation are:

- a decrease in lattice mobility, following the law (3)

$$\frac{1}{\mu} = K_\mu N_I$$

N_I being the number of imperfections or of chemical impurities, related to the irradiating flux through (3):

$$N_I = N_{I0} + K'\phi$$

It follows that (3):

$$\frac{1}{\mu} = \frac{1}{\mu_0} + K_\mu \phi$$

- If the energy of the imperfections in the forbidden band, is far from the band boundary, the number of free carriers decreases by the same amount by which the number of created imperfections increases (3)

$$N = N_0 - K_n \phi$$

where:

N = number of free carriers

K_n = degrading constant

ϕ = flux

The three above mentioned kinds of degradation occur, in the electronic device, together with superficial degradation.

Their effect on the electrical characteristics of the device is obviously dependent on the particular device under consideration.

Mobility and diffusion constant are much less degraded than τ, so that no noticeable degradation occurs before the device has already been damaged by degradation of τ. For this reason only the τ degradation effects are considered.

2) The variations, induced in the electrical parameters of bipolar integrated circuits, are now considered.

a) **Transistor parameters** – The main cause of malfunctioning is a variation of transistor gain. The gain can be described in terms of the Webster formula (8):

$$\frac{1}{\beta} = \frac{S A_s W}{A_c D_p} + \frac{W^2}{2 D_p \tau_p} + \frac{W \sigma_b}{L_e \sigma_e}$$

where:

S = surface re-combination velocity

A_s = area of the re-combination surface

W = base thichness

A_c = area of the conduction path

D_p = minority carrier base diffusion constant

τ_p = minority carrier base lifetime

σ_b, σ_e = conductivity of base and emitter regions

L_e = emitter diffusion lenght

The first term describes the effect of that part of the base current that can be attributed to surface re-combination, while the second term accounts for volume re-combination.

The third term gives the emitter efficiency.

At average irradiation doses the main contribution comes from variations of the second term (related to lifetime) (3), and therefore

$$\Delta \frac{1}{\beta} \cong \Delta \frac{1}{2} \frac{W^2}{D_p \tau_p}$$

By taking the law of variation of $1/\tau$ into account, one has (3)

$$\frac{1}{\beta} = \frac{1}{\beta_0} + \frac{1}{2} \frac{W^2 K \phi}{D_p}$$

where W is the base thickness, or else (3)

$$\frac{1}{\beta} = \frac{1}{\beta_0} + 0{,}194 \frac{K \phi}{f_{\alpha co}}$$

where $f_{\alpha co}$ is the transistor cutoff frequency.

From these formulae it can be seen that lower degrading velocities can be obtained by using transistors with high cutoff frequencies (low base thickness).

Fig. 2 shows the behaviour of gain in a transistor irradiated with 1 MeV electrons (3).

Note that, at low values of irradiation, the effect of surface re-combinations can no longer be neglected. A faster degrading of gain will then be observed. Fig. 3 (4) shows the behaviour of d.c. gain as a function of the number of days spent in orbit, at the maximum irradiation altitude, (3300 Km above the equator), for a planar epitaxial n-p-n transistor shielded by a 0.3 g/cm² shield. Three different values of collector polarization current have been studied.

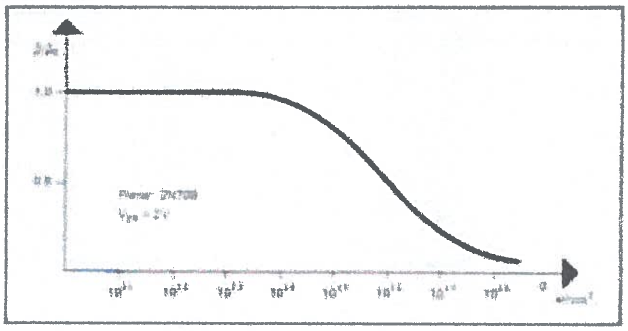

Fig. 2 Transistor gain degradation — Bulk effects

Full curves show degrading due to surface effects only, and dotted lines that due to bulk effects only. Note that surface effects dominate during the first 200 days, while bulk effects dominate thereafter. The effective gain degradation is given by a combination of the two.

Note that emitter-collector saturation current (V_{ces}) and open emitter base-collector leakage current (I_{cbo}) of the transistor, are also degraded. The effect of these variations is however negligible compared with gain degradation. An electronic flux changing V_{ces} by 1 mV, will in fact produce a 15% variation in gain, and the effect of ΔI_{cbo} is also negligible.

b) Inverse diode current — Current I_j, in an n-p junction, is given by (6):

$$I_j = A\left(\frac{e D_p p_{no}}{L_p} + \frac{e D_n n_{po}}{L_n}\right)\left[\exp\left(\frac{e V_j}{KT}\right) - 1\right]$$

e = electron charge

D_p, D_n = hole and electron diffusion constants

L_p, L_n = hole and electron diffusion lengths

p_{no}, n_{po} = hole and electron densities, in n and p regions

V_j = voltage across the junction

K = Boltzmann constant

T = absolute temperature

One of the terms in the first bracket is usually dominant because of the differences in doping and in charge concentration levels at the two sides of the junction.

For negative voltage higher than 0.2 V the reverse current is given by (8):

$$I_j = -A\,\frac{e D_n n_{po}}{L_n}$$

and recalling that $L_n^2 = D_n \tau_n$ (3)

$$I_j = -A\,e\,n_{po}\sqrt{\frac{D_n}{\tau_n}}$$

valid for a heavily doped n-region diode.

If n_{po} does not vary, I_j will be proportional to the inverse of the square root of τ_n.

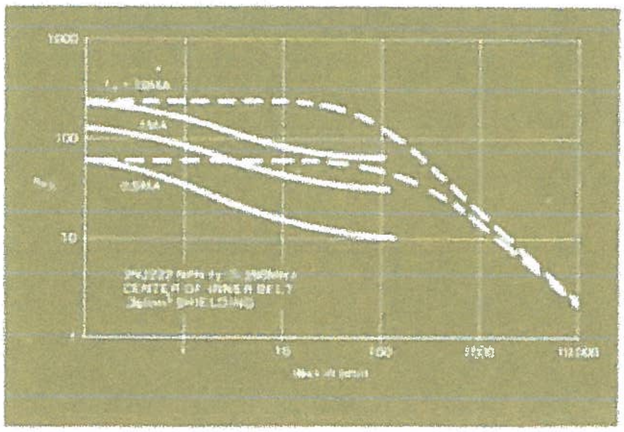

Fig. 3 Transistor gain degradation

c) Direct diode characteristic — The direct diode voltage is related to the logarithm of the inverse of the saturation current. At constant direct current a slow decrease of direct voltage will be observed, when radiation flux increases.

In practice this kind of variation is not very noticeable. It is moreover opposed by the increase in diode series resistance (see fig. 4) brought about by the charge removal process which reduces the free charge concentration.

This variation will, therefore, be negligible.

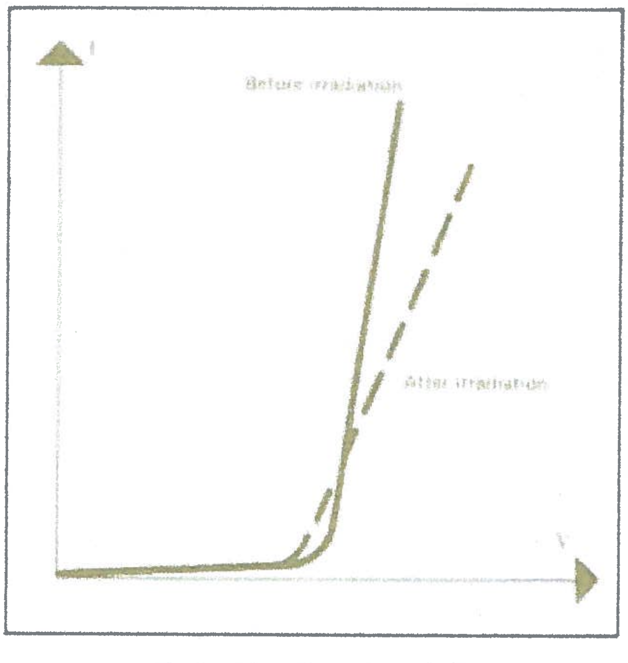

Fig. 4 Direct diode characteristic

d) Junction capacity — By reducing the number of free carriers in the less heavily doped region of the junction, irradiation allows the space charge zone of the region to expand, thereby causing a decrease in capacity. The result appears from the following formula (7)

$$C = \left[\frac{e\,a\,\epsilon^2 A^3}{12\,(v + v_b)}\right]^{1/3}$$

a = concentration gradient = $\frac{dn}{dx}$
A = area of junction
ϵ = permittivity
V_b = junction built-in voltage
V = inverse applied voltage

"a" decreases with flux, causing C to decrease.

e) **Resistance** – Resistivity in a semiconductor is inversely proportional to mobility and to the number of free carriers. Mobility and number of free carriers decrease with irradiation, so that resistance increases.

$$\rho = \frac{1}{\sigma} = \frac{1}{\mu e N}$$

ρ = resistivity
σ = conductivity
μ = majority carrier mobility
e = electron charge
N = concentration of majority carriers

The effect of the integrated electron flux is given by (7)

$$\rho = \frac{1}{\mu e\,(N_0 - K'\phi)}$$

from which, for small values of Δ_ρ (7),

$$\Delta\rho = K'\rho_0^2\,\mu\,e\,\Delta\phi \qquad (K'\phi \ll N_0)$$

where ρ_0 = initial resistivity

The variation of ρ is therefore dependent on the square of ρ_0.

3) The above variations in parameters, cause the following variations to occur in the characteristic parameters of integrated circuits.

- Input threshold voltage:
  this is determined by circuit design and usually increases with radiation because of one of the following effects (7)
  - increase of some resistance
  - increase of direct diode current and of base direct voltage
  - decrease in gain.

- Output voltages:
  these depend critically on the saturation characteristics of the integrated circuit output transistors.
  Following the decrease in gain and the increase in resistance, these voltages increase quite significantly with radiation. This is the main reason for failures (7).

- Rise time:
  in a common emitter configuration working in saturation regime, the current rise time is given by (7)

$$t_r = \tau \ln \frac{1}{1 - 0{,}9\,\dfrac{I_{cs}}{\beta_f I_B}}$$

where
I_B = base drive current
I_{cs} = saturation current $\cong V_{cc}/R_L$

For circuits having $\beta_f I_B \gg I_{cs}$, t_r starts decreasing like the minority carrier lifetime at the beginning of irradiation, while once $\beta_f I_B$ becomes comparable with I_{cs} (due to decreased gain), t_r increases.

- Storage time:
  storage time is given by the following approximate expression (7)

$$t_s = \tau \ln \frac{1}{\dfrac{I_{cs}}{\beta_f I_B}} = \tau \ln \tau \frac{2D}{W^2} \cdot \frac{I_B}{I_{cs}}$$

Its value increases with τ so that it will decrease under irradiation.

- Delay time:
  this depends on the time constant of the circuit preceding the output transistor base, and on the output transistor threshold voltage. It increases slightly with ϕ (7)

- Fall time:
  fall time may increase or decrease with radiation, according to the particular characteristics of the circuits under consideration (7).

4) Tests carried out on a integrated circuit (3) have shown that an integrated flux of a few 10^{15} el/cm² of 1 MeV electrons, did not (besides decreasing the gain of the transistors by about 50%) cause the other parameters to degrade to a point where failures could be expected.

This shows that variations in the integrated circuit parameters due to radiation, can almost exclusively be attributed to gain degradation of the active elements in the circuit, and to the consequent increase of V_{BEon} and V_{SAT}.

Variations of the saturation voltage lie in the range 40 to 90% (7) and causes change of output level.

Input threshold current varies by 3 to 10% (7).

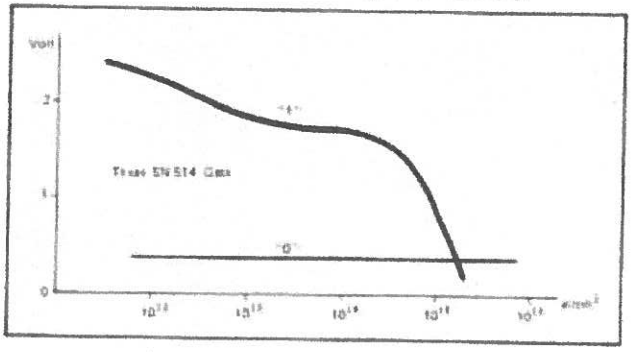

Fig. 5 Noise immunity degradation

Noise immunity is also affected by radiation. As an example, fig. 5 shows the behaviour of noise immunity for a Texas SN 514 logical gate (3).

It can be seen from the figure that for $\phi = n.10^{15}$ el/cm^2, noise immunity for the logical 1 level, corresponding to transistor saturation, has dropped to zero.

Maximum operating frequency of flip-flop circuits is another parameter that is noticeably affected by radiation. As an example, fig. 6 shows the behaviour of this parameter for the Texas SN 511 flip-flop (3).

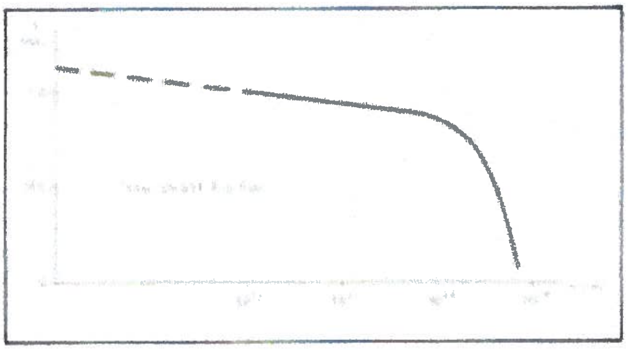

Fig. 6 Maximum working frequency degradation

It can be seen from this figure that for $\phi \cong 10^{13}$ el/cm^2 F_{max} tends to zero.

5) Conclusions on bipolar logical integrated circuits.

The main cause of damage is the variation of transistor gain.

$$\frac{1}{\beta} = \frac{1}{\beta_0} + \frac{1}{2} \frac{W^2 K \phi}{D_n}$$

shows that the variation is proportional to the square of the base thickness, W.

In order to achieve higher radiation resistance it is therefore advisable to use transistor having thin bases (high cutoff frequencies), even where speed is not a problem.

Radiation resistance can be increased by an order of magnitude, leading to tolerable doses of 10^{16} el/cm^2.

The variation of β produces an increase in output transistor saturation voltages. This causes the logic levels to change, since they are obtained through saturated transistors, more precisely, the "0" logical level will increase and the "1" level will decrease. The two changes can occur simultaneously should the outputs be active.

There is no indication, for integrated circuits in common use, that any given configuration, logical function or construction method may be intrinsically better than any other one.

It is however clear that both tansistor construction and circuit design tolerance for gain variations, are of considerable importance for the integrated circuit response to radiation.

Available data shows that any currently used microcircuits operate satisfactorily after having been exposed to fluxes of 1×10^{15} e/cm^2 (E = 3 MeV). Others will withstand a $\phi = 1 \times 10^{16}$ e/cm^2.

These values are obtained under the worst possible conditions, at maximum fan-out, etc. They are therefore conservative results.

For electron energies higher than 1 MeV the main effect is bulk damage. At the low side of the energy spectrum, the main effect is ionization.

If the circuit under consideration is sensitive to surface damage or to leakage currents (like MOS), these lower energies can produce damage at $\phi < 10^{15}$ e/cm^2.

Note that if circuit fan-out is decreased, circuit life becomes longer due to the decrease in the required current.

6. FET and MOS technologies

1) Tests carried out on FET transistors have shown that this technology is more resistant to radiation induced damage (3).

Fig. 7 shows the behaviour, as a function of radiation, of two characteristic FET parameters.

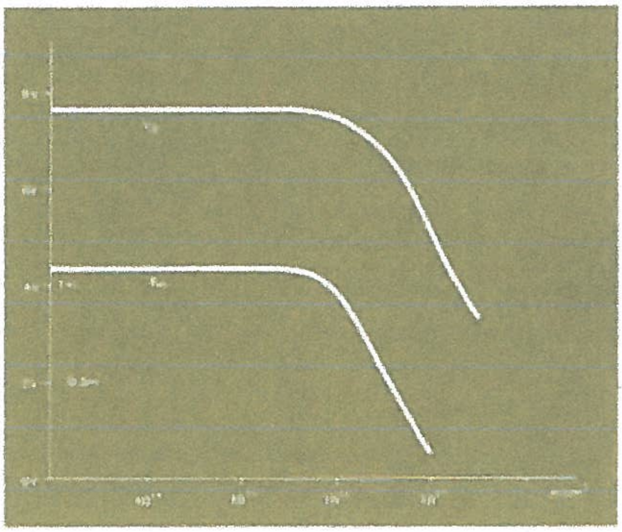

Fig. 7 FET degradation

Fig. 7 shows that damage occurs for fluxes larger than 10^{16} el/cm^2. It is unfortunately difficult to build FET's into integrated circuits.

2) MOS integrated circuits are not subject to bulk damage, like degradation of τ but they are mainly damaged through surface ionization. A 3×10^3 rad/cm^2 irradiation, equivalent to 10^{11} el/cm^2, produces permanent degradation of their characteristics (9).

The main effect of radiation on MOS circuits is change of threshold voltage, which, in turn, causes the transfer characteristic to degrade.

Fig. 8 shows the change in threshold voltage as a function of incident flux.

The curve shown is part of a set of curves that were obtained experimentally on a RCA COS/MOS CD 4007 integrated circuit (inverter). The tests were carried out at the Princeton, New Jersey, RCA laboratories (9).

The curves show that the so called PLASMA AL_2O_3 technology is better than the conventional SiO_2' one. A third technology, called "Deposited AL_2O_3", produces intermediate results.

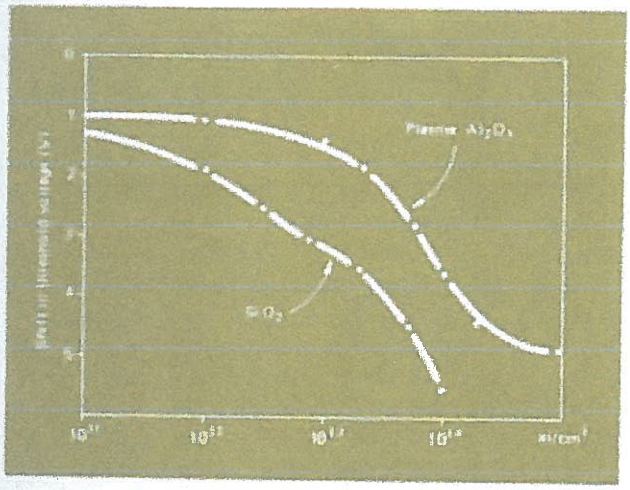

Fig. 8 Shift in threshold voltage for CD 4007 inverter, with input at 10V square wave (50% duty cycle, 10kHz)

7. Conclusions

The data reviewed in this paper leads us to the following conclusions:

a) MOS integrated circuits are suitable for use on those space missions where the orbit is not subject to intense radiation fluxes, or for which flight duration is such that the integrated flux does not exceed the permissible threshold for damage.

b) FETS are suitable as discrete components and as parts of anologic circuity.

c) Bipolar integrated ciruits are the best compromise for satellite electronics. It may also be recalled that some radiation-resistant integrated circuits are now commercially available (e.g. Texas RSN series).

Radiation resistance is mostly obtained through use of dielectric insulation, thin-film resistors and small geometry transistors. All of this is coherent with the results outlined in this paper.

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