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A GENERAL SURVEY OF TRANSIENT-RADIATION EFFECTS ON ELECTRONICS (TREE), WITH PARTICULAR REFERENCE TO SEMICONDUCTOR DEVICES

by

F.A. Johnson

REPORT R 656
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ABSTRACT

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The basic effects produced in semiconductors by both ionizing and displacement radiation are summarized and related to the parameter changes which are observed in semiconductor devices. Ionization and displacement effects produced by transient radiation in diodes, transistors, four-layer devices and integrated circuits are described, and a brief summary is given of the effects of radiation on miscellaneous components such as resistors, capacitors and coaxial cables. Various techniques for radiation hardening of semiconductor devices and circuits are reviewed, and methods for predicting the effects of radiation are discussed briefly.

RÉSUMÉ

Les effets de base produits dans les semiconducteurs par les radiations tant d'ionization que de déplacement sont résumés et reliés aux modifications des paramètres qui sont observés dans les dispositifs à semiconducteurs. Les effets d'ionisation et de déplacement produits par des radiations transitoires dans les diodes, les transistors, les dispositifs à quatres couches et les circuits intégrés sont décrits, et on donne un bref sommaire des effets des radiations sur des composants divers tels que les résistances, les condensateurs et les câbles coaxiaux. Quelques techniques variées pour le renforcement des dispositifs et circuits à semiconducteurs contre les radiations sont revues, et des méthodes pour la prédiction des effets des radiations sont discutées brièvement.

1. INTRODUCTION

It is difficult to distinguish categorically between the effects due to transient and to steady-state radiation in semiconductor devices since both types of radiation can cause long-lived or permanent damage, and a steady-state condition can often be reached, in effect, before the end of a transient radiation pulse. Measurements of changes in device parameters under either radiation condition can often give information applicable to the other condition since the essential effects are the same for a given radiation type, the differences usually being merely of degree or of integration of effects over the time scales involved.

Transient γ-radiation generally has an immediate effect on the charge distribution in a semiconductor device and results in a prompt current or voltage pulse whose decay is usually governed mainly by circuit time constants. Thus the disturbance produced in a circuit may persist very much longer than the radiation pulse itself. On the other hand neutrons are considered to produce permanent damage effects of which, for the case of a transistor, the resulting reduction in gain is the most important manifestation. However, some damage recovery occurs immediately, and the damage effects which are apparent only seconds after the transient has passed are often much less than those observed within microseconds or milliseconds of the end of the pulse. Thus a transient radiation pulse, composed of γ-rays and neutrons, can have short- and long-term effects on semiconductor devices and circuits, and these effects must be taken into consideration in the design of circuits or systems which are expected to continue to operate satisfactorily after exposure to such a transient.

Transient-radiation effects in semiconductor or other electronic devices are mainly of interest in the context of exposure to radiation from a nuclear explosion, where it is essential either that a device function both during <u>and</u> after the intense transient, or that it function at least soon after the transient has passed regardless of whether or not it has been disabled during the transient. Of particular importance are digital computer-type circuits which, while perhaps not expected to operate during a transient, must be able to retain their stored information, and thus the component binary circuits must be prevented from changing state under the influence of the transient.

Steady-state radiation effects are important for devices which must operate near reactors or in satellites in space where the radiation is continuous and where the gradual deterioration of device performance must be allowed for in the circuit design or kept to a minimum. Efforts to harden semiconductor devices against radiation effects often can be more conveniently evaluated initially using steady-state radiation, but the methods and principles evolved will generally be applicable also to the transient case.

2. SUMMARY OF BASIC RADIATION EFFECTS IN SEMICONDUCTORS

The effects of radiation on semiconductor materials or devices can be conveniently subdivided according to the result of the interaction which takes place in the crystalline material, either ionization of atoms in the lattice without disturbance of the lattice order, or displacement of atoms from their normal lattice positions (1). Thus radiation, on the basis of the effect it produces, can be termed ionizing radiation or displacement radiation.

2.1 Ionizing Radiation

Ionizing radiation, such as γ-rays or electrons, generates electron-hole pairs throughout the whole body of a semiconductor, about 4×10^{13} pairs/cm^3 being produced in silicon per rad. Provided that the energy imparted to the electron in such a process is large compared to the energy of the forbidden energy gap, 1.11 eV for the case of silicon, an energy of 3.6 eV is required for the creation of each electron-hole pair (2). In the case of a transistor the subsequent collection of some of these pairs by the emitter and collector junctions results in what is termed a primary photocurrent. Since the electric fields at the two junctions are in such directions as to prevent majority carriers from flowing across the junctions, the majority carriers are confined to the regions in which they are generated. Those electron-hole pairs which are generated in the depletion regions of the junctions are immediately swept out of these regions by the large internal fields, the electrons being directed into the n-type material and the holes into the p-type. This current thus results in a prompt component of the primary photocurrent if the causative radiation is a transient pulse. Electron-hole pairs which are generated in the essentially field-free region of the remaining bulk of the semiconductor diffuse under the influence of their respective concentration gradients, and some of those which are minority carriers in a particular region, and within a diffusion length of a junction, will reach that junction and be swept across. Those minority carriers which are further away than a diffusion length from the junction recombine via defect centers, which have energy states within the forbidden gap (3), before they can reach the junction and so do not contribute to this delayed component of the photocurrent (4). The net result of the two processes is a build-up of majority-carrier charge in the base region of a transistor. From the above description of the origin of the primary photocurrent it follows that the effective volume surrounding a junction, from which electron-hole pairs can be collected, may be written as (5):

$$V = (L_n + L_p + W)A \qquad (1)$$

where L_n = diffusion length of electrons in the p-type material

L_p = diffusion length of holes in the n-type material

W = width of carrier depletion region (junction)

A = effective area of junction

To the extent that the photocurrents are generated in a fixed volume dictated by the geometry of the device and/or the diffusion length of the carriers in the material, such photocurrents are essentially independent of junction voltage. However, in cases where the depletion region about the junction is comparable in volume to the diffusion region then the photocurrents are dependent upon the junction voltages (6).

Ionizing radiation, through the generation of electron-hole pairs, can also increase the conductivity of semiconductor material; this can become significant if the induced excess-carrier concentration is comparable to the existing majority-carrier concentration on which the conductivity depends. The impedance of rectifying junctions is even more susceptible to transient-radiation effects than is bulk conductivity because the properties of such junctions (especially if reverse biased) are determined not so much by the majority-carrier concentration as by the very much smaller minority-carrier concentration which can be changed significantly at very low dose rates (3).

2.2 Displacement Radiation

Displacement radiation, such as fast neutrons (> 10 keV), or high-energy γ-rays and electrons, produces defects of various types in the semiconductor crystal structure so that the disorder in the lattice is increased (7). Simple point defects are produced when the energy of the incident radiation is sufficient to knock a silicon atom out of its normal position in the crystal lattice into an interstitial position, leaving a vacancy in its former position in the lattice. The displacement of a silicon atom from its lattice site, resulting in the creation of such a vacancy-interstitial, or Frenkel, pair, requires an energy expenditure of about 15 eV (2), which implies that neutrons of about 200 eV or electrons of 250 keV are required (8). The vacancy which is produced is generally thermally unstable at room temperature and can move through the lattice, in much the same manner as does a hole, until it is trapped and immobilized by an oxygen impurity, a donor atom, or another vacancy, to form a stable defect. Such defects introduce additional states into the forbidden energy gap of the semiconductor material and can act as:

i) recombination centers for electrons and holes, resulting in a reduction in the minority-carrier lifetime.

ii) trapping centers which remove majority carriers from the conduction process and thereby increase the resistivity of the material.

iii) additional scattering centers which decrease the mobility of the carriers.

The reduction of minority-carrier lifetime is the most important effect so far as transistors are concerned, since it results in a reduction of the gain (h_{fe} or β), a lower high-frequency limit, and is reflected in increased leakage current (9). As a result of the resistivity increase caused by the introduction of additional trapping centers both n- and p-type silicon tend toward more intrinsic behaviour, indicating that donor and acceptor levels are both introduced simultaneously and resulting in a net increase of acceptors in n-type and of donors in p-type (10,11).

In silicon a majority of the defects which are formed by 1-MeV electrons or Co^{60} γ-rays are relatively simple point defects (12). More complex displacement defects can be produced by particles which have sufficient energy to impart, in a single collison, significant energy to the primary recoiling atom so that it is capable of displacing and ionizing many additional atoms in the lattice. Thus, in particular, neutrons tend to produce defect clusters which are the result of a cascade of displacements whose damage to the crystal lattice is concentrated in a small region. Neutrons are especially effective in producing defect clusters since their interactions with the atoms of the lattice are of the hard-sphere type (elastic scattering) with a high energy transfer; even a 1-MeV neutron deposits sufficient energy to create several hundred displacements within a region about 500Å in diameter (12). For charged particles, which interact through the Coulomb force, higher energies are required for cluster formation, such as ~ 12 MeV for deuterons and 15-45 MeV for electrons (13). Such defect clusters cause similar degradation in transistor parameters and performance as do the simple defects, but, since the defect density within a cluster can be much higher than the density of the normal dopant atoms in the crystal, the defects in the cluster may behave significantly differently than do simple defects. There is evidence that these disordered regions are less effective in reducing lifetime than some of the simpler forms of damage produced at lower energies, and this could be related to the possibility that the thermally stable divacancy (formed when two adjacent silicon atoms are knocked out of their lattice positions) may be the active recombination center within the defect cluster (12).

A phenomenon which is of bulk origin and unique to neutron damage, and so related to the damage clusters, is the transient annealing which occurs in neutron-irradiated silicon near room temperature (14). Depending on the radiation pulse width, shape and flux, the peak damage level "fast anneals" to a lower degradation level in less than a second, at which point the remaining damage is relatively stable unless further annealed at a high temperature (15). Another property of neutron-irradiated silicon, also attributed to the effect of defect clusters, is that the carrier-removal rate is essentially independent of impurity concentration in both n- and p-type (14), with the result that the rate of degradation of lifetime due to neutron bombardment is nearly the same for both types (16). This is in contrast to the effects of the point defects produced by electron damage where the minority-carrier capture cross-section of the recombination centers is about 400 times greater for n-type silicon than for p-type (for 700-keV electrons) (17). This difference is attributed to the fact that the energy levels responsible for neutron-induced degradation are near the center of the forbidden energy gap, whereas those which dominate recombination in electron-bombarded specimens are more shallow states nearer the gap boundaries (16).

Lattice displacement damage, such as described above, can change the electrical properties of semiconductors at extremely low densities of damage sites and therefore at relatively low levels of integrated flux. The electrical characteristic most sensitive to radiation damage is the minority-carrier lifetime (8), and thus minority-carrier devices such as bipolar transistors and associated monolithic integrated circuits are amongst the most sensitive devices to displacement effects at normal operating temperatures (18). Other bulk effects, due to displacement damage, which have been observed in bipolar transistors are changes in:

i) junction depletion capacitance

ii) junction breakdown voltage

iii) saturation voltage

iv) punch-through voltage

v) base-spreading resistance

vi) collector body resistance

vii) junction leakage currents

viii) switching times

As well as displacement damage fast neutrons can indirectly produce ionization by (n, p) and (n, α) reactions with the silicon and other atoms in the semiconductor crystal. As the neutron energy increases significant ionization effects are also produced since the displacement recoils receive sufficient energy to become ionized, and 14-MeV neutrons are especially effective in this regard (5).

The reduction in minority-carrier lifetime as a result of radiation-induced displacement damage can be measured in many ways, either directly on bulk samples or indirectly by measurements of changes in various semiconductor device characteristics such as current gain, diode forward voltage or leakage currents. Under the assumption that the lattice damage is proportional to the integrated flux and thus also to the density of the resulting recombination centers, and since the lifetime is inversely proportional to the density of recombination centers, the dependence of lifetime τ on fluence or integrated flux Φ (particles/cm^2) can be written:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_\tau \Phi \quad \text{(also sometimes written } \frac{\Phi}{K_\tau}\text{, with inverse units for } K_\tau\text{)} \qquad (\underline{2})$$

where τ_0 = initial minority-carrier lifetime, seconds.

K_τ = energy-dependent lifetime damage constant, cm^2/particles-sec.

The reduction in carrier lifetime is a manifestation of the fact that the recombination centers impede the diffusion of the minority carriers, and thus the amount of radiation damage can also be expressed in terms of a diffusion-length (L) damage constant K_L where the damage is measured as an increase in $1/L^2$:

$$\frac{1}{L^2} = \frac{1}{L_0{}^2} + K_L \Phi \qquad (\underline{3})$$

where L_0 = initial minority-carrier diffusion length.

This form of representation is convenient for the characterization of damage to solar cells since K_L has a more direct relationship to the mechanism of device failure (19).

Since τ and L are related as:

$$L = \sqrt{D\tau} \qquad (\underline{4})$$

where D = minority-carrier diffusion constant, it follows that

$$K_\tau = D K_L \qquad (\underline{5})$$

Of particular importance to semiconductor device characteristics is the dependence of the common-emitter forward current gain, h_{fe} or β, on lifetime.

$$\beta = \frac{2D}{W^2}\tau \quad \left(= \frac{2L^2}{W^2} \text{ in terms of the diffusion length}\right) \qquad (\underline{6})$$

where W = effective base width, and the factor $\frac{2D}{W^2}$ is the reciprocal of the average transit time $\bar{t}$ of minority carriers in the base region of a transistor for the case of a uniform base; for a linear graded base the factor is $\frac{4D}{W^2}$ (21). The transit time $\bar{t}$, which is generally unaffected by any radiation damage, can also be related to the current gain-bandwidth product f_T (defined as that frequency at which the common-emitter current gain becomes unity, also called the alpha cut-off frequency) through the approximation:

$$f_T \approx \frac{1}{2\pi \bar{t}} \quad \text{or} \quad \bar{t} \approx \frac{1}{2\pi f_T} = \frac{1}{\omega_T} \qquad (\underline{7})$$

Thus from the dependence of lifetime on fluence given by equation ($\underline{2}$) above, the degradation of β can be expressed as:

$$\frac{1}{\beta} = \frac{1}{\beta_0} + \bar{t} K_\tau \Phi = \frac{1}{\beta_0} + \frac{1}{\omega_T} K_\tau \Phi \qquad (\underline{8})$$

neglecting emitter efficiency and surface effects. Alternatively, the measurement of such a parameter change may be used, under certain conditions, to provide a measure of the neutron exposure (22). Sometimes an empirical damage factor K is used instead of K_τ to indicate that recombination in the base region is not the only damage mechanism contributing to the degradation of β (recombination in the emitter-junction transition layer can also be important (23)). K_τ(or K) is a most sensitive measure of the amount of displacement damage, but since τ depends on the resistivity of the semiconductor material, the injection level of minority carriers, temperature, and the integrated radiation level, a unique value for K_τ can be expected only if the resistivity, impurity content, and injection level of the semiconductor is specified, as well as the energy spectrum of the incident radiation (8).

3. TRANSIENT-RADIATION EFFECTS IN SEMICONDUCTOR DEVICES

An examination of the transient effects of radiation in various semiconductor devices such as diodes, bipolar transistors, field-effect transistors, and integrated circuits (in increasing order of complexity) will naturally reveal many similarities in behaviour since all such devices are fabricated from variously doped versions of the same material, silicon (the study will be restricted mainly to silicon devices), and most possess the common feature of the presence of one or more p-n junctions necessary for their operation. Thus, for example, damage mechanisms which produce effects which are easily observable in transistors by virtue of the very sensitive dependence of gain on radiation-induced damage can also be assumed, or shown by other techniques, to occur in diodes. Even though manifestations of the damage might not be so obvious in this case, there could be implications involved which are pertinent to hardening or to selection of appropriate diode devices suitable for a radiation environment. Much work has also been done on radiation damage to, and ionization effects in, bulk semiconductor material using techniques such as the Hall Effect, photoconductivity, infrared spectroscopy, electron spin resonance, etc. (24), and the results often have direct application to device technology and the understanding of the effects of radiation, either transient or steady state.

Thus while radiation effects in the various different types of semiconductor devices will have a fundamental similarity, as pointed out above, differences might be expected with increasing complexity in device function and method of fabrication. For this reason the following discussion of transient-radiation effects in semiconductor devices has been sub-divided according to basic device type, so that as the complexity of the device increases the radiation effects can be related, in part, to simpler structures discussed earlier. However, some effects which are inferred to occur in simpler devices may be more appropriately discussed in the context of more complex device behaviour since, because of its importance or ease of measurement, a particular effect may have been more extensively investigated in the complex device, and the understanding and theoretical analysis may have been emphasized from this viewpoint. Reference will also be made to effects observed under steady-state radiation conditions or in bulk semiconductor material if appropriate in relation to the case of transient radiation. Immediate implications of various transient or steady-state effects to device hardening will be pointed out as they arise, but more general methods of hardening will be discussed in a separate section.

3.1 Diodes

3.1.1 Ionization Effects in Diodes

For a reverse-biased p-n junction diode even a rather weak pulse of ionizing radiation will cause a considerable immediate increase in the reverse leakage current due to the generation of electron-hole pairs throughout the body of the diode and the subsequent drift and diffusion of these carriers (25). This radiation-induced photocurrent is due to two processes (as briefly summarized earlier):

i) Carriers of either type which are created in the depletion region are quickly swept out of this region by the internal electric field to produce a current pulse of about the same shape as the radiation pulse. This is the prompt or drift component.

ii) Minority carriers generated in the bulk regions away from the junction diffuse to the depletion region and are swept across to produce a current pulse which will usually persist long after the radiation pulse has ceased. This is the delayed or diffusion component. The amplitude and rate of decay of this component both increase with reverse voltage on the diode.

For a forward-biased diode the generation of carriers in the bulk region decreases the carrier gradient at the junction and produces a transient decrease in the forward conduction current (4).

Tunnel diodes exhibit a relatively small photo-response to ionizing radiation because of their small junction dimensions and high doping levels, the latter characteristic having the effect of adding recombination centers in the depletion region which aid in the removal of the radiation-generated electron-hole pairs. Resistance to radiation-induced switching is important for tunnel diodes, and it has been found that high current (2 and 5 mA) silicon devices are about an order of magnitude more tolerant to pulses of ionizing radiation than are lower current types. For instance, silicon 4.8-mA tunnel diodes, biased at 74% of peak current and exposed to 20-ns pulses of 2-MeV electrons, did not switch at exposure rates of 1.1 x 10^9 R/s (44R) (26).

In the case of PIN diodes the transit time in the intrinsic region is relatively short compared to the carrier lifetime usually found in uncompensated high-resistivity material, and thus recombination in this region does not play a major role. For an intense radiation pulse, however, the drift of generated carriers in the intrinsic region causes a change in the internal field distribution. This impedes the drift of the carriers and has the effect of producing a substantial and slowly decaying tail on the photocurrent waveform which persists long after the ionizing pulse has terminated, and whose amplitude, relative to the peak response in the first few nanoseconds after the pulse, increases with increasing dose rate. The collection efficiency, as outlined above,is expected to be significantly reduced at relatively low radiation levels, $\sim$ 6 rad(Si), or at energy deposition rates of $\sim 10^9$ rad(Si)/s, where the device will have limitations as a radiation detector under conditions requiring nanosecond resolution (27).

The transient-ionizing-radiation response of diodes operating in avalanche breakdown is especially important because of the widespread use of such devices as oscillators or as voltage-regulating elements. For a typical Zener diode which is biased near but below breakdown, the transient photocurrent response increases with bias voltage because of the avalanche multiplication of the primary photocurrent by the high fields at the junction. More heavily doped diodes, which are especially tolerant of neutron-induced degradation (see Sec. 3.1.2 below), should also exhibit a smaller photocurrent because of the smaller width of the depletion region and the reduced minority-carrier lifetime which are characteristic of such devices; however, because of the avalanche multiplication of photocurrent described above, the expected reduction in photocurrent may not be observed if such diodes must be operated at voltages near breakdown. For the case of diodes which are biased above their avalanche-breakdown voltage, the transient photoresponse falls as the (reverse) bias current is increased, a result of the fact that the impedance of the diode junction also decreases. Thus, for minimum transient disturbance, a Zener diode should be operated at a high current and with a low resistance presented to its terminals and, for equal bias currents, a lower breakdown-voltage diode exhibits a smaller transient than does a higher voltage type (28).

3.1.2 Displacement Effects in Diodes

Diodes are also sensitive to displacement radiation and show effects attributable to radiation-induced damage, as described above. The dominant effect is usually an increase in the forward voltage drop caused by an increase in the effective series resistance of the diode due to removal of majority carriers from the conduction process in the base material. The degradation of minority-carrier lifetime, on the other hand, causes the diode saturation current to increase and thus tends to decrease the diode forward voltage (20). Devices with high base conductivity should be relatively tolerant to radiation since a high conductivity implies a large impurity concentration in the base material which tends to decrease the relative effect of any defects which are introduced (29). High doping levels are also responsible for the radiation resistance of germanium tunnel diodes, especially n-on-p types (p-base), to integrated neutron fluxes of 1.5×10^{16} n/cm^2 (31). In general, tunnel diodes, being majority-carrier devices, are less sensitive to radiation than are most semiconductor devices.

The decrease in minority-carrier lifetime which is produced by displacement radiation actually tends to improve the performance of switching diodes. Thus, since the switching and storage times depend directly on the minority-carrier lifetime, the speed of operation of such diodes is enhanced (31). Similarly diodes, such as the 1N696 and 1N697, which have gold-doped bases, and hence a short minority-carrier lifetime in their base regions, do not exhibit appreciable degradation of their forward voltage characteristics up to 10^{14} n/cm^2 (29).

The electrical characteristics of PIN diodes are highly dependent on the lifetime of the excess charge carriers in the intrinsic region and thus are extremely sensitive to any change in this lifetime caused by neutron damage, a property which makes such diodes suitable as dosimeters (32). However, with judicious design, it is possible to achieve greater radiation tolerance from a PIN-type junction than from an equivalent p-n junction (33).

Majority-carrier depletion-layer devices such as varactor diodes and avalanche (IMPATT or TRAPATT) diodes are generally considered to be relatively insensitive to radiation damage because they do not depend on the minority-carrier lifetime. However, in the junction depletion regions of these devices trapping effects, and the associated time constants, can influence their radiation vulnerability through a transient time-dependence of the depletion-layer width which is produced. Following a neutron pulse, traps which are not in an equilibrium charge state exist with a concentration an order of magnitude larger than for the equilibrium case, and these states lose their excess charge very slowly. However, injection of minority carriers speeds up this recovery substantially (34). The RF output of avalanche diodes degrades because of the recombination in the space-charge region of carriers in transit, and hence a device with a narrower space-charge region will be more radiation (neutron) resistant. These diodes also exhibit an increase in breakdown voltage due to carrier removal at the edges of the space-charge region, and a device with heavy doping and an abrupt doping profile will be more resistant to such carrier removal than will a diffuse-junction device (35).

3.2 Transistors

3.2.1 Ionization Effects in Transistors

The most important effect of transient ionizing radiation on transistors is the production of a primary photocurrent, with prompt and delayed components, as already outlined for the case of p-n junction diodes. It was also pointed out earlier that the net result of the processes contributing to this primary photocurrent in a transistor was a build-up of majority-carrier charge in the base region. The response of transistors to this internal flow of charge is much the same as the response to majority current flowing into the base from the external base lead of the device under normal operating conditions, that is, amplification of this current occurs through transistor action to produce a secondary photocurrent in the collector circuit (36). If the transistor is biased off, then there will be no secondary photocurrent produced unless the primary photocurrent is large enough to generate a sufficient voltage drop across the base resistance to forward-bias the base-emitter junction (2). A more detailed examination of the process indicates that a prompt dose of 0.5 rad can be expected to produce a collector photocurrent many times larger than the quiescent current, and substantial electric fields may be produced in the bulk collector region, especially if this is of high resistivity. These fields aid the drift of the minority carriers to the junction where they contribute to the primary photocurrent and thus to the majority current in the base, resulting in a further increase in collector current. Thus the coupling between the primary and secondary photocurrents is regenerative and results in an unstable build-up of collector current. This build-up is ultimately quenched by recombination or depletion in the base region of the excess minority carriers from the collector (majority carriers in the base) because of the massive concurrent injection of opposite carriers from the emitter (2,27). At a high dose, 5 rads, the photocurrents are very large and a device can be driven into saturation. In this case the ionization may also produce sufficient carriers to increase the conductivity of the collector region, with the result that the saturation secondary-photocurrent collector waveform may show an initial peak due to this conductivity modulation of the collector.

The photocurrents produced by transient-ionization effects in transistors must be analyzed differently depending on the relation of the radiation pulse width to the minority-carrier lifetime and on whether or not the transistor is driven into saturation (2,37,38,39):

i) Pulse width long compared to the minority-carrier lifetime.

   In this case virtually all the minority carriers that exist within a diffusion length of the base contribute to the photocurrent, which approximates the value which would be obtained under steady-state radiation conditions.

ii) Pulse width short compared to the minority-carrier lifetime in the collector.

   a) If the number of carriers generated is large then the transistor can be driven into saturation (collector forward-biased) and will be held there, after the radiation pulse has terminated, by the minority charge stored in the collector-base diode. This charge is usually considered to be stored in the base region for alloy transistors, but for mesa and planar types the storage is mainly in the bulk material of the rather high resistivity collector. Thus, in the latter case, the transistor will remain in saturation until the excess minority-carrier concentration in the collector is reduced to a value below that required to maintain saturation, this time depending on the effective minority-carrier lifetime. Measured radiation storage times, for both epitaxial and non-epitaxial transistors, are found to correlate well with electrical storage times.

b) When the transistor is not driven into saturation the calculation of the resulting photocurrents is very complex and computer solutions are generally required. Because the pulse is short compared to the minority-carrier lifetime a significant number of these carriers do not have time to diffuse to the junction and to contribute to the current before the generation of carriers ceases and the photocurrents start to decay. Difficulty arises in describing the currents as functions of time since the radiation, primary photocurrents, voltages, junction capacitances etc. are all changing during the pulse.

The method of fabrication and the doping levels of a transistor have an important bearing on the relative contributions of the various regions to the primary photocurrent. For instance, early alloy transistors were characterized by relatively wide low-doped base regions, whereas more modern transistors are produced with wide low-doped collector regions and thin bases (2), with the result that most of the primary photocurrent in alloy-junction transistors originates in the base and associated depletion regions, while for non-epitaxial planar and mesa types the major part of the photocurrent originates in the collector (39). Also, for alloy transistors, the minority-carrier lifetimes in both the collector and emitter are very short and hence a negligible number of carriers diffuse into the base (4). For most other transistors the contribution of the emitter-base junction primary photocurrent can usually be neglected in comparison to that of the collector-base junction because the latter junction is generally larger than the emitter junction. In addition the diffusion length, and hence the lifetime, of minority carriers is shorter in the emitter than in the collector for most planar and mesa transistors (40). From the above discussion it is apparent that the primary photocurrent has a strong dependence on the minority-carrier lifetime near the junctions, and advantage can be taken of this in the selection or manufacture of radiation-resistant transistors. Thus gold doping of either the emitter or collector regions can reduce lifetime by up to two orders of magnitude and photocurrents by one order (41,42).

It is generally assumed that the primary photocurrent which is produced by a transient pulse of radiation scales linearly with dose or dose rate. However, many silicon devices exhibit an anomolous photocurrent at relatively modest dose rates (10^9 rad/s). In such cases, due to the geometry of the devices, the photocurrent in the active base region flows in a transverse direction and produces a transverse voltage drop along the base-emitter junction which can cause breakdown at the periphery of this junction. The base and emitter are then connected by a low-impedance path and the device assumes a common-emitter configuration wherein the primary photocurrent is amplified by the device gain. Any non-epitaxial device with a narrow base width and a relatively large collector breakdown voltage is suspect. If such devices are operated in a circuit which can exhibit a small base-to-collector impedance, then this effect must be considered in the determination of the transient response. Of particular significance is the fact that hardened circuits which employ compensation devices in the base circuit are frequently sensitive to this effect since, during irradiation, the compensation element can provide the necessary low-impedance path (43).

A serious problem, especially for power transistors, is the destructive breakdown of a transistor due to excessive heating at a localized spot in its interior. This phenomenom is termed second breakdown, and usually results in a collector-emitter short which may or may not destroy the transistor (2,44,45). Since second breakdown is thermal in origin, a finite time is required to raise the temperature of the small region in the transistor where breakdown takes place, resulting in a characteristic time lag between cause and effect. The thermal mechanism is regenerative and can be initiated by a concentration of current in a restricted region of the base. A pulse of ionizing radiation can induce the necessary additional current which may then be concentrated in a restricted region by current crowding or an irregularity in the transistor. Second breakdown has been induced in the type 2N914 transistor by a 200-ns-wide electron pulse from a 10-MeV linac, and, with serious implications for hardening attempts, it was found that at 1 or 2 x 10^{10} rad(Si)/s the threshold voltage for breakdown was below the rated (BV_{CEO}) breakdown voltage of the transistor.

Ionizing radiation can also induce surface effects in planar bipolar transistors which manifest themselves in essentially permanent damage such as increased leakage current and decrease in gain. The reduction in gain is caused by the introduction of extra base-current components which appear to shunt the base-emitter junction (46), and each component can be related to a particular degradation mechanism at the surface. The fact that the changes are caused by surface rather than bulk damage effects is clearly indicated by the small total ionizing dose required for onset of the damage under various conditions (47). The behaviour of the collector leakage current I_{CBO} provides a particularly sensitive indication of surface stability and is a useful parameter for the investigation of such surface effects.

In the case of oxide-passivated silicon planar transistors surface damage occurs because gamma radiation introduces fast interface states (states which can exchange charge rapidly with the bulk silicon) at the intersection of the emitter-base space-charge region with the SiO_2 passivating layer. These states, which represent permanent damage, act as recombination centers for minority carriers and increase the surface recombination velocity, resulting in an increase in the surface recombination base current and degradation of the surface minority-carrier lifetime and of current gain, and affecting the reverse leakage current I_{CBO} (46,48). It has been found that the type of packaging (metal can or plastic envelope) of the transistor has a strong influence on the degradation in current gain if the p-n junctions are reverse biased during irradiation (49). In addition this surface damage factor is smaller for transistors irradiated with no collector-base reverse bias than for those irradiated with bias, and the apparent degradation in gain observed after the irradiation depends strongly on the magnitude of the collector current subsequently employed (50).

The resistance of planar transistors to ionizing radiation can be improved in a number of ways. Thus irradiation of the oxide layer and interface region of a transistor with a high dose (10^{10} rad) of ionizing radiation (∿ 25-keV electrons), under conditions where the damage anneals out immediately, can result in an order of magnitude reduction in the degradation of current gain observed for a subsequent radiation exposure (49). Another method employs SiON passivation of the surface instead of SiO_2 , and in this case there appears to be no generation of new interface states at doses up to several megarads. However, the bias-temperature stability of the SiON structures is not as good as for pure SiO_2 under conditions of negative bias, but could be acceptable for devices whose primary function is to be radiation hard near room temperature (41).

Another related permanent effect produced in planar bipolar transistors is the introduction of a positive space-charge within the SiO_2 passivating layer. This can result in surface channel formation if the space charge is of sufficient magnitude to cause inversion of the silicon under the interface, and this form of degradation is usually dominant at the collector-base junction because, for the particular example of an NPN transistor, the surface of the p-type base is less heavily doped in this region than in the vicinity of the emitter-base junction. When the p-type base of such an NPN transistor is inverted near the p-n junction a channel is formed that appears as an extension of the n-side of the junction over the surface of the p-side directly under the oxide layer. Thus the junction area is increased, resulting in an increase in junction capacitance, and a surface channel component of base current is introduced (the magnitude depending to a large degree on the quality of the semiconductor surface at the interface) which contributes to degradation of current gain and to increased reverse leakage current (46,48). At large doses the channel tends to recede due to decrease of the positive space-charge caused by radiation-induced photoemission of electrons from the silicon across the interface into the oxide. SiON, instead of SiO_2, passivation results in an almost complete absence of space-charge build-up (41), but the stability problems referred to previously constitute a drawback.

The surface effects which have just been described are not always equally in evidence. Thus it has been observed (51) that some PNP transistors can be damaged more if passive during irradiation than if under bias, whereas for some NPN transistors the reverse is true. In the former case the effect is attributed to radiation-induced surface states, whereas in the latter positive charge accumulation in the oxide layer appears to exert the major influence.

The two surface-effect base current components discussed above affect the current gain principally at low currents. At high injection levels, where emitter crowding can occur, a third effect, base surface recombination, also contributes to degradation of current gain (46).

Field-effect transistors (as exemplified by IGFET, insulated-gate; MISFET, metal-insulator-semiconductor; MOSFET, metal-oxide-semiconductor) were originally expected to be less susceptible than junction transistors to transient-radiation effects because they are majority-carrier devices, and do not depend directly on the properties of a p-n junction for their operation. However, due to the physical structure, resulting from the fact that the device is grown on a silicon substrate, p-n junctions do exist between various parts of the device and the substrate. Thus photocurrents can be induced across the source-substrate and drain-substrate isolation junctions by a pulse of ionizing radiation. In general the minority-carrier lifetimes and the areas associated with these junctions are both small, and the resulting photocurrents are comparable to those observed in high-speed switching diodes (52), the predominant transient-induced response occurring in the drain circuit (53). Significant improvements can be effected if the device is fabricated on a sapphire instead of on a silicon substrate to produce, for instance, a thin-film MOSFET (or SOS, silicon-on-sapphire, device); in this case the channel, in the form of a thin film of epitaxial silicon, is deposited directly on the sapphire and the resulting device contains no p-n junctions. The main effect of an ionizing-radiation pulse on such a device is a transient increase in channel current due to the photocurrent generated in the channel, although charge scattering and electron emission from the gate electrode and gate leads contribute to the total radiation-induced current (54).

Junction field-effect transistors (JFET) on the other hand, are relatively insensitive to the permanent effects of ionizing radiation (55). There is no change in the characteristics for doses up to 10^9 rads other than a relatively minor increase in the gate leakage (reverse) current. This excess current is caused by an increase in the density of fast surface states, which lead to excess surface generation currents. The major transient-radiation effects on JFETs are an increase in the channel conductivity, due to radiation-induced excess carriers, and the production of diode (such as drain to gate) photocurrents and secondary photocurrents (56). A JFET generates less output photocurrent and less secondary photocurrent per unit area than does a bipolar transistor but, for the same operating current, the JFET requires a larger area, and thus for a given device application the transient response of the two is roughly the same (57). Heavy channel doping of a JFET tends to reduce the transient currents provided that the operating voltage of the device and the radiation rate are below the values where the photocurrent starts to rise rapidly with voltage. Additional gold doping of the device, to reduce or "kill" minority-carrier lifetime, can significantly reduce the transient photocurrents at all voltages. A detailed model of the transient effects on JFETs is not yet available.

MOSFETs are usually fabricated with an oxide insulating layer (the gate or channel oxide) over the surface of the device, and ionizing radiation also causes a positive space-charge build-up in this layer in a manner similar to that described previously for bipolar transistors. This build-up of charge, which is relatively permanent at or below room temperature, causes MOSFETs to be especially sensitive to ionizing radiation. For this reason, this effect has been studied extensively in relation to MOS structures and can be accounted for by the different behaviour of electrons and holes subsequent to their generation in the oxide by the incident radiation. Since the mobility of the holes is very much less than that of the electrons, the holes are trapped or recombine with electrons before they can leave the oxide, whereas the electrons can easily drift toward the positive electrode and be swept away. Due to a significant potential barrier at the Si-SiO_2 interface the silicon is unable to supply electrons to the oxide to compensate for those swept away, and a positive space-charge build-up occurs near the interface (58), although some short-term annealing of the radiation-induced space charge does occur (59). Since the build-up of charge is attributed to the trapping of holes in the insulator, it can be expected to be sensitive to the defect structure of the oxide which, in turn, is a function of the conditions under which the oxide is fabricated. Thus MOS devices which are coated with thermally (steam) grown oxides can be made considerably less sensitive to radiation than those in which the usual dry-oxygen growth process is used, although the latter types can be made more radiation resistant by the addition of a coating of phosphosilicate glass (60). The effect of even moderate doses of ionizing radiation on MOS devices is a change in threshold voltage V_T (gate voltage required for conduction) and a lateral shift of the capacitance-voltage (C-V_G) characteristic, or of the $I_D - V_G$ forward transfer characteristic, along the voltage axis in the negative direction, attributed to the effects of the oxide charge, while a similar shift of the characteristic coupled with a change in shape is attributed to the additional effects of the introduction of new bias-dependent interface states. It has been found that the better the pre-irradiation C-V_G characteristic of the device (i.e. the nearer to ideal) the less sensitive is the device to radiation, an ideal characteristic indicating a high degree of order at the interface and a low initial value of oxide charge (60). Other MOS transistor parameters show very little change at dose levels as high as 2×10^7 rad(Si) (61).

A number of attempts have been made to improve the radiation hardness of MOSFETs by modifying the SiO_2 insulating layer or using different dielectric materials. Thus a considerable degree of control over the damage due to ionizing radiation can be obtained by doping the gate oxide with chromium. In this case smaller gate threshold shifts are produced when the device is irradiated with zero or negative gate bias and the increase in interface states is smaller, with no adverse effects on device stability or electrical characteristics (62). Implantation of nitrogen ions into the SiO_2 layer can also reduce the build-up of space charge by radiation but has little effect on the number of interface states created (63). Replacement of the silicon-oxide insulation with silicon nitride, Si_3N_4 (MNS device), results in a greatly reduced shift in gate turn-on voltage because of reduced space-charge build-up, and source-drain leakage currents in the off-state are practically eliminated (64); high temperature heat treatment can reduce the thermal instability of the device and at the same time further increase the radiation resistance (65). Surface films of SiO_2 covered with silicon nitride (MNOS devices) are also effective in reducing the radiation-induced space charge (66), and it has been suggested that, in addition, for this type of film, chromium doping of the oxide would also reduce the build-up of interface states (67). Silicon oxynitride films, with composition near Si_2ON_2, have also been used instead of SiO_2, and these are nearly insensitive to space-charge build-up for doses up to ∿ 10 megarads for dose rates of at least 10^{10} rad/s. In this case the development proceeded on the premise that a dielectric film in the form of a solid solution produced by combining two materials, one of which preferentially traps electrons and the other holes, would show a composition range in which the radiation-induced space-charge build-up is minimized (68). Devices in which plasma-grown Al_2O_3 is used as the channel insulator show an increase of more than an order of magnitude in radiation hardness over units with SiO_2 channel oxide. This increased hardness is similarly attributed, in part, to the presence of negative trapping centers to balance the charge trapped in positive trapping centers, resulting in a small net trapped charge (69).

On the basis of the development of new techniques for forming gate insulators there is optimism that future generations of MOS devices may have a lower radiation sensitivity which will be better characterized and controlled than at present (61).

3.2.2 Displacement Effects in Transistors

The most important effect of displacement radiation (neutrons) on a transistor is the reduction of the minority-carrier lifetime in the base region through the introduction of additional recombination centers and the consequent reduction in the forward current gain, as expressed by equations (2) and (8) given earlier (Sec. 2.2). Thus, qualitatively, it can be expected that a device having a thin base, such as a VHF transistor (hence small transit time, equation (8)), high cut-off frequency (inversely proportional to transit time, equation (8)), small junction area (hence small intercepted fluence Φ), and low initial minority-carrier lifetime in the base (equation (2)) such as would be the case for a gold-doped device, will be more resistant to neutron displacement damage (18).

A more detailed examination of the reduction of transistor current gain by fast-neutron bombardment indicates that two simultaneous displacement-damage mechanisms are operative (70, 71, 72). At moderate and high current injection (i.e. emitter current) levels neutron-induced recombination current in the neutral bulk-base region usually dominates the degradation of current gain, whereas at low and intermediate injection levels the neutron-induced recombination current in the emitter-base space-charge region contributes to the degradation of gain through reduction of the emitter efficiency. These differences are attributed to the fact that the neutron-induced defect clusters behave differently in the high-field emitter-base space-charge region than in the low-field neutral bulk-base region (73). The contribution of space-charge region recombination is probably dominant in modern narrow-base transistors even at high injection levels (74). In order to minimize this recombination component the transistor design should employ the highest possible base doping near the emitter consistent with maintaining emitter injection efficiency, leading to a device with a narrow base and steep base-impurity and emitter-junction profiles (75). The resulting abrupt-emitter structures show a substantial increase in neutron tolerance and are harder by a factor of 10 than the best commercial devices available and have a current gain greater than 10 after an exposure of 10^{16} n/cm^2 ($E > 10$ keV) (76).

The temperature dependence of the recombination currents discussed above is such that the damage threshold of silicon transistors in a fast-neutron environment can be substantially increased if they are operated at a high ambient temperature (8, 23). This dependence on temperature can again be related to the characteristics of the neutron-induced defect clusters which, as indicated earlier, tend to anneal out at high temperatures, but are also sensitive to the temperature at the time of their formation. In addition, the defect clusters are sensitive to the presence of injected carriers both during their formation and afterwards, and this property has implications for the design of radiation-tolerant circuits. Thus about 25% more gain degradation can occur in transistors which are passive (terminals open) or have both junctions reverse biased during exposure to a single pulse of about 7 x 10^{13} n/cm^2 than in those which are carrying typical operating currents. After irradiation, continuation of carrier injection causes the damage manifestation to anneal to some relatively stable plateau in 10^4 seconds or less, whereas for the passively-irradiated cases annealing effects can continue for months (23). This injection dependence of gain degradation can be more specifically related to the effect of the junction electric field on the introduction of damage into the space-charge region. Thus, for devices irradiated under steady-state conditions to a total fluence of 1.1 x 10^{15} n/cm^2, the rate of introduction of damage into the emitter-base space-charge region was found to be an increasing function of the junction electric-field strength during irradiation; in addition the introduction rate accelerated for the case of low fluences and high electric fields. In general, for a given junction field the rate of introduction of damage decreased with increasing neutron fluence. These field-strength and fluence dependencies indicate that the use of transistors and circuit designs which permit operation at lower junction field strengths (i.e. forward-bias conditions) during exposure to neutron irradiation would be advantageous (73), in accord with earlier observations (23).

The above discussion has indicated that neutron-induced damage, as revealed by the degradation of common-emitter current gain measured at some time after a transient pulse or after the end of an exposure to steady-state radiation, depends on temperature and on the injection of minority carriers both during and after the radiation exposure, and that under certain conditions the damage quickly anneals (usually within seconds) to a less severe level where it remains more or less stable. The rapid annealing phase is attributed to reordering processes occurring in the defect clusters which are produced by the radiation, and it is assumed that the annealing rate is governed by a second-order recombination of mobile and immobile defects within the cluster and that this initially rapid reaction gradually slows down as the mobile defects diffuse out of the cluster (77, 78). The short-term annealing rate in p-type silicon is especially sensitive to the minority-carrier injection level, whereas in n-type the injection dependence is very small and in the opposite sense, i.e. an increase in the injection level reduces the annealing rate (79, 80). This contrasting behaviour is attributed, in part, to the existence of defects in unstable positive-charge states within the defect clusters which depend on the available electron concentration for their neutralization (81). Because this short-term annealing effect is so much more pronounced in p-type silicon than in n-type, semiconductor devices with p-type active regions, such as NPN transistors and n-on-p (p-base) solar cells, show a very strong injection dependence of room-temperature rapid annealing (82), although at reasonably high injection levels the annealing is approximately equal in both p- and n-type devices (79).

This initial rapid annealing effect, which is generally termed transient annealing, has significant implications for circuit design and can limit the radiation tolerance which can be achieved in certain classes of electronic circuits and systems (83). Thus circuits which are required to function within seconds after a neutron exposure must not only be designed to operate with the relatively stable but reduced gain then existing, but must also be able to tolerate, without adverse effects on subsequent performance, the very much reduced gain which obtains during the brief transient annealing phase. For this reason the variation of gain during transient annealing, under different conditions of temperature and injection level, must be known or measured for many types of transistors before adequate prediction of circuit vulnerability can be attempted. For the convenience of circuit designers such data is usually presented in the form of an Annealing Factor which can be defined as:

$$AF(t) = \frac{\text{radiation-induced defect density at time } t}{\text{density of stable defects which do not anneal}}$$

This is equivalent to the ratio of the effective neutron fluence $\Phi(t)$ which is required to produce the damage observed at time t to the actual fluence Φ. Thus the Annealing Factor is a correction factor that must be applied to the calculated or measured damage effects which persist long after the radiation pulse has terminated in order to obtain the damage effect for times immediately after the pulse (2). Typical measurements on a Fairchild 2N914 NPN transistor with a collector current of 200 μA indicate, at 348°K, an AF of about 2 at 100 μsec after an exposure to a 50-μsec burst of 1.8×10^{13} n/cm^2, while at 213°K the AF is about 5 at the same time after the pulse (83). Other measurements, using n-on-p solar cells exposed to 7-μsec pulses of fission neutrons with a fluence of 2×10^{10} n/cm^2, have been reported in which an AF as high as 50 has been observed as late as 90 μsec after the neutron pulse under conditions of extremely low injection (80).

As pointed out above, the strong dependence on injection level is the most striking feature of the transient annealing behaviour of NPN transistors. The effect of current injection is so strong in fact that annealing virtually ceases when the current flow through the device is interrupted and only proceeds when the current is reapplied (82, 83, 84). This feature of the annealing process raises serious questions about the magnitudes of annealing factors which may occur in devices which, as a protective measure to avoid serious photocurrent problems due to ionizing radiation or because of the particular information content (i.e. 0 or 1) of a logic circuit, may be non-conducting prior to and during a nuclear burst and then are switched to a conducting state sometime afterwards (85). Thus such so-called circumvention techniques, while perhaps effective in avoiding problems due to ionizing radiation, can contribute to a delay in the return to expected satisfactory operating levels of circuits exposed to displacement radiation.

As well as changes in gain, transistors suffer a degradation in their saturation characteristics after neutron irradiation, especially at high current levels. This effect is most important for those devices with high-resistivity (i.e. lightly-doped) collector regions, such as power transistors, in which the collector is lightly doped in order to obtain high breakdown-voltage characteristics (2). Earlier it was pointed out that modern transistors usually have wide low-doped collector regions, and thus the behaviour of modern devices at high currents and in saturation is more dependent on the characteristics of the collector than of the base region. Mesa and planar transistors can have relatively large collector body resistances and, at high currents, can be in saturation because of the voltage drop across the bulk collector resistance even when the collector-base terminals are apparently reverse biased.

The effects produced by neutron radiation cause the collector resistance to increase for a number of reasons (86). Thus increased recombination current in the base, due to the decreased minority-carrier lifetime in the base region caused by displacement damage, results in current crowding as this current flows laterally outwards to the base contact. This causes a voltage drop which debiases the central part of the emitter and confines the injected carriers to the emitter periphery so that the effective area through which the collector current flows is decreased. For a sufficiently high neutron fluence carrier removal also occurs in the collector and so increases the resistivity. In addition, the effective length of the collector increases because the diffusion length (related to the minority-carrier lifetime) of the carriers is reduced to less than the physical length of the collector, and conductivity modulation of the region of collector current flow, which normally acts to keep the resistance low in the saturation state, cannot be maintained throughout the whole of the region. As a result of this increase in collector resistance, for a fixed voltage between the collector-base terminals, the critical collector current for which the transistor goes from the active to the saturated mode occurs at progressively lower collector currents with increasing fluence. Also because of the increase in collector resistance the saturation voltage, as measured at the external terminals of a device, increases after irradiation. This increase can be quite large for non-epitaxial transistors with relatively low doping in the base region, such as the 2N1613, but is generally much smaller for low-voltage epitaxial types. Because of the gain degradation caused by displacement damage in the base an increase in base current is required in order to drive a transistor into saturation. Thus a 2N1613 with a collector current of 100 mA, which required a base current of only 1.5 mA for saturation before irradiation, required 24 mA after exposure to 1.3×10^{14} n/cm^2 (2). For an expitaxial transistor, such as the 2N918 (87), the gain at high current levels is a strong function of the collector voltage because of radiation-induced carrier removal in the collector epitaxial region which causes an increase in collector resistance, as described previously. Under these conditions the normal carrier concentration in the collector is smaller than the density of carriers flowing through it from the base, and as a result the base region effectively widens and extends into the lightly-doped collector region and, since the base transit time thereby increases, the gain decreases. Thus excessively high base drive is required to maintain saturation because of the increased recombination in the extended base. This situation can be improved if, as well as a thin base, the transistor has a more highly doped and narrower collector epitaxial layer. The latter condition, however, implies that such a device will have a low collector-base breakdown voltage, and is a trade-off which is required more generally in the design of radiation-tolerant devices. From a manufacturing point of view it is fortunately easier to make thin-base transistors using relatively heavily doped material than lightly-doped material. This base-widening (or Kirk) effect can also occur in non-irradiated transistors of various types and is responsible for a decrease in the alpha cut-off frequency f_T which is observed at high current levels. The radiation-induced carrier-removal effect in the collector causes base widening to occur at lower current levels than is the case for non-irradiated devices.

MOSFETs, being majority-carrier devices, are not particularly sensitive to the displacement effects produced by fast neutrons. However fast neutrons also produce significant ionization which causes a positive charge build-up in the oxide, as described earlier in connection with ionization effects, and this constitutes the major cause of damage to MOSFETs in a typical nuclear-explosion environment (58).

JFETs, also majority-carrier devices, did not originally exhibit an expected resistance to permanent neutron damage, and this was attributed to the fact that the early devices were low-doped alloy types. Planar technology has now allowed the manufacture of these devices with heavily-doped channels which show superior resistance to neutron damage (56), being usually regarded as radiation hard up to 10^{15} n/cm^2 and inherently more radiation tolerant than bipolar transistors (88). As a result, considerable recent interest has been evoked in the use of JFETs in radiation-hardened systems. However, as has been noted in other cases, the gain in radiation hardness attained through increase of the channel-region carrier concentration results in a reduction of the breakdown voltage, but modification of the usual epitaxial structure to incorporate multiple epitaxial layers can increase the breakdown voltage to a value higher than that characterized by the channel doping (89).

The most important degradation mechanism of JFETs by fast neutrons is carrier removal in the channel region which causes changes in such parameters as drain current and transconductance through decrease of the conductivity of the undepleted silicon and reduction of the net doping density in the gate depletion region. Since the carrier-removal rate for holes is greater than for electrons an n-channel device exhibits less severe degradation than does a more highly doped p-channel device and hence is to be preferred for use in a radiation environment (89). Other damage effects which are observed include an increase in DC reverse-bias leakage current between the gate and source, and an increase in noise (90). A factor of three increase in noise can be produced by a mere 10^{12} n/cm^2 (14 MeV), and this could possibly limit the usefulness of JFETs in some applications. This effect is attributed to neutron damage centers in the depletion region between the gate and channel which fluctuate in charge and thus modulate the channel or drain current.

3.3 Four-Layer Devices

3.3.1 Ionization Effects in Four-Layer Devices

A four-layer PNPN device, such as a silicon controlled rectifier (SCR), is an interesting extension of the usual transistor structure and is often considered to be the simplest example of an integrated circuit. It can be looked upon as a transistor with an additional "latching" junction, or as a combination of a PNP and an NPN transistor in a positive-feedback configuration. Because such a structure is representative of the four-layer paths which can exist between the individual circuit elements of an actual integrated circuit and which can be made active under certain conditions by ionizing radiation, an examination of the transient effects of radiation on an SCR can contribute to analysis and understanding of radiation-induced effects in more complex devices. The same general effects can be expected to occur in other similar devices such as silicon controlled switches (SCS) and Schockley diodes (31).

An SCR can be triggered from the high-impedance OFF state to the low-impedance ON state by injection of majority carriers into either one of the two base regions. Sufficient majority carriers, both those produced in the base regions and those which diffuse in as primary photocurrent, can be supplied by an ionizing radiation dose of about 1 rad (91). The switching time depends on the total dose, increasing as the dose decreases, and thus there is a threshold or critical radiation dose required to turn on the device which is reached when the turn-on time becomes comparable to the lifetimes in the base regions and the regenerative charge build-up process in these regions cannot be sustained. Thus for ionizing-radiation pulses which are short compared to the carrier transit time in the anode-base region the dose rate is not important, whereas for pulse widths greater than the transit time the constant generation of carriers increases the effective forward bias of the anode-base junction and enhances the internal regenerative process. Thus a decrease of carrier lifetime in either of the anode-base or cathode-base regions increases the critical dose required to cause the device to turn on by reducing both the anode-base junction forward bias and injection level below the values required to allow the regenerative charge build-up to occur. Similarly, an increase in impurity density in the base regions also causes the sensitivity of the device to ionizing radiation to decrease by reducing the effective forward bias of the junctions through an increase of the built-in junction fields. Effective radiation hardening of such a device can also be accomplished by a circuit design in which the radiation-generated charges are withdrawn from the base regions before they have time to build up (92).

3.3.2 Displacement Effects in Four-Layer Devices

Wide-base four-layer PNPN devices are very sensitive to the permanent-damage effects of fast neutrons because the gain and saturation requirements of normal operation, and the very large base widths, demand a long minority-carrier lifetime (typically 100-250 ns) and they degrade rapidly in a nuclear environment. The radiation-induced defects reduce the current gains of the two transistors of which an SCR can be considered to be constituted, with a consequent increase in the gate current, holding current and breakover voltage required to switch the device on or make it conduct. For a sufficiently large fluence the product of the gains of the two transistors becomes less than unity, and no amount of gate current applied to an SCR will make it conduct (31).

On the other hand narrow-base PNPN structures are more resistant to neutron damage than are bipolar transistors with comparable base widths (93). This superiority is a result of the collinear flow of majority and minority carriers in the bases of a PNPN device, in contrast to the case of bipolar transistors where majority-carrier flow in the base is perpendicular to the main minority-carrier flow and current crowding can occur. Also, in the PNPN device, the collinear flow of carriers gives rise to field-aided transport in both base regions, and thus the minority carriers are caused to move across the bases more rapidly than in the case of diffusion-controlled bipolar devices. For this reason a PNPN device can tolerate a far shorter lifetime than can a transistor of comparable base width. In addition, at the same level of neutron radiation, much higher power-handling capabilities can be achieved in the PNPN structure than in a bipolar transistor. The most severely degraded parameter in a neutron environment is the forward ON voltage, and this can limit the usefulness of a conventional wide-base triple-diffused PNPN device to fluences below 10^{13} n/cm^2, whereas a narrow-base type can tolerate nearly 10^{15} n/cm^2. Modifications to produce a device with a P^+NIPN^+ structure should result in a tolerance approaching 10^{16} n/cm^2.

As was pointed out above, narrow-base PNPN devices are not grossly affected by significant reductions in the lifetime of the minority carriers such as would be produced by the increased recombination rate caused by neutron-induced displacement damage and, after such damage, they should also be relatively insensitive to undesired turn-on by a transient-ionization pulse. Thus it has been estimated (93) that an ionizing dose rate of more than 10^9 rad/s would be required to turn on such a device in which an initial minority-carrier lifetime of 50 ns had been degraded, through neutron damage, to 0.3 ns.

3.4 Integrated Circuits

The individual diodes and transistors of which an integrated circuit (IC) is made up generally exhibit a response to transient radiation similar to that discussed previously for discrete types. Thus the degradation produced in IC transistors by fast neutrons is most apparent in the resulting reduction in gain, and ionizing radiation produces photocurrents and other effects through the same processes as occur for discrete transistors.

Due to the method of construction of ICs, however, wherein the circuit elements are grown on a silicon substrate in a manner similar to that described earlier for field-effect transistors, the dominant portion of the photoresponse of such circuits can be attributed to the large-area reverse-biased substrate junctions underlying the circuit components (94). Thus the effects produced by ionizing radiation in monolithic p-n junction-isolated circuits is about an order of magnitude larger than in discrete-element circuits. This results from the fact that the substrate junction, in combination with the microcircuit p-n junctions close above it, gives rise to parasitic diode and transistor elements, and the primary and secondary photocurrents in these parasitic elements tend to dominate the overall response. The radiation hardness of such junction-isolated ICs can be improved if the devices are gold doped in order to reduce the minority-carrier lifetime or diffusion length. Improvement results because the substrate photocurrents are reduced by a much greater amount than other photocurrents since the lifetime of the substrate (which initially is relatively long) is reduced much more by the gold-diffusion process than is the collector lifetime of a circuit transistor (6). As for the case of field-effect transistors, the use of dielectric-isolation techniques practically eliminates the substrate photoresponse through elimination of the substrate junctions which are responsible; silicon-dioxide isolation is especially effective in this regard and results in almost as good isolation as that between discrete devices (94,95).

The transient response of a junction-isolated monolithic transistor is primarily due to the primary photocurrent in the collector-substrate junction of the transistor (96). The use of dielectric isolation reduces such transient-radiation effects by about an order of magnitude, which is consistent with the fact that the area of the collector-substrate junction is about an order of magnitude larger than the collector-base and resistor junctions which remain in the dielectrically-isolated circuits. However the removal of the substrate junction does not necessarily harden the circuit. It is found that the presence of the substrate junction often causes an increase in hardness because there is an interaction, in the form of a competition for excess minority carriers, between the collector-substrate junction and the collector-base junction of a monolithic transistor which can dramatically reduce the normal transistor photocurrent (95,97). The mechanism for such competition is suggested to be the free-carrier drift in the electric field generated by the current flow through the bulk resistance of the collector region (98). The net effect is the substitution of a substrate primary photocurrent for the secondary photocurrent which would normally be generated in the transistor.

The primary photocurrent which is produced in the collector-substrate junctions of some IC transistors has been found to depend on temperature more than does the current produced in the collector-base junctions, and has been shown to be responsible for a significant variation in device failure threshold with temperature (99). Thus, while the primary photocurrent of the collector-base junction is relatively independent of temperature, that of the collector-substrate junction may decrease by a factor of from three to five as the temperature increases from -50°C to +125°C. This decrease in current is difficult to explain theoretically since it is exactly opposite to the increase predicted on the basis of the fact that minority-carrier lifetime increases with temperature. Thus micro-circuit failure can be expected to occur first at the low-temperature extreme (20,99) both because of the increase in substrate photocurrent described above and because of the normal decrease in transistor gain which occurs with decreasing temperature.

The general features of the response of actual junction-isolated monolithic ICs to the effects of transient radiation can be explained on the basis of the photocurrents produced by ionizing radiation and the reduction in gain of the component transistors which is produced by displacement radiation (96), as indicated previously. Thus the primary photocurrent from the collector-substrate junction will flow in the same direction in the collector load resistance of a transistor in a gate or logic circuit as does the normal collector current and is therefore more important when the transistor is OFF than when it is ON. When the transistor is OFF the photocurrent makes it appear as if the transistor is trying to turn on during irradiation, whereas when it is ON the maximum collector current is already flowing and the photocurrent only adds to this current. Also, in the OFF state the transistor is insensitive to effects in the base circuit since the base-substrate photocurrent is of the same polarity as is that in the collector and thus of the wrong polarity to turn the transistor on. As a result of this insensitivity to effects in the base circuit the transient-radiation response is generally insensitive to fan-in from preceeding circuits. Ionizing-radiation effects on transistors in the ON state are significant only when they act to decrease the collector current, that is, to turn the transistor off. Such effects are not always apparent but when they do occur they usually can be traced to a large-area base-substrate junction photocurrent. Effective elimination of this type of transient response can be accomplished, within limits, by increasing the supply voltage to move the operating point further into saturation.

The reduction in transistor gain which results from the permanent damage produced by displacement radiation manifests itself, as for discrete transistors, as an increase in the saturation voltage of the transistor and can eventually result in the transistor coming out of saturation. Thus, in the case of a two-element flip-flop, the maximum current in the ON side decreases with neutron fluence because of the gain degradation, with the result that the flip-flop may degenerate into two inverters so degraded that the ON output of one can no longer maintain the OFF state of the other (100). The threshold for such failures is also dependent on the fan-in or fan-out of the particular stage or of the stages connected to it. On the basis of the above considerations and of actual measurements it is possible to formulate practical rules for the design of radiation-resistant monolithic logic circuits and to assess the relative hardness of the various logic families such as DTL, RTL, RCTL etc. (96,101).

It has been pointed out that junction-isolated ICs contain reverse-biased junctions underlying the circuit components, and thus a typical IC transistor can be considered to be part of a four-layer PNPN structure similar to that which is found in SCR devices and which is responsible for their particular characteristics as described previously (Sec. 3.3.1). The substrate junctions of an IC can become forward biased during an ionizing-radiation pulse because of the photocurrent produced, and the whole device can be driven into saturation through the positive-feedback action which is inherent in an active four-level structure, with the result that the IC is triggered into a bistable condition which holds the transistor in the ON state after the ionizing pulse has passed. Such a phenomenon is referred to as radiation-induced latch-up, and is characterized by a change in operating point of the circuit which is accompanied by a large increase in power-supply current which may burn out the device; the original circuit condition can generally be restored only by interruption of the power supply. Four-layer action, as described above, is generally considered to be the most important sustaining mechanism for latch-up in ICs; other effects inherent to structures containing p-n junctions and which can cause latch-up are second breakdown of a resistor-substrate junction and transistor sustaining-voltage breakdown (97,102). A common feature of all these mechanisms is that the V-I characteristics associated with them are double-valued, and for a given low voltage either a very low or a very high current can flow, the first condition being associated with normal operation and the second being initiated by internal breakdown induced, in this instance, by ionizing radiation. Four-layer paths that will support PNPN action are common in ICs which are formed by triple or quadruple diffusions, but similar paths in ICs which are constructed with epitaxial processes and which utilize a highly-doped buried layer, do not appear to be sensitive to latch-up initiation by photocurrents (102). So-called dielectrically-isolated ICs are not necessarily free from latch-up problems since, depending on construction techniques, some groups of circuit elements may still be isolated from each other by junctions, the dielectric isolation being only between groups, and four-layer paths can exist within such individual groups.

The phenomenon of IC latch-up, discussed above, involves a change of operating state of the circuit, this new state being stable, unless manually reset, and capable of destroying the IC. Another similar effect may also occur, called incipient latch-up, in which the circuit changes its state under the influence of radiation but recovers of its own accord, after an excessive time delay, to its original condition.

MOS ICs generally show the same basic radiation-induced effects as do discrete devices, the most important of which is the shift in the threshold voltages of the individual transistors. The extent of this shift is strongly influenced by the magnitude of the bias voltage on the gate electrode during irradiation, being practically negligible when no bias is applied, and this property is of particular importance for MOS logic devices. The failure modes of such logic devices are more complex than those of simple devices because the charge trapping in the gate oxide is strongly influenced by the gate-oxide field, and this field is constantly changing as logic pulses pass through the device (103). For this reason the particular failure mode which is produced by a pulse of ionizing radiation could be expected to be very dependent on the actual states of the individual MOS logic circuits at the time of the pulse. Thus, for NAND gates exposed to a 0.1-μsec pulse of ionizing radiation, turn-on of the OFF gates can be attributed to substrate photocurrents, and turn-off of the ON gates can be attributed to g_m amplification of the gate-voltage changes, resulting in a change in the drain current (104). For other types of logic circuits a change of state may depend on the clock condition at the time of the radiation pulse. In all cases the induced substrate photocurrents returned to zero within a few 100 ns, no latch-up phenomena being observed in this instance.

Complementary-symmetry (CMOS) ICs, which incorporate a number of p- and n-channel transistors on a single silicon chip, have an inherently low response to the transient effects of radiation because of the built-in diode compensation of the complementary-pair configuration. Thus, for a sub-microsecond pulse of ionizing radiation with a peak dose rate approaching 8×10^8 rad(Si)/s, the transient change in output voltage of a CMOS inverter is small and can be attributed simply to the net junction photocurrent flowing at the output node (53). At higher dose rates, however, a transient malfunction occurs which is due to a non-destructive mechanism involving a four-layer path through the device. This can lead to a permanent (but non-destructive) latch-up condition if the gate-circuit impedance is atypically low; for usual input impedances this latch-up condition can be avoided at least up to 5×10^9 rad(Si)/s.

Resistors in monolithic ICs are generally formed by diffusion of an isolation region (or tub) into the main semiconductor-wafer substrate followed by a second diffusion of opposite type into a masked area of the tub to produce a region of lightly-doped semiconductor material which is the resistor itself. Because of its light doping the resistor can be readily conductivity modulated by the electron-hole pairs generated by ionizing radiation, and thus large changes in resistance can occur at relatively low dose rates (95). The combination of the junctions associated with the substrate, the tub and the resistor constitutes a parasitic transistor which connects the resistor with the substrate, although the effects associated with this transistor must be considered distributive in nature due to the voltage drops along the resistor (105). For the case of a dielectrically-isolated diffused resistor such a parasitic transistor is absent, but there still remains a reverse-biased junction, or parasitic diode, between the resistor and the tub which can inject photocurrent into the resistor material. Effects such as described above can be virtually eliminated by the use of thin-film resistors (Ta/Ta_2O_5), but, in general, only marginal improvement in hardness of the microcircuit as a whole results because the circuit response is usually determined by the collector photocurrent of one of the transistors of the circuit itself (6).

4. RADIATION EFFECTS ON MISCELLANEOUS COMPONENTS

Various components such as resistors, capacitors, vacuum tubes etc. can also be affected by transient radiation, but since most are passive devices or do not contain p-n junctions the effects produced are generally not critical to circuit operation. This relative insensitivity to nuclear radiation is reflected in the paucity of published papers related to such components. However, for completeness, brief mention will be made of some of the more important radiation effects or of component types preferred for use in a general radiation environment.

4.1 Vacuum Tubes and Gas-Filled Tubes

Vacuum tubes are generally considered to be very radiation hard.

Miniature and sub-miniature xenon-filled tetrodes, such as the 2D21 and the 5643, tend to fire spuriously when exposed to transient pulses of ionizing radiation (106). This effect is caused by ionization of the gas filling and, because of the time required for gas multiplication and the drift of ions, there is a characteristic firing delay of some tens of μsec. Due to various de-ionizing processes in the gas the total dose accumulated is not a sufficient criterion upon which to base a firing prediction, but rather the rate at which the dose accumulates determines when the critical ion population is reached. Typically, a few thousand rads, delivered at a rate of the order of 2×10^7 rad/s, are sufficient to cause firing. The operating plate voltage of the tube is an important factor in determining whether firing occurs, and a low value is desirable if spurious effects are to be reduced.

4.2 Quartz Crystals

Ionizing radiation has been found to affect the behaviour and output frequency of oscillators (operating in the 5-MHz range) in which the frequency-determining elements are quartz crystals (107). Natural quartz shows significant frequency shifts of 2 parts in 10^{11} per rad, and also large transient changes in Q sufficient to cause oscillations to cease for the order of minutes when exposed to 3700 rads delivered in 4.5 μsec. Synthetic quartz, on the other hand, shows only 1% of the frequency shift of natural quartz, and the change in Q is so small that no change in the oscillator output can be observed. Thus synthetic quartz offers a great increase in radiation resistance over natural quartz and is to be preferred for environments in which over 5000 rads of ionizing radiation can be expected (108,109).

4.3 Resistors

For values less than 900 ohms, wire-wound types on ceramic cores with a silicon outer coating are to be preferred, whereas for high-resistance applications the metal-oxide film types with a glass core have been found to perform well (110).

A resistor with excellent radiation stability is the thin-film Cr-SiO cermet (111), whose resistance has been found to change less than 1% during exposure to 1×10^{15} e/cm^2 (1.5 MeV).

4.4 Capacitors

The major transient-ionizing-radiation effect in capacitors is a transient increase in the electrical conductivity of the dielectric through production of free electrons by the creation of electron-ion pairs (110,112, 113). Gamma rays generate relatively isolated ion pairs, whereas other types of radiation tend to generate dense paths of ionized electrons, with the result that the transient response of a material of low dielectric constant is less for a densely-ionizing particle than for a lightly-ionizing one, whereas there is little difference in response for the case of a material of high dielectric constant. In general, neutrons are less effective per unit dose rate than are gamma rays in producing induced conductivity.

The recombination time of the free charge carriers which are created in the dielectric is usually very short (10^{-11} - 10^{-12} sec), and thus the additional current which is produced as these carriers drift under the influence of the applied electric field across the capacitor generally ceases as soon as the transient ends. However some of the carriers are trapped by impurities or imperfections in the dielectric and are only slowly released by thermal excitation, with the result that appreciable conduction can remain in the dielectric long after the transient has passed. Thus the radiation-induced photoconductivity consists of prompt and delayed components. This leakage is often insignificant but can have an appreciable effect in circuits where long time constants exist which can act to integrate the two components. In circuits containing short time constants the effect of the delayed component is usually negligible, and thus the use of small capacitors is generally advisable. The choice of a dielectric with the best prompt and delayed characteristics depends on the circuit application and also on the expected dose rate.

The radiation equivalent circuit of a capacitor is very simple and consists only of a radiation-induced shunt resistance R_S in parallel with the usual capacitor leakage resistance R_O which is considered to shunt an ideal capacitor C, and R_S varies inversely as the radiation-induced photoconductivity.

4.5 Coaxial Cables

Radiation effects observed in coaxial cables are related to those found in capacitors since the dominant radiation interactions occur in the dielectric in both cases. As well as an increased conductivity in the dielectric due to the creation of ion pairs, a space-charge distribution can be produced in the cable dielectric and excess charge can accumulate in the metal parts because of electron ejection and injection caused by backscattering and secondary-emission processes (114,115). The space-charge distribution can produce local fields of the order of 150 V/cm in the dielectric, and any externally applied voltage across the cable tends to bias the dielectric so that charge redistribution cannot occur until the local field builds up. The space charge redistributes itself because of the increased conductivity of the dielectric and diffuses to the center conductor and to the shield where the charge flow can be measured. A small terminating resistor ($\sim$ 100 ohms) enhances the charge redistribution or changes the balance of charge due to conduction through the resistor, whereas larger resistors ($>$ 10 k-ohms) do not have any appreciable effect.

It should be noted that neutrons can cause appreciable production of ion pairs in the hydrogenous dielectrics such as polyethylene which are commonly used in cables, and the induced conductivity can amount to 10 to

50% of that produced by the same dose rate of gamma radiation (116).

4.6 Ovonic Devices

Amorphous materials, because of their intrinsic lack of long-range order, are expected to be less affected by radiation than are normal semiconductors provided that radiation-induced devitrification does not occur (117). The reason for this greater radiation tolerance is that amorphous and vitreous semiconductor materials contain high concentrations of traps and recombination centers in the forbidden energy gap which minimize the effects of ionizing radiation and of the local re-arrangement of atoms caused by neutron bombardment. Thus the recombination lifetime in these materials is more than six orders of magnitude shorter than the lifetime of minority carriers in silicon transistors.

In exposures to 40 successive 20-ns pulses of 2.5-MeV bremsstrahlung, at a dose rate of 1.8×10^{11} rad/s, ovonic threshold switches (OTS) exhibited no transient switching, and no photocurrent could be detected. When the devices were placed directly in the electron beam transient switching occurred in every case, but this was due to voltages induced in the signal leads rather than to the direct effect of the electrons. The devices were also unaffected by pulsed neutrons with a fluence of 1.8×10^{14} n/cm^2, and could still function after an exposure to an integrated flux of $> 1.2 \times 10^{17}$ n/cm^2, the latter flux being considered marginal for most passive components and well above the anticipated neutron fluence levels for most military applications of electronics.

5. HARDENING TECHNIQUES

Hardening of semiconductor circuits and systems so that they will not be disabled by transient-radiation effects can be accomplished in a number of ways. Thus the semiconductor device itself can be designed and fabricated in such a manner that the effects of radiation on it will be minimized or kept within tolerable limits, and radiation screening techniques can be carried out during the manufacturing process, thereby resulting in a hardened component. At the circuit level, compensation techniques can be employed to ensure minimum upset to the circuit, and the expected degradation of device parameters can be allowed for in the circuit design. In addition, advantage can be taken of particular device properties under certain circumstances.

As pointed out previously, the most important failure mechanism due to neutrons is degradation of device gain, and thus control of device base width in the manufacturing process is mandatory; structures in which such control is difficult, such as microcircuits and PNP transistors, should be avoided if possible (118). So far as ionizing radiation is concerned, intrinsic hardening of devices is impractical for dealing with transient photocurrents, and therefore the circuit or system must be designed to tolerate the transient currents, or means must be provided for effective circumvention.

4.1 Hardening of Devices at the Fabrication or Manufacturing Stage

It has been pointed out previously that the use of dielectric isolation reduces the photocurrents due to ionizing radiation for both FETs and ICs, and that the conductivity modulation produced in diffused resistors can be avoided by the use of thin-film resistors. The minority-carrier lifetime in various regions of a transistor can also significantly affect the radiation resistance of the device, and gold doping, which reduces lifetime, is particularly effective in contributing to device hardness. It might be expected that the impurity doping profile in the base or collector regions would also have some influence on radiation response, and in some cases this has been found to be so, but generally lifetime is the most significant parameter. This conclusion is supported by the observation that two transistors with similar low collector lifetimes (due to gold doping), but with different collector doping profiles, exhibited similar photocurrents (95), whereas another transistor with the same profile but not gold doped showed a higher radiation response.

The primary photocurrent response of IC transistors is controlled by the minority-carrier collection volume which is a function of the area of the base window and of the lifetime of the minority carriers in the collector. Therefore the minimum primary photocurrent sensitivity of IC transistors is determined to a large extent by the geometry and lifetime limitations of the IC process itself (119), but a shallow base diffusion can contribute to further reduction of photocurrent.

While it is generally desirable that the radiation-induced degradation of device parameters should be minimized, even a severe degradation of gain can be tolerated provided that the post-irradiation value can be predicted and thereby compensated for. It was pointed out previously that neutron-induced damage tends to anneal out at high temperature, and this phenomenon provides a basis for establishing neutron damage assurance even under severe radiation environments (18,120). It is found that, by sufficiently raising the annealing temperature for many ICs and discrete transistors, a complete restoration of values of pre-irradiated parameters is possible. For instance the pre-irradiated h_{FE} value of a 709 IC amplifier is fully recovered at 325°C. Furthermore, subsequent neutron exposures of previously irradiated and annealed components illustrates a remarkable degree of repeatability of both damage and annealing characteristics. The application of such irradiation-annealing cycles is economical and reliable in the wafer stage of manufacture, and also feasible for packaged off-the-shelf semiconductor components. The method is claimed to be superior to various prediction techniques using electrical parameters, whereby limits are placed on pre-irradiated values of current gain (β or h_{FE}) and gain-bandwidth product (f_T) to ensure that the current gain will not degrade below a minimum value for a given neutron fluence. Another advantage of the method is the capability of rejection of mavericks (devices of unexplained behaviour) at the wafer stage. Some radiation-hard devices which have been processed in the above manner are now available commercially.

Hardness assurance at the manufacturing stage can also be accomplished by the use of a statistical model to provide correlation of device radiation performance with selective non-destructive electrical screening measurements (86). The model can be generated by using experimental data from an appropriate sample of parts and is applied to all subsequent parts from the production line family, thereby providing 100% device screening without resorting to additional radiation testing. While a single screening factor such as base width, f_T, or base transit time (the latter being the key prediction parameter) can be used to assure transistor gain response in the normal active region, the prediction of power transistor gain and saturation voltage at high currents in a neutron environment precludes such a simple approach since both base- and collector-region characteristics must be considered. For this case selected electrical screening measurements, such as gain at several conditions of current and voltage, and capacitance at emitter and collector junctions, together with data from emitter-collector delay-time characteristics if increased accuracy is desired, are applied to a set of empirically-derived multiple-regression equations. Subsequent radiation tests showed that gain and saturation voltage performance could be predicted to within 20% with regression equations derived from a previous representative test sample from the same production line. Other work (121) in the application of multiple linear-regression techniques indicates that, while only pre-radiation electrical measurements are needed to predict neutron response, the accurate prediction of response to γ-radiation requires that electrical measurements be made after the irradiation phase of an irradiation-anneal cycle.

Another method of providing an effective hardness assurance screen can be derived from a correlation between the current dependence of the neutron damage factor (Sec. 2.2) for transistor β degradation and the carrier transit time across both the emitter-base junction and the base region (74). An electrical measurement of a parameter t', related to this transit time and with the same current dependence as the change in inverse β, can be used to generate a current-independent damage factor or constant for each transistor type of interest. The product of this derived damage constant with t' may then be used as a figure of merit for hardness assurance.

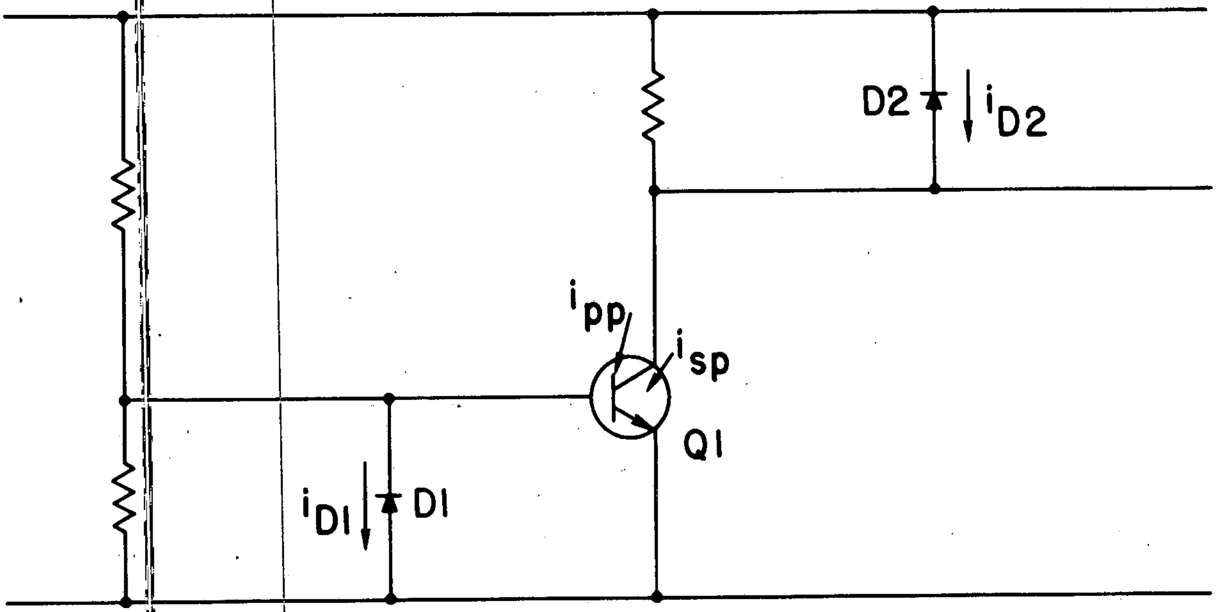
Since many visible IC defects, particularly those associated with metallization interconnects (voids, scratches etc.) are believed to be directly related to the ability to survive in certain nuclear environments, especially where large photocurrents may be generated, improved visual inspection of ICs is particularly important to radiation-hardened systems. In order to reduce the subjectivity of visual inspection, optical spatial-filtering techniques can be applied to produce an IC defect image (122). The filter used is a negative image transparency of the Fourier transform of a defect-free circuit; the filter blocks that portion of the Fourier transform of a test IC which matches the reference IC, and only circuit differences, including physical defects, are re-imaged. The results are generally excellent for metallization defects on optically smooth circuits but are poorer for low contrast defects where there is a high degree of surface roughness. Evaluation of the technique is being carried out for possible routine production-line use.

5.2 Hardening of Devices by Compensation Techniques

It is impossible to avoid completely the degradation of gain which is produced in semiconductor devices by fast neutrons, and thus precautions must be taken to ensure that the gain which remains after such an exposure is adequate for continued satisfactory operation of the circuit. Typical techniques which have been used in the design of power circuits for use in neutron environments of up to 3×10^{14} n/cm^2 include the compound connection of transistors and the operation of saturated transistors at low forced gains (123,124). The compound connection gives a gain equal to the product plus the sum of the gains of the two component transistors of the circuit, and generally provides adequate assurance that sufficient common-emitter current gain will be maintained after neutron exposure. The operation of a saturated transistor at low forced gain means that such a transistor is initially operated more deeply into saturation than is called for under normal circumstances, and the expectation is that the reduced gain which obtains after neutron exposure will still be sufficient to maintain the saturation condition.

The techniques of designing against the transient effects of ionizing radiation are similar to those which have been found to be effective against noise environments; these include filtering, cancellation, common-mode rejection, spike-clipping, current and voltage limitation, etc. (125). The incorporation of magnetic circuitry (pulse transformers) into a circuit design minimizes the effects of fast γ-pulses by ensuring proper photocurrent and voltage time phasing so that the power dissipation in associated semiconductor switching transistors remains minimized (123). Additional tolerance to ionizing radiation can be achieved by the use of low circuit resistances, where possible, to minimize the effects of injected currents while still providing paths of sufficiently high impedance (i.e. to act as current limiters) to avoid catastrophic damage (124).

A simple and effective method of hardening transistor circuits is the compensation of transistor or diode primary photocurrents by means of other photosensitive elements such as diodes or diode-connected transistors. A typical arrangement is illustrated in the accompanying figure, where the effects of the primary photocurrent i_{pp} at the base of transistor Q1 are compensated by a similar photocurrent produced in the back-biased diode D1 (36). See figure on page 34. Thus ideally, the proper bias is maintained on the transistor so that it does not turn on, and secondary photocurrent i_{sp} is thereby avoided. Appropriate selection of diode D1, and choice of the magnitude of its reverse bias, permits reduction of transistor primary photocurrent by a factor of ten. At higher dose rates, however, compensating diodes of this type generally do not significantly change the radiation response because the diode primary photocurrent alone cannot match the secondary photocurrent produced in the transistor at the higher injection levels (95). Diode D2 in the figure supplies to the collector of Q1 the primary photocurrent which i_{pp} draws away, and thus tends to maintain the collector potential undisturbed. However the addition of D2 is usually not worthwhile unless i_{sp} has been reduced by a factor of the order of the



current gain of the transistor, which is difficult to achieve.

Many other techniques are available for compensation or reduction of the effects of ionizing radiation, but circuit design can also be an important factor. Thus the biasing resistors in the base circuit determine how much I_{CO} (collector-base leakage current) or radiation-induced photocurrent can flow before a transistor becomes forward biased. If a large amount of such current is permitted, by the use of small resistors, the OFF state of a digital switching circuit will tend to be stabilized, but the performance in the ON state will be limited by reduction of the drive capability. Silicon transistors generally have a very small thermal I_{CO} and can accommodate large resistors in the base circuit even if thermal compensation over a large temperature range is required. However such a design would make the circuit vulnerable to transient radiation since a relatively small amount of photocurrent could then cause the transistor to become forward biased (37).

5.3 Special Hardening Techniques

Some semiconductor devices, depending on temperature, operating voltage, or previous radiation history, exhibit a degree of tolerance to radiation which may provide the basis for a hardened circuit.

For the case of MOSFETs it has been found (126) that moderate amounts of ionizing radiation at large positive gate voltages, followed by partial annealing, reduces the subsequent sensitivity of the device to low doses of radiation at lower gate voltages. Typical improvements in hardness of two orders of magnitude are possible if the expected dose does not exceed a few x 10k rads. At higher doses the hardening is not permanent because of a slow change in the oxide space charge.

It has also been found that a factor of ten improvement in the radiation resistance of circuits incorporating MOSFETs can be obtained by using optimum device types (n-channel MOSFET) at gate voltages ($\sim$ 0 volts) which minimize the radiation-induced threshold voltage shift (127). Experimentally it is observed that as a MOSFET is irradiated the drain current initially increases, due to an increase in the positive space-charge in the oxide, reaches a maximum, and then starts to decrease exponentially; the drain current then remains near the final irradiation value when irradiation ceases. The above behaviour thus suggests a useful hardening technique: irradiation of the device, with $V_G = 0$, until the maximum drain current is reached, at which time the device may be put into normal operation (again with $V_G = 0$) and be expected to be relatively insensitive to the effects of additional ionizing radiation, about 10^7 R being required before the drain current would change by a factor of two.

The effects of specific dopant impurities in a transistor, in conjunction with operation at a particular low temperature, indicate a possible new approach to attaining radiation hardness in semiconductor devices (128). For most silicon bipolar transistors h_{FE} drops rapidly with decreasing temperature and approaches zero at about 100°K. However, for NPN silicon transistors having gallium doping in the base region, h_{FE} falls with temperature in the usual manner until about 135°K when it starts to rise and reaches a peak, dependent on collector current, at about 76°K. Near the region of this peak the gain actually decreases with increasing current, which is opposite to its behaviour at high temperatures. For very low collector currents the peak-region gain at low temperatures can actually exceed the room-temperature gain. This temperature dependence of h_{FE} is produced by a change in emitter efficiency due to differential rates of impurity de-ionization, or carrier freeze-out, in the base and emitter regions. The characteristics described above are of importance because it is found that the tolerance of such a device to fast-neutron irradiation is significantly greater at the temperature at which the gain peak occurs than at room temperature. Thus 10^{14} n/cm^2 reduces the room-temperature gain to 9% of its original value, whereas at the temperature associated with the peak the gain is reduced to only 44% of its original value. The damage constant, obtained from the slope of a plot of $1/h_{FE}$ versus neutron fluence, is five times larger at 300°K than at 76°K. From another viewpoint, the room-temperature gain is reduced by one half for a neutron fluence of 1.4×10^{13} n/cm^2, whereas at the temperature of the peak a fluence of 1×10^{14} n/cm^2 is required. This increased radiation tolerance near the peak results from a reduction in the recombination in the emitter-base space-charge region at low temperature. Thus it may be possible to determine an optimum doping profile in conjunction with dopants having particular ionization energy levels which will enhance the gain and/or radiation tolerance at a particular temperature.

The specific operating conditions of a circuit have also been found to have a bearing on the resulting radiation hardness. Usually the technique for predicting the performance of high-frequency ($f_T > 100$ MHz) transistors in a fast-neutron environment is to assume that the device behaves as it does in a DC or low-frequency mode. However the operating characteristics of nearly all such devices change at high frequencies and thus it should be expected that the high-frequency performance in a neutron environment should also change (129). An investigation of the effects of fast-neutron bombardment on a typical NPN transistor (2N914) of a common-emitter amplifier operating at high frequencies has indicated that the forward gain s-parameter (which can be related to h_{FE}) increases as a function of fluence for increasing frequencies near or above f_T, and that there is a frequency where this parameter is relatively unchanged with neutron fluence. Thus, in this instance, there is evidence that a suitable choice of operating frequency could contribute to the hardness of a circuit in a neutron environment.

It was pointed out earlier (Sec. 1) that an important consideration for digital computer-type circuits was that they should not lose their stored information while under the influence of transient-radiation effects. Many approaches have been developed to provide such transient immunity and one which shows particular simplicity and promise is the use of temporary storage media. In typical circuits designed according to this principle transistors are allowed to saturate under the influence of the photocurrents produced by ionizing radiation, but the temporary storage feature effectively acts to impart hardness to the circuit (130). One method takes advantage of the fact that an amount of transient radiation which is sufficient to impair the action of a semiconductor junction has comparatively little effect on a capacitor. Thus transistor flip-flops can be capacitatively loaded in such a way that the capacitors maintain a memory of the flip-flop state even though the transistors themselves are disabled. The capacitors then drive the transistors to their pre-irradiated states after the transient effects have subsided and the transistors have recovered their operational capability. Another method makes use of magnetic devices, such as square-loop cores, for hardened storage. The cores are connected in such a manner that they are exposed to equal and opposite mmf drives as a result of transistor photocurrents. Hence, no matter what state a core is in, the transient γ-induced photocurrents in every transistor connected to its windings will not produce sufficient ampere-turns to disturb its state. Circuits which incorporate these hardening techniques have operated satisfactorily up to 8×10^{10} rad (Si)/s.

6. PREDICTION OF RADIATION EFFECTS ON ELECTRONICS

The prediction of radiation effects on electronic circuits requires, amongst other things, knowledge of the parameter and carrier-density changes to be expected in a semiconductor device for given levels of radiation, and the effect of these changes on device or circuit operation. Thus, for ionizing radiation, the photocurrents can often be predicted simply on the basis of the known radiation-induced generation rate of electron-hole pairs in silicon, and of an estimate of the effective volume from which these pairs may be collected. The degradation of device gain produced by various fluences of fast neutrons may be estimated from the effects produced in devices of a similar type, or may be determined for the actual device through irradiation-anneal cycles as described previously. Such calculated or experimentally determined radiation-induced effects can then be superposed on a linear model of the particular device and related to the behaviour of the circuit as a whole. Sophisticated methods of prediction, particularly applicable to transient effects, have been developed which make use of transistor models and equivalent circuits and which require computer solution of the field equations which determine carrier distributions and diffusion. A number of specialized computer programs have been developed for this purpose (131). Some prediction difficulties arise because radiation excites some failure modes that are not important in other environments, and also other failure modes that are not easily correlated with electrical measurements (118).

Typical work on the development of computer programs (27,132) illustrates the general principles whereby the electrical characteristics of a device, and the perturbations produced by ionizing radiation, can be predicted by solving the basic charge-transport equations in the device, subject to the boundary conditions at external electrical contacts. The distribution and motion of carriers are then obtained by solving the continuity equations for both electrons and holes, in conjunction with Poisson's equation. The mobility and lifetime of the carriers, and the radiation-induced carrier generation, are described by non-linear functions of the carrier density and current. Other computer-oriented prediction techniques make use of various equivalent circuits in order to characterize a diode or transistor in all regions of operation. Such equivalent circuits may be based on a charge-control model (133) or on the more common Ebers-Moll characterization; the two models are essentially equivalent but the latter is generally more easily interpretable from a circuit application standpoint (134).

The application of computer prediction techniques to the analysis of circuit behaviour in a transient-radiation environment is a large and very specialized field. A number of such transient analysis programs have been developed over the years and many are generally available under certain conditions (131). A partial list of such programs follows, together with a brief description where available:

RECAP	Linear direct-current nodal equations are written by the computer from the circuit topology. Each transistor is represented by a value of β, a radiation-induced leakage current (introduced as a current generator between collector and base terminals), and the non-linear input characteristics, I_E versus V_{BE}, as obtained on a curve tracer (135).

ECAP	Very efficient program for linear, frequency-dependent circuit analysis. Recognizes only "classical" circuit elements and networks; thus the magnitude and value of current from the current generators which are added to the circuit model to take account of radiation-induced photocurrent must be calculated from ancillary R-C-I networks derived from the lumped-model representation of classical circuit elements (136).
SCAN	Performs a DC worst case and statistical analysis of electronic circuits using both linear and non-linear circuit elements. Consists of a set of general-purpose computer programs which permit an automated capability of analyzing DC, AC and transient behaviour of circuits using linear or piece-wise linear modeling techniques. Uses a combination of FORTRAN and special-purpose programming. Modified to SCAN II or revised SCAN (119,134).
TRAC	This is a modification of the SCAN Transient program and is designed for ease of entering, no programming experience being required. The program allows the analyst to decide which circuits show sufficient sensitivity to require detailed modeling. Large-signal radiation equivalent circuits are used for semiconductor components. Primary photocurrent is modelled by means of a parallel current-generator, which makes the implementation of the actual model in a computer program simpler to employ than does a formulation which simply adds a term onto the reverse saturation current of the appropriate junction. This conventional model simulates the photocurrent response as though it were generated entirely in the diffusion region. A more accurate revised model also includes the depletion-region portion of the response, and its dependence on junction bias, and provides two levels of approximation for the photocurrent response (134,137,138).
SECURE	Intended for subsystem/system analysis. Has the capability of handling linear and non-linear functional blocks, logical equations, and complete circuit descriptions. Uses large-signal radiation equivalent circuits for semiconductor components. An important capability of this code is the inclusion of individual circuit analysis to produce the necessary information regarding circuit performance and hardness. Thus, to avoid computer overloading, the relatively insenstive circuits can be represented by functional blocks and the radiation sensitive circuits can be represented by detailed equivalent circuits. These circuits can then be directly substituted, without additional coding, into a system simulation (118,139).
SCEPTRE	Employs a non-linear circuit model, and uses large-signal radiation equivalent circuits for semiconductor components. A very flexible program, useful for radiation-effects component modeling as well as circuit vulnerability analysis. Is capable of modifying electronic device models to incorporate new radiation-effects information and to include models for new devices (118,131,136).

CIRCUS	Includes built-in models for transistors, diodes, tunnel diodes, and four-layer devices; photocurrent sources are included for each semiconductor junction (131).
NET-IR	The radiation-effects version of the NET-I Circuit Analysis program (131).
PREDICT	

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IEEE TNS 11-5, Nov. 1964, p. 82.

135. Digital Computer Techniques for Determining Circuit Behavior in a Pulsed Nuclear Environment
W.E. Craig and H.W. Mathers
IEEE TNS 10-5, Nov. 1963, p. 168.

136. Lumped-Model Analysis of Microcircuit Vulnerability
J.P. Raymond, W.W. Chang and R.E. Burdis
IEEE TNS 15-6, Dec. 1968, p. 271.

137. Statistical Modeling of Semiconductor Devices for the TREE Environment
G.C. Messenger and E.L. Steele
IEEE TNS 15-6, Dec. 1968, p. 133.

138. Transient Radiation Current Model for Semiconductor Devices
W.H. Dierking, G.E. Katz and E.L. Steele
IEEE TNS 16-6, Dec. 1969, p. 144.

139. Predicting Combined Neutron Degradation and Gamma Induced Effects on a
Closed Loop System
C.T. Kleiner, J.M. Tanke and M.J. Romano
IEEE TNS 15-6, Dec. 1968, p. 245.

8. APPENDIX

The following publications, which have not been referenced in the text, are compendia of information on transient-radiation effects and hardening techniques.

(i) TREE (Transient-Radiation Effects on Electronics) Handbook
Editors: J.J. Kalinowski and R.K. Thatcher, Battelle Memorial Institute,
DASA 1420
Edition Number 2, Revision Number 2, September 1969.
A "limited-distribution" document.

Intended to provide information useful in designing and evaluating electronic equipment that is expected to be exposed to the radiation environment produced by a nuclear-weapon burst. The information content can be categorized as follows:

a) Supporting information (explanation of terms, interaction of radiation with matter).
b) Environmental information (nuclear-weapon-burst and simulated environments).
c) Information on the effects of radiation on electronic materials and devices.
d) Circuit considerations (hardening and analysis of circuits, computer programs).
e) System considerations (general approach for developing systems that will function in a transient-radiation environment).

A Classified Supplement (DASA 1420-1) of this Handbook contains additional information on the interaction of transient radiation with electronic materials, and also additional hardening suggestions, both explicit and implicit.

This version of the TREE Handbook has now been superseded by (ii), below.

(ii) TREE (Transient-Radiation Effects on Electronics) Handbook (U)
Volume I
Editor: R.K. Thatcher, Battelle Columbus Laboratories
DNA 1420H-1
Edition Number 3, December 1971.
Classified "Confidential".

Abstract (U)

It is the purpose of this document to present information which will be useful to the design engineer when designing electronic systems for survival in a nuclear-burst environment. The information presented covers only those areas directly related to electronic parts, circuits, and systems. The nuclear-burst environment covered is both transient and steady state and includes all radiation effects except external EMP. Areas which are covered in detail are the simulated versus burst environment, interaction of transient radiation with matter, discrete semi-conductor devices, integrated circuits, capacitors, resistors, miscellaneous electronic materials and devices, circuit hardening, and network-analysis techniques. Supplementing this document is "TREE Handbook, Volume II", which discusses the nuclear-weapon-burst environment, interaction of transient radiation with matter, system hardening, and internal EMP.

(iii) TREE Preferred Procedures (Selected Electronic Parts)
Co-Editors: R.K. Thatcher and D.J. Hamman, Battelle Memorial Institute,
DASA 2028
Edition Number 1, May 1968.
A "limited-distribution" document.

Provides recommended procedures which experience has shown are efficient for determining transient-radiation effects on electronic parts. Areas which are covered in detail are experimental design, experimental documentation, dosimetry and environmental correlation, and preferred measurement procedures for diodes, transistors, and capacitors.

(iv) TREE Simulation Facilities
Author: R.W. Klingensmith
Contributing Editor: R.K. Thatcher
DASA 2432
Edition 1, September 1970.
Distribution unlimited.

A reference document which fully characterizes, on a technical basis, individual TREE simulation facilities in the U.S.A.

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13. ABSTRACT

The basic effects produced in semiconductors by both ionizing and displacement radiation are summarized and related to the parameter changes which are observed in semiconductor devices. Ionization and displacement effects produced by transient radiation in diodes, transistors, four-layer devices and integrated circuits are described, and a brief summary is given of the effects of radiation on miscellaneous components such as resistors, capacitors and coaxial cables. Various techniques for radiation hardening of semiconductor devices and circuits are reviewed, and methods for predicting the effects of radiation are discussed briefly.

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