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RADIATION EFFECTS DESIGN HANDBOOK

Section 1. Semiconductor Diodes

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16. Abstract

This document contains summarized information relating to steady-state radiation effects on semiconductor diodes plus an introductory section on terminology. The radiation considered includes neutrons, gamma rays, electrons, and protons. The information is useful to the design engineer for making estimates of radiation effects on diodes.

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PREFACE

This document is the first section of a Radiation Effects Design Handbook designed to aid engineers in the design of equipment for operation in the radiation environments to be found in space, be they natural or artificial. This Handbook will provide the general background and information necessary to enable the designers to choose suitable types of materials or classes of devices. It also will include, where possible, predictive techniques for forecasting behavior of materials, devices or equipment, and correlation factors for comparing different radiation environments.

Future sections of the Handbook are expected to discuss such subjects as transistors, electrical insulators, capacitors, solar cells, polymeric materials, thermal-control coatings, structural metals, and interactions of radiation.

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GLOSSARY

Absorbed Dose. The radiation energy absorbed per unit mass of a material at the place or point of interest, or the time-integrated absorbed-dose rate [Unit: rad (material)], one rad being equivalent to 100 ergs/gram or 0.01 joule/kilogram. Dose is preferred.

Absorbed-Dose Rate. The energy absorbed per unit time and mass by a given material from the radiation field to which it is exposed [Unit: rad (material)/s]. Dose rate is preferred.

Breakdown Voltage. The value of reverse voltage (negative anode voltage) at which the current increases by many orders of magnitude through Zener or avalanche breakdown.

Breakover Voltage. The value of positive anode voltage at which a silicon-controlled rectifier or switch changes to the conductive state with the gate circuit open.

Bremsstrahlung. German for "radiation resulting from a stopping process" or, literally, "from braking". Designates electromagnetic radiation generated when high-energy charged particles are accelerated (or decelerated) by electric and/or magnetic fields. Bremsstrahlung sources in the laboratory are typically generated by the interaction of electron beams with the nuclear Coulomb field of the atoms in target materials. The cross section for this interaction increases strongly for electron energies above 1 MeV. The bremsstrahlung energy spectrum is continuous and ranges from zero up to the maximum energy of the incident particles. Bremsstrahlung and high-energy X-radiation are of the same nature, with bremsstrahlung being the continuous portion of the X-ray spectrum.

Bulk Damage. Radiation-induced defects in the crystal lattice of a material which, in a semiconductor, act as additional recombination centers for minority carriers and thus decrease the lifetime of the minority carriers.

Conduction Current (radiation controlled). An abnormally high leakage current flowing in insulators or semiconductors because of a radiation-induced increase in their conductivity.

Diode Switching Time. The time required for a diode to switch between the conductive and nonconductive states.

Displacement Effects. The effects of displacements in the lattice structure of a material that results from particulate irradiation. See bulk damage.

Dose. Equivalent, but preferable, to absorbed dose.

Dose Rate. Equivalent, but preferable, to absorbed-dose rate.

Dynamic Resistance. Slope of the forward voltage and current characteristics in the "linear" operating region.

$$(r_d = \left.\frac{\Delta v_{\text{DIODE}}}{\Delta i_{\text{DIODE}}}\right|_{\text{AT SELECTED OPERATING POINT}}$$

Electromagnetic Radiation. Radiation associated with a periodically varying electric and magnetic field that is traveling at the speed of light, including radio waves, light waves, X-rays, and gamma radiation.

Electron. A small charged particle having charge equal to 4.803×10^{-10} esu and a mass of 9.109×10^{-28} gram. In general use, it most often refers to a negative charged particle, which is more correctly termed negatron; positron refers to a particle having a positive charge.

Energy Spectrum. The distribution of radiation, such as γ-rays, X-rays, neutrons, electrons, and protons, as a function of energy.

Exposure. ". . . the quotient of ΔQ by Δm, where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in a volume element of air, whose mass is Δm, are completely stopped in air . . ." Here Δ refers to an increment small enough so that ". . . a further reduction in its size would not appreciably change the measured value . . . and, on the other hand, is still large enough to contain many interactions and be traversed by many particles." Unit: roentgen (r) = 2.58×10^{-4} coulomb/kilogram. In certain contexts the dictionary definition of exposure is implied.

Fission. The splitting of a heavy nucleus into two (or, very rarely, more than two) fragments – the fission products. Fission is accompanied by the emission of energy; kinetic energy of neutrons and fission products and the associated gamma rays. It can be spontaneous or it can be caused by the impact of a neutron, a fast charged particle, or a photon.

Fluence. The number of particles or photons or the amount of energy that enters an imaginary sphere of unit cross-sectional area. The time-integrated flux.

Flux. At a given point, the number of photons or particles or energy incident per unit time on a small sphere centered at that point, divided by the cross-sectional area of that sphere.

Forward Characteristic. The current-voltage characteristic of a diode when biased in the forward direction or direction of least resistance to current flow through the device. The anode is biased positive in relation to the cathode.

Forward Current. The current that flows in a diode when biased in the forward direction.

Forward Voltage. The voltage applied between the anode and cathode of a diode whereby the diode operates in the conductive state.

Forward Voltage Drop, V_F. The value of voltage between the anode and cathode of a diode when biased in the forward direction. Generally measured at a specific current.

Gamma Rays. Highly penetrating, high-frequency electromagnetic radiation from the nuclei of radioactive substances. They are of the same nature as X-rays, but of nuclear rather than atomic origin. (In many references, a distinction between gamma rays and X-rays is not made.)

Gate Current. The current flowing between the gate and cathode of a silicon-controlled rectifier or switch.

Gate Voltage. The voltage applied between the gate and cathode of a silicon-controlled rectifier or switch.

Holding Current. The forward current below which a silicon-controlled rectifier or switch returns to the forward blocking state after having been in forward conduction, gate open.

Ionization. The separation of a normally electrically neutral atom or molecule into electrically charged components.

Ionizing Radiation. Electromagnetic radiation (gamma rays or X-rays) or particle radiation (neutrons, electrons, etc.) capable of producing ions, i.e., electrically charged atoms or molecules, in its passage through matter.

$\underline{I_R}$. See reverse leakage current.

$\underline{I_{RO}}$. The reverse leakage current measured initially or at the beginning of a test.

Junction Leakage Current. See reverse leakage current.

Leakage Currents. See reverse leakage current.

Majority Carrier. In semiconductors, the type of carrier that constitutes more than half the total number of carriers. The majority carriers are electrons in an n-type semiconductor and holes in a p-type semiconductor.

Minority Carrier. The type of carrier that constitutes less than half the total number of carriers in a semiconductor. The minority carriers are holes in an n-type semiconductor and electrons in a p-type semiconductor.

Neutron. A particle with no electric charge, but with a mass approximately the same as that of the proton. In nature, neutrons are bound in the nucleus of an atom, but they can be emitted or knocked out in various nuclear interactions.

Neutron Fluence. Time-integrated neutron flux (Unit: n/cm^2).

Neutron Flux. The product of the neutron density (number per cubic centimeter) and the neutron velocity; the flux is expressed as neutrons per square centimeter per second. It is numerically equal to the total number of neutrons passing, in all directions, through a sphere of 1 cm^2 cross-sectional area per second.

Neutrons, Fast. Neutrons with energies exceeding 10 keV, although sometimes different energy limits are given.

Neutrons, Thermal. Neutrons in thermal equilibrium with their surroundings. At room temperature their mean energy is about 0.025 eV.

Nuclear Radiation. Particulate and electromagnetic radiation emitted from atomic nuclei in various nuclear processes.

Permanent Effects. Changes in material properties that persist for a time long compared with the normal response time of the system of which the material is a part.

Proton. An elementary particle having a positive charge equivalent to the negative charge of an electron (4.803×10^{-10} esu) but possessing a mass approximately 1845 times as great.

Rad. A unit of dose equal to 100 ergs per gram. In defining a dose, the material must be defined, e.g., H_2O, C, Si.

Radioactivity. Spontaneous nuclear disintegration occurring in elements such as radium, uranium, and thorium and in some isotopes of other elements (e.g., Co^{60}). The process is usually accompanied by the emission of alpha and beta particles and/or gamma rays.

Reference Voltage. The value of voltage maintained by a reference or Zener diode when operated at a specified current.

Replacement Current. A current tending to reestablish charge equilibrium after perturbation of the normal charge distribution by radiation.

Reverse Characteristic. The current-voltage characteristic of a diode when biased in the reverse direction or direction of greatest resistance to current flow through the device. The anode is biased negative in relation to the cathode.

Reverse Current. See reverse leakage current.

Reverse Leakage Current, I_R. The current that flows when the diode is biased in the direction of greatest resistance. The reverse current as normally measured is a combination of reverse saturation current, carrier generation current, and surface leakage current.

Reverse Recovery Time. The time required for the reverse current or voltage to reach a specified value after instantaneous switching from a steady forward current to a reverse bias in a given circuit.

Temporary Effects. Changes in material properties that persist for a time, but which are followed by complete or nearly complete recovery to the preirradiation condition.

Valley Current. The current flowing when a tunnel diode is so biased in the forward direction that it is operating in the valley portion of its current-voltage characteristic. The current at the second lower positive voltage at which $dI/dV = 0$.

V_F. See forward voltage drop.

$\underline{V_{F_O}}$. The forward voltage drop measured initially or at the beginning of a test.

$\underline{V_Z}$. See reference voltage.

$\underline{V_{Z_O}}$. The reference or Zener voltage measured initially or at the beginning of a test.

Zener Voltage. See reference voltage.

SECTION 1. SEMICONDUCTOR DEVICES

INTRODUCTION

Semiconductor devices are the most sensitive of all electronic components to radiation. Thus, for most applications, semiconductor-device performance probably will determine the maximum radiation flux and/or fluence that an electronic circuit will tolerate. Therefore, radiation should be listed along with temperature and electrical bias as one of the more important factors in the total environment that determines semiconductor-device performance in an application.

Radiation affects semiconductor-device performance both permanently and temporarily. Permanent effects are attributed to changes in the physical properties of the irradiated semiconductor materials (bulk damage) caused primarily by energetic particles (including secondary electrons). The kind and magnitude of the effects observed will depend upon the radiation type, flux, fluence, and energy. Temporary effects are caused by the generation of excess free carriers in the junction regions and result from exposure to ionizing particulate radiation (electrons and protons), electromagnetic radiation (X-rays or gamma-ray photons), or high-energy neutrons. Semipermanent ionization effects include charge buildup on or in the oxide layer and the creation of increased interface state density at the interface between the oxide and the semiconductor material. This type of damage is semipermanent in that at least partial recovery of degradation in operating parameters is often observed when electrical biasing is removed, and slow recovery generally is observed with continuous electrical operation after exposure. This recovery can be rapidly accelerated when devices are thermally annealed or operated at elevated temperatures of electrical stressing.

General Background

Semiconductor devices generally may be separated into the two categories: majority-carrier devices and minority-carrier devices. Field-effect transistors (FET's) and Schottky barrier diodes are the primary representatives of the majority-carrier device category. Most other semiconductor devices including bipolar transistors, solar cells, diodes, rectifiers, and silicon-controlled devices are minority-carrier devices. A generalized pictorial representation of these devices is presented in the appropriate subsections.

The radiation effect of greatest interest in minority-carrier devices, such as bipolar transistors, is the decrease in the lifetime, τ, of the minority carriers. This decrease results from the radiation-induced defects in the semiconductor crystal lattice which, in turn, can act as additional recombination centers for the minority carriers. This decrease in τ is reflected most prominently in a decrease in transistor gain and the short-circuit current (and for practical purposes the maximum available power) of solar cells. These effects are normally referred to as bulk or permanent damage.

The expression usually used to relate lifetime decrease to radiation fluence is

$$\frac{1}{\tau_\Phi} = \frac{1}{\tau_o} + K_\tau \Phi \quad ,$$

where

τ_o is the initial minority-carrier lifetime

τ_Φ is the lifetime after the radiation exposure

Φ is the radiation fluence (particles/cm^2)

K_τ is the lifetime damage constant [cm^2/(particle$\cdot$ s)].

This expression will be developed further in the section on transistors to show its relationship to the transistor current-amplification factor, h_{fe} or β. The resulting expression will be useful in predicting β degradation as a result of exposure to radiation.

Also to be presented later will be values of the constant, K_τ, for use in prediction of device behavior.

In addition to bulk damage, radiation affects the semiconductor surface properties. Ionizing radiation can interact with atmospheric gas at the semiconductor surfaces, with surface contaminants and with passivation layers producing electric fields at the junction surfaces, resulting in changes in the surface recombination behavior of the current carriers. These are the most apparent effects at low fluences. As one would expect, the magnitudes of these effects vary widely, even among units of the same type made by the same manufacturer. Larger differences can be expected between device types and from manufacturer to manufacturer. Although some planar-oxide passivated devices often show little vulnerability to ionizing radiation, more recent data show that some of the devices most sensitive to gain changes are indeed planar oxide-passivated devices. This appears to be due, at least in part, to the creation of new interface states.

For radiation levels at which transistor-current gain, h_{fe}, and diode forward voltage drop, V_F, are significantly altered, a permanent increase in junction-leakage current can also be expected. This effect may become very significant at higher fluences.

Ionizing radiation can create free-charge carriers which will participate in the conduction process. This has the effect of generating photocurrents, that is, currents that are generated in the reverse direction across any p-n junction. The photocurrents at the base-emitter junction of transistors may be amplified by the current gain. The magnitude of this effect will depend upon the radiation flux and, although the magnitude of the photocurrents are generally small when compared with normal operating currents, they may be significant in certain applications.

The preceding paragraphs have emphasized radiation effects on minority-carrier devices because experience shows these to be critical components in many current applications. However, majority-carrier devices also are critical in many applications. Experimental work has shown that radiation can produce surface effects in field-effect transistors (FET's) that will adversely affect the performance of these devices. It has been found, particularly in metal-oxide-semiconductor field-effect transistors (MOS-FET's), that disruptive radiation-induced changes in gate threshold voltage and channel conductivity can in some instances occur at exposure levels comparable to those at which bipolar transistors are still useful. However, for many radiation environments both junction FET's and the MOS-FET's have proven as satisfactory as bipolar transistors used to accomplish the <u>same</u> function. The expected significant superiority of FET transistors over bipolar transistors, because of their independence from the minority-carrier lifetime, has not been realized. This is primarily a surface passivation problem which is slowly being improved.

It should be noted that some of the radiation-induced changes in semiconductor-device parameters may be of some benefit for some applications. For example, in switching applications, increased switching speed and less chance of breakdown failure would result from the radiation-induced decrease in diode switching time and increase in breakdown voltage. The effects of radiation on semiconductor devices must be evaluated in terms of the tolerance of a circuit application to radiation-induced changes in the critical device parameters.

Neutron fluence values for radiation experiments normally are reported in units of neutrons per unit area with energies above some threshold value, n/cm^2 (E >?). This E value varies from one experiment to another. Therefore, in order that data could be compared on a common basis, the fluence values reported by the various experimenters were converted to n/cm^2 (E >0.01 MeV) using appropriate dosimetry multiplication factors. The neutron-energy spectrum was assumed, for convenience, to be of the form

$$n(E) = 0.453\ e^{-E/0.965}\ \sinh\ (2.29E)^{1/2*} ,$$

*L. Cranberg, "Fission Neutron Spectrum of U^{235}", Phys. Rev., 103, pp 662-670 (1956).

where E is the neutron energy in MeV. The multiplication factors used from this expression were

For Fluence with E >	Multiply by
0.1 MeV	1.01
0.3 MeV	1.07
1.0 MeV	1.44
2.9 MeV	4.34

to obtain fluence with E > 0.01 MeV. This procedure may result in errors as great as 50 percent if the actual energy spectrum is at wide variance with the spectrum assumed.

Another useful method of discussing neutron displacement effects in semiconductors is the use of "1 MeV equivalence". This term is more fully described in the section of this Handbook entitled "The Radiations in Space and Their Interactions with Matter".

For the purposes of this and future sections, the following radiation environmental descriptions are used unless specifically noted otherwise in the text.

(1) Neutron radiation – that radiation environment resulting from the operation of a steady-state nuclear reactor. The spectrum is assumed to be of the form given above, and the environment includes the associated gamma radiation.

(2) Gamma rays – highly penetrating, high-frequency electromagnetic radiation from the nuclei of radioactive substances. They are of the same nature as X-rays, but of nuclear rather than atomic origin. (In many references, a distinction between gamma rays and X-rays is not made.)

(3) Electron and proton radiation – particulate radiation, produced by machine sources, that is used to simulate the environment in the Van Allen belts.

Subsequent portions of this Handbook will describe the typical radiation-induced changes in important semiconductor device parameters to provide a basis for helping to select candidate device types for the user's application and for establishing the general sensitivity to radiation of the application circuitry.

DIODES

This portion of the Handbook is concerned with the effects of radiation on semiconductor diodes and includes information on single-junction p-n devices and three multiple-junction special-purpose devices. The single-junction devices, in their order of presentation are switching diodes, rectifiers, general-purpose diodes, voltage-reference diodes, tunnel diodes, varactor diodes, microwave mixer diodes, and Schottky barrier diodes. Due to a lack of information on the effects of radiation on their characteristics and their limited application tunnel, varactor, microwave mixer, and Schottky barrier diodes are discussed in the final section of this part of the Handbook, which is entitled "Special-Purpose Diodes". In addition to containing information on these four devices, the effects of radiation on the multiple-junction devices (silicon-controlled rectifier, silicon-controlled switch, and Schockley diode) are also included in this special-purpose diode section.

Semiconductor diodes, due to their sensitivity to radiation and the quantities required in today's circuitry, have received considerable attention to determine the effects of radiation on their electrical properties. This attention has included exposure to various radiation environments, with measurements of electrical characteristics before, after, and/or during the irradiation. Results of these investigations have shown permanent changes in diode characteristics including increases in forward-voltage drop and reverse current and decreases in reverse-recovery time. These permanent changes are the subject of this section of the Handbook.

The major amount of the radiation testing has been concerned with those devices classified as switching and voltage-reference diodes and rectifiers. These are single-junction devices, whose structural diagram shown in Figure 1 is basic to all single-junction semiconductor devices. These devices differ only in junction width and area, which contributes to the current and frequency capabilities of the device. The doping of the basic material may also differ, depending upon the ultimate purpose of the device. The information available from various investigators on these units has been combined, with the neutron radiation environments converted to show fluences with $E > 10$ keV, assuming a fission spectrum of the form $n(E) = Ae^{-E/B} \sinh\sqrt{CE}$, where E is the neutron energy in MeV. This is one of the standard spectra used in describing the fast-neutron energy distribution of the neutron leakage at a nuclear reactor coreface. (See Introduction for correlation.) Similarly, this same notation has been used where information is limited but available from more than one investigator or test program on lower-use devices such as varactor, tunnel, microwave, and Schottky barrier diodes. However, if the information available was limited to one investigator or test program, the radiation environment has not been changed from that which was originally reported.

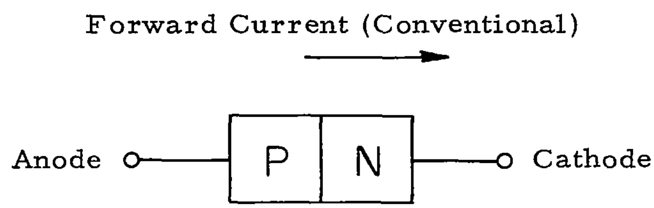

FIGURE 1. STRUCTURE DIAGRAM OF SINGLE-JUNCTION DEVICE

Parameters that are common to most of the single-junction devices and indicative of their satisfactory operation are forward voltage drop, reverse current, and breakdown voltage. These are the parameters generally measured in determining the effects of radiation on semiconductor diodes, with forward voltage drop being the most sensitive to radiation and the most often measured parameter. The one exception to this is the breakdown or reference-voltage of zener or voltage-reference diodes which is of greatest importance in the application of these devices and, therefore, receives the greatest attention when determining the effects of radiation on these devices. The order of data presentation in the following sections, when the information is available, is as follows: forward voltage drop, reverse current, and breakdown voltage. The one exception is the section discussing the effects of radiation on voltage-reference diodes, where reference voltage or breakdown voltage is the predominant parameter and the first discussed. Data presentation is graphic wherever possible and consists of shaded envelopes that enclose the data points plotted for a particular parameter. A data set, as referred to on the graphs, is the information reported on a device or group of devices having the same type number and which have been exposed to the same radiation environment, under the same electrical bias conditions, in a particular test.

In using the information given in the following paragraphs, the reader should remember that the intent is to provide preliminary or early design data. However, if the circuit is designed to tolerate a specific fluence, it should be expected to function in a fluence slightly below this value. This permits a small margin of safety to exist.

Switching Diodes

The failure mechanism or degradation process of greatest significance which semiconductor diodes experience from radiation exposure (nuclear or space) is the creation of defects in the semiconductor's lattice structure. These lattice defects act as additional trapping centers and, therefore, increase the resistivity of the material. Since diode current varies inversely with the resistivity and exponentially with voltage*, the forward-voltage drop at a specific current increases with radiation fluence. Through this mechanism the degradation of the forward characteristic is the dominant effect of radiation on switching diodes or other diodes and rectifiers where this characteristic is important in the application of the device.

The fluence at which a switching-diode experiences an increase in forward-voltage drop sufficient for the diode to be unsatisfactory for an application is, among other things, dependent upon junction and cross-sectional area. The greater these areas (which have a direct relationship to the diode's current or power rating) for similarly manufactured devices, the lower the radiation fluence required to cause substantial degradation of the diode's forward characteristic. This is illustrated by a comparison of Figures 2, 3, and 4, which are composites from the available data and show changes observed in forward-voltage drop (V_F) as a function of neutron fluence. Silicon switching diodes having current ratings equal to or less than 0.5 ampere, greater than 0.5 ampere and less than or equal to 1 ampere, and those rated above 1 ampere, respectively, are represented by the curves in Figures 2, 3, and 4. Data points shown on these and other graphs in this diode section are representative and are not meant to be comprehensive. A series of the same data-point characters (o, $\triangle$, +) on a graph is indicative of observed changes with fluence in a set of data. Based upon an increase to twice the initial value of V_F as a failure criterion, the diodes of lower current ratings are satisfactory to minimum neutron fluences of 5.0×10^{14} and 2×10^{14} n/cm^2 (E > 10 keV), while those of the higher current ratings may exceed this criterion at 1×10^{14} n/cm^2 (E > 10 keV). This failure criterion has been chosen arbitrarily and may or may not be suitable for a particular application. It is, therefore, left to the designer to establish his circuit's failure criteria and determine its limitations for radiation exposure.

Although the degradation of the forward characteristic of a switching diode is normally the limiting factor in the useful life of the diode in a radiation environment, permanent changes also are experienced in the reverse characteristic. The creation of lattice defects and the subsequent decrease in minority-carrier lifetime

*Beam, W. R., Electronics of Solids, McGraw-Hill (1965).

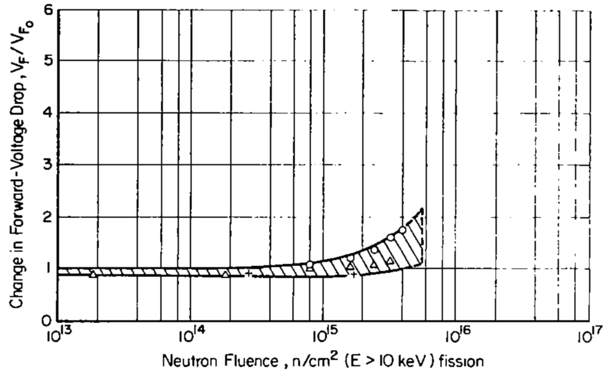

FIGURE 2. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR SWITCHING DIODES HAVING A CURRENT RATING OF 0.5 AMPERE OR LESS

15 Sets of Data

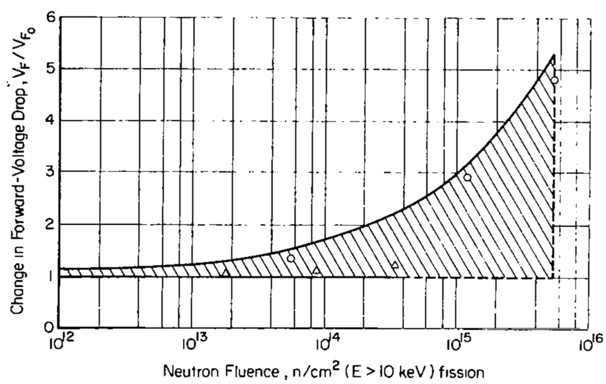

FIGURE 3. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR SWITCHING DIODES HAVING A CURRENT RATING GREATER THAN 0.5 AMPERE BUT LESS THAN OR EQUAL TO 1 AMPERE

2 Sets of Data

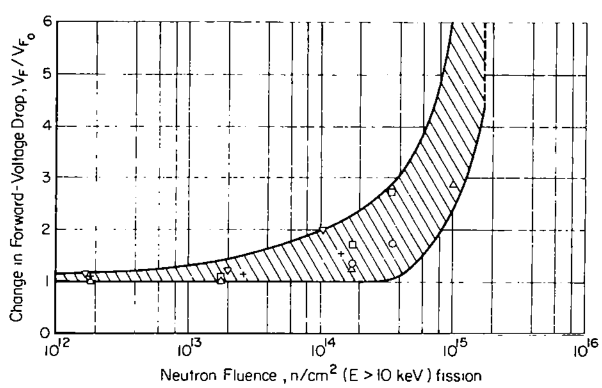

FIGURE 4. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR SWITCHING DIODES HAVING A CURRENT RATING GREATER THAN 1 AMPERE

7 Sets of Data

described earlier are responsible for some of the change observed in the reverse characteristic. The reverse-saturation current increases as the inverse of the square root of the minority-carrier lifetime, while the carrier-generation current is inversely proportional to the minority-carrier lifetime. A third component of the reverse-leakage current is surface leakage which is generally not calculable and is dependent upon surface condition, surface recombination, and the presence of surface charge. These three components of reverse current are not satisfactory for categorizing the effects of radiation on this parameter, however, because of an inability to know in advance which component may be dominant. The information regarding the effects of radiation on the reverse current of switching diodes or similar types of devices is best separated by current or power rating as was done above for forward-voltage drop. Composites of the available information from various reports and technical articles on the effect of radiation on the reverse current of silicon switching diodes are separated in this manner in Figures 5 and 6. Changes in reverse-leakage current for the switching diodes having current ratings of 1 ampere or less are plotted as a function of neutron fluence in Figure 5, while those for diodes rated in excess of 1 ampere are represented by Figure 6. Comparison of the composite results of the various investigators as presented in these two figures shows little difference in the degradation of the reverse characteristics of the two groupings of diodes.

Comparison of Figures 5 and 6 with Figures 2, 3, and 4 show a strong increase in reverse current at fluences as much as an order of magnitude lower than those at which the forward-voltage drop shows a similar increase. The degradation of the forward-voltage drop will normally govern the useful limits of the diodes; however, since an increase in leakage currents from nanoamperes or even a few microamperes to values 25 or 50 times greater than initial value usually will not seriously impair the diodes' performance. An increase of several orders of magnitude in many instances would not be serious.

The decrease in minority-carrier lifetime that occurs with increasing radiation fluence is also responsible for an improvement in two of the parameters important to the performance of a switching diode. The switching time and storage time are directly dependent upon minority-carrier lifetime, and decrease with radiation. Thus, the speed of operation of the diode improves. Information available on measurements of reverse-recovery time, which is a measure of switching capability, is insufficient for providing graphic illustration of the effect of radiation on this parameter. However, the information which is available shows a variation of from little or no change to a decrease of 75 percent with exposure to a neutron fluence of 2×10^{14} n/cm^2 (E > 10 keV) for silicon-switching diodes.

Breakdown voltage usually shows an increase with increasing fluence. Insufficient data prevent the plotting of this parameter as a

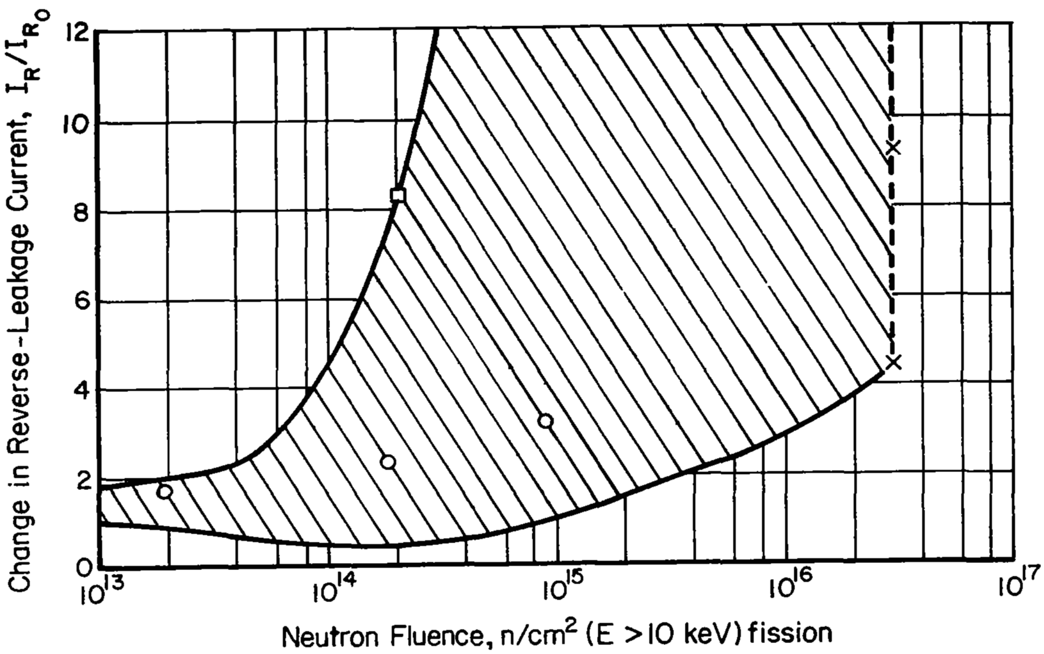

FIGURE 5. COMPOSITE OF CHANGES IN REVERSE CURRENT VERSUS NEUTRON FLUENCE FOR SWITCHING DIODES HAVING A CURRENT RATING OF 1 AMPERE OR LESS

6 Sets of Data

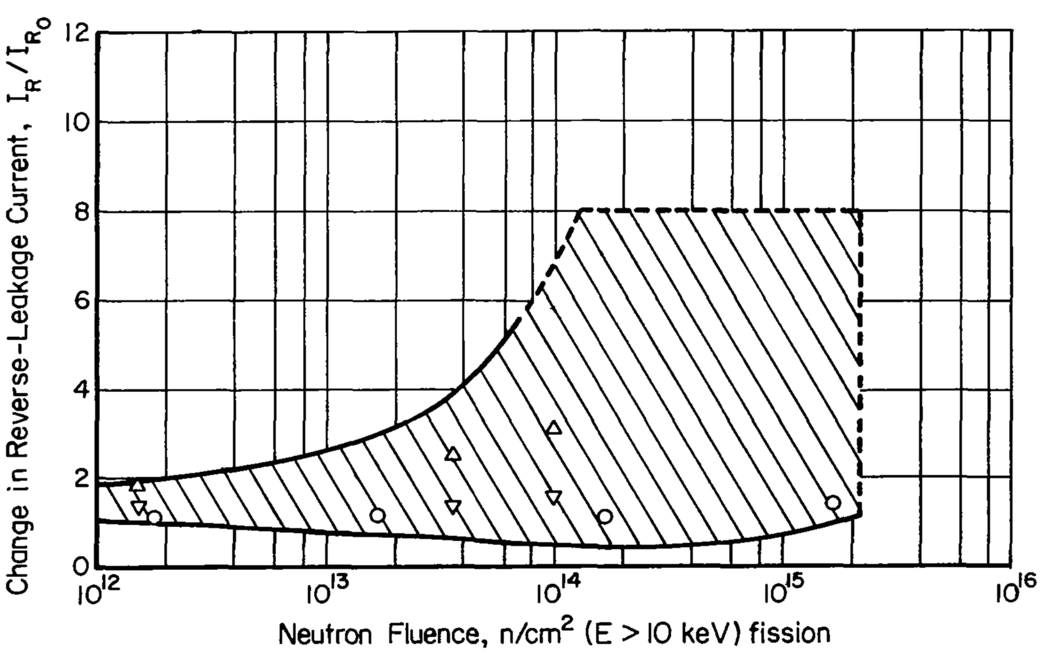

FIGURE 6. COMPOSITE OF CHANGES IN REVERSE CURRENT VERSUS NEUTRON FLUENCE FOR SWITCHING DIODES HAVING A CURRENT RATING GREATER THAN 1 AMPERE

4 Sets of Data

function of fluence and what data are available show little or no change of consequence in the application of the diodes.

Information concerning permanent-degradation effects of electron radiation on the characteristics of switching diodes is limited to one report on silicon devices, and shows a maximum increase in forward voltage drop of 26.1 percent after exposure to an electron fluence of 5×10^{15} e/cm^2 (E = 1.5 MeV).(1) Reverse currents increased several orders of magnitude with this fluence but remained within satisfactory limits. One exception was a diode that had an initial reverse current of 49 nanoamperes but increased to 1.85 milliamperes with exposure to a fluence of 5×10^{15} e/cm^2 (E = 1.5 MeV). It is believed that this increase is due to the destruction of the lattice near the junction by rapid absorption at very high dose rates, i.e., 1.77×10^{12} e/(cm$^2\cdot$ s). The reverse-recovery time decreased the same as with neutron irradiation, the decrease varying from 10 percent to as much as 73 percent with this electron fluence.

Limited information on the effects of gamma radiation from a cobalt-60 source indicates there is little or no change in diode characteristics with exposures to 8.8×10^5 rads (C).

Rectifiers

Rectifiers experience the same degradation mechanisms described above for switching diodes. These mechanisms cause the forward-voltage drop and reverse current of the rectifiers to increase with increasing radiation fluence. The effect of neutron fluence on the forward-voltage drop of silicon rectifiers is presented graphically in Figures 7, 8, and 9. The graphs are composites of the available information concerning the permanent degradation of this parameter and show the amount of increase that may be expected with exposure to a neutron environment. Figure 7 is representative of the change that may occur with rectifiers having current ratings of 1 ampere or less, and Figure 8 similarly represents rectifiers rated above 1 ampere but less than or equal to 10 amperes. Figure 9 is a composite of results on those rectifiers rated above 10 amperes. These figures show little difference in the minimum fluence at which the rectifiers experience a strong increase in forward-voltage drop. The graphs indicate that the higher current devices (above 1 ampere) may double their forward-voltage drop at a minimum fluence of 1×10^{13} n/cm^2 (E > 10 keV) while those of the lower current rating increase similarly at minimum fluence of 1.3×10^{13} n/cm^2 (E > 10 keV).

Permanent effects of neutron irradiation on the reverse characteristics of silicon rectifiers are illustrated in Figures 10, 11, and 12. These figures present composite graphs of information from various investigators according to the current ratings of the rectifiers, with

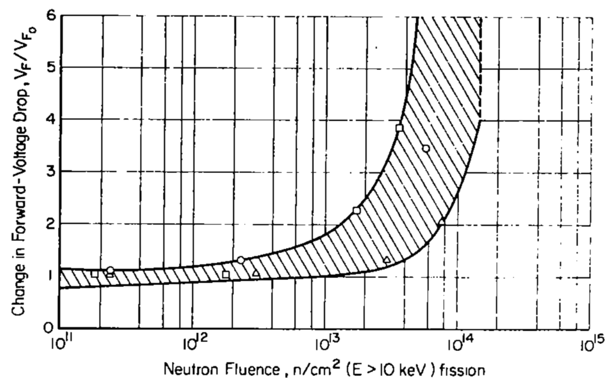

FIGURE 7. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR RECTIFIERS HAVING A CURRENT RATING OF 1 AMPERE OR LESS

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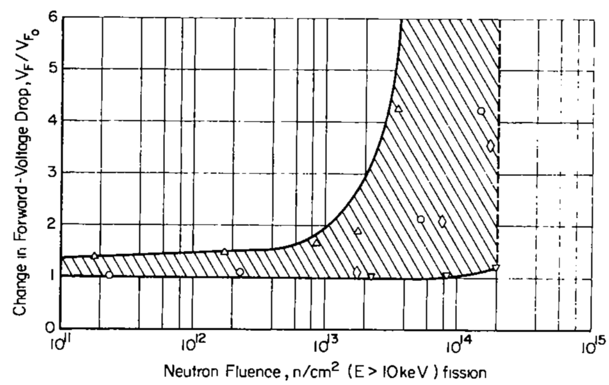

FIGURE 8. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR RECTIFIERS HAVING A CURRENT RATING GREATER THAN 1 AMPERE BUT LESS OR EQUAL TO 10 AMPERES

13 Sets of Data

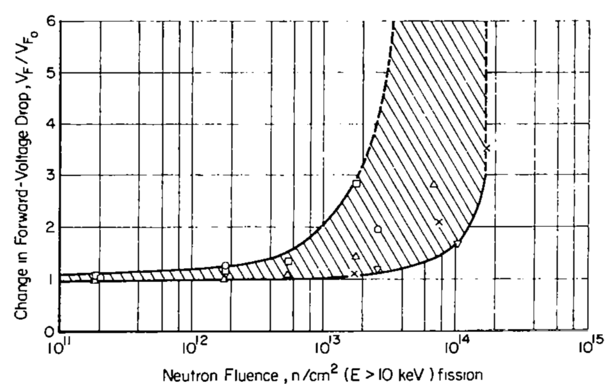

FIGURE 9. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR RECTIFIERS HAVING A CURRENT RATING GREATER THAN 10 AMPERES

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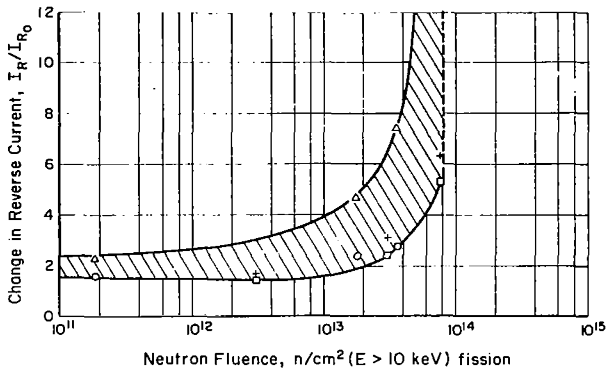


FIGURE 10. COMPOSITE OF CHANGES IN REVERSE CURRENT VERSUS NEUTRON FLUENCE FOR RECTIFIERS HAVING A CURRENT RATING OF 1 AMPERE OR LESS

4 Sets of Data

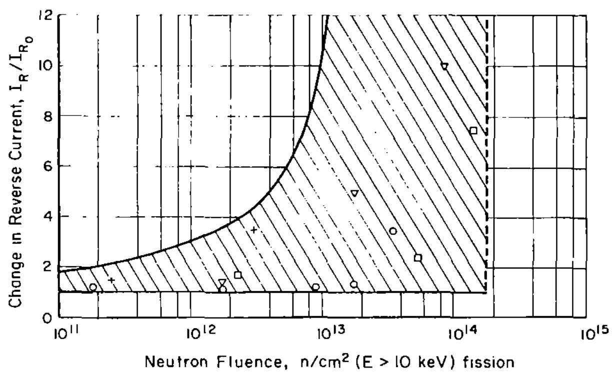


FIGURE 11. COMPOSITE OF CHANGES IN REVERSE CURRENT VERSUS NEUTRON FLUENCE FOR RECTIFIERS HAVING A CURRENT RATING GREATER THAN 1 AMPERE BUT LESS OR EQUAL TO 10 AMPERES

6 Sets of Data

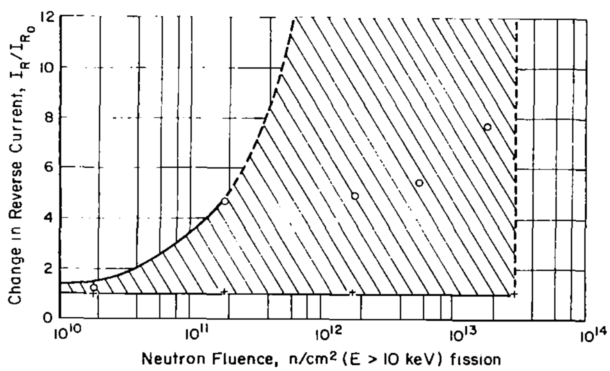


FIGURE 12. COMPOSITE OF CHANGES IN REVERSE CURRENT VERSUS NEUTRON FLUENCE FOR RECTIFIERS HAVING A CURRENT RATING GREATER THAN 10 AMPERES

4 Sets of Data

each group covering a specific range of current rating. The data summarized in Figure 10 are from results of radiation tests on rectifiers rated at 1 ampere or less. Figure 11 is a similar summary of data for rectifiers rated above 1 ampere and equal to or less than 10 amperes; data for those units having current ratings in excess of 10 amperes are summarized in Figure 12. These figures illustrate the increase in sensitivity to radiation that occurs with increasing current or power rating that is characteristic of many semiconductor devices. Based upon the information presented in these graphs, rectifiers rated above 10 amperes may experience a strong increase in reverse current at approximately 10^{11} n/cm^2 (E > 10 keV), while those rated at 10 amperes or less do not experience a similar increase until at least 10^{12} n/cm^2 (E > 10 keV), an order of magnitude greater neutron fluence. A similar difference in sensitivity may also be noted between the rectifiers having current ratings of 1 ampere or less and those rated above 1 ampere.

Limited information on the effects of electron irradiation on the electrical characteristics of silicon rectifiers indicate the forward-voltage drop did not increase more than 20 percent and the dynamic resistance doubled with an electron fluence of 5×10^{15} e/cm^2 (E = 1.5 MeV).[1] The reverse current increased by approximately one order of magnitude, from a few nanoamperes to a maximum of 2 microamperes.

General-Purpose Diodes

General-purpose diodes have received only a limited amount of attention in the study of radiation effects on semiconductor diodes. Therefore, information on the effects of radiation on diodes of this type is not sufficient for a graphic presentation of the effects observed. The effects that have been observed are, as expected, the same as those discussed above for switching diodes and rectifiers. Limited neutron irradiation results show a fluence of approximately 10^{15} n/cm^2 (E > 10 keV) as the exposure at which the forward-voltage drop of 250- and 500-milliwatt silicon units may double in value. An increase of as much as a factor of four has been observed with a fluence of 2.5×10^{15} n/cm^2 (E > 10 keV). It is suggested that the graphs and information on switching diodes be used as a guide in the application of general-purpose diodes in a radiation environment.

Data on the effect of electron irradiation on the characteristics of silicon general-purpose diodes are also very limited but do show an increase of 200 to 375 percent in forward-voltage drop following exposure to an electron fluence of 8×10^{15} e/cm^2 (E = 1.5 MeV).[1] The reverse current remained below 10 nanoamperes.

Voltage-Reference Diodes

Exposure to a radiation environment produces lattice defects in voltage-reference or zener diodes as it does in rectifiers and switching diodes. The degradation of a diode's electrical characteristics through the production of these defects and the subsequent decrease in minority-carrier lifetime is as discussed previously in the section on switching diodes.

Degradation that occurs from the irradiation of voltage-reference diodes includes changes in breakdown voltage and increases in forward-voltage drop and reverse current. The diodes' maintenance of a constant breakdown voltage, or for some low voltage-reference units a constant forward-voltage drop which determines the reference voltage, is important in the application of these devices. Therefore, any changes in these parameters from exposure to a radiation environment must be considered by the circuit designer: allowances must be made in his design or adequate shielding must be provided to limit the radiation fluence. The composite graph of the changes in reference voltage observed by various investigators as a function of neutron fluence presented in Figure 13 presents the maximum change in reference voltages that has been observed at the indicated fluence. Many times the reference voltage remains within 1 or 2 percent out to fluences of 10^{14} n/cm^2 (E > 10 keV).

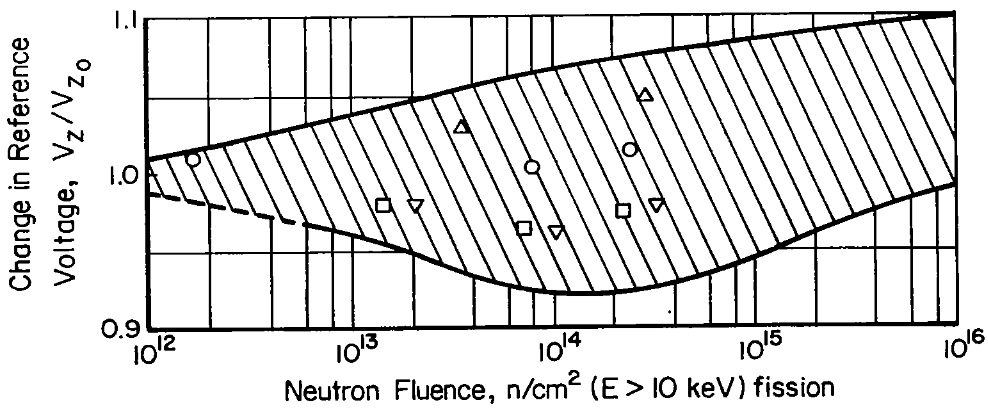


FIGURE 13. COMPOSITE OF CHANGES IN REFERENCE VOLTAGE VERSUS NEUTRON FLUENCE FOR REFERENCE DIODES

34 Sets of Data

Another factor that must be considered but that has had limited investigation is the combined effect of radiation and temperature on reference voltage. Graphs of how temperature affects the amount of change observed in reference voltage when 1N745A, 1N968B, 1N829, and 1N939 diodes are irradiated are shown in Figures 14 through 17.[2] These graphs demonstrate that the amount of change in reference voltage from irradiation may diverge, converge, or cross with increasing temperatures (Figures 14, 15, and 16) or remain essentially constant (Figure 17). The degradation of the reference voltage from exposure to a radiation environment may also be sensitive to the current at which the diode is operating. Therefore, depending upon the application, the amount of degradation of the reference voltage from irradiation must be determined at the current and temperature at which the diode is expected to operate.

The forward-voltage drop of reference diodes remains within ± 25 percent of the initial value to neutron fluences of approximately 2×10^{14} n/cm^2 (E > 10 keV) but may increase by a factor of three at 3×10^{15} n/cm^2 (E > 10 keV), as shown in Figure 18. A change in forward-voltage drop may or may not be significant, depending upon the application, and it is left to the designer to determine whether such a change would be detrimental to the performance of his circuit.

Because most investigators do not include the measurement of reverse current in testing the effects of radiation on reference diodes, data are somewhat limited. The data that are available indicate degradation similar to that experienced by switching diodes. That is, the minimum fluence at which the reverse current increases by a factor of 10 or more is approximately 2×10^{14} n/cm^2 (E > 10 keV). It is recommended that the graph in Figure 3 be used as an indication of reverse-current behavior with radiation fluence.

Gamma irradiation of reference diodes using cobalt-60 as a radiation source has caused essentially no change in reference voltage with total exposures of 8.8×10^5 rads (C).

Information on the effects of electron irradiation on voltage-reference on zener diodes is too limited for a graphic presentation, but do indicate that the reference voltage will change less than 1 percent at fluences of 5×10^{15} or 1×10^{16} e/cm^2 (E = 1.5 MeV).[1] Reverse curcurrent also remains stable with little or no increase at this fluence.

Special-Purpose Diodes

The data available on the effects of radiation on special-purpose or limited-use diodes and silicon-controlled devices are too limited for graphical presentation, and the devices themselves are not comparable to other devices for which data are available.

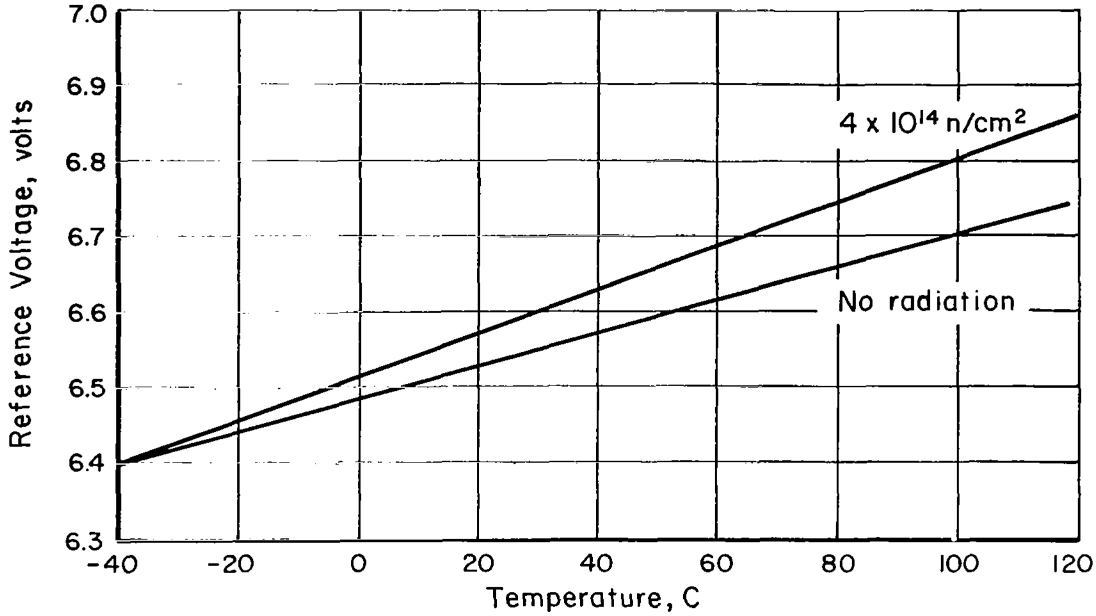


FIGURE 14. VOLTAGE-TEMPERATURE CHARACTERISTICS FOR IN745A(2)

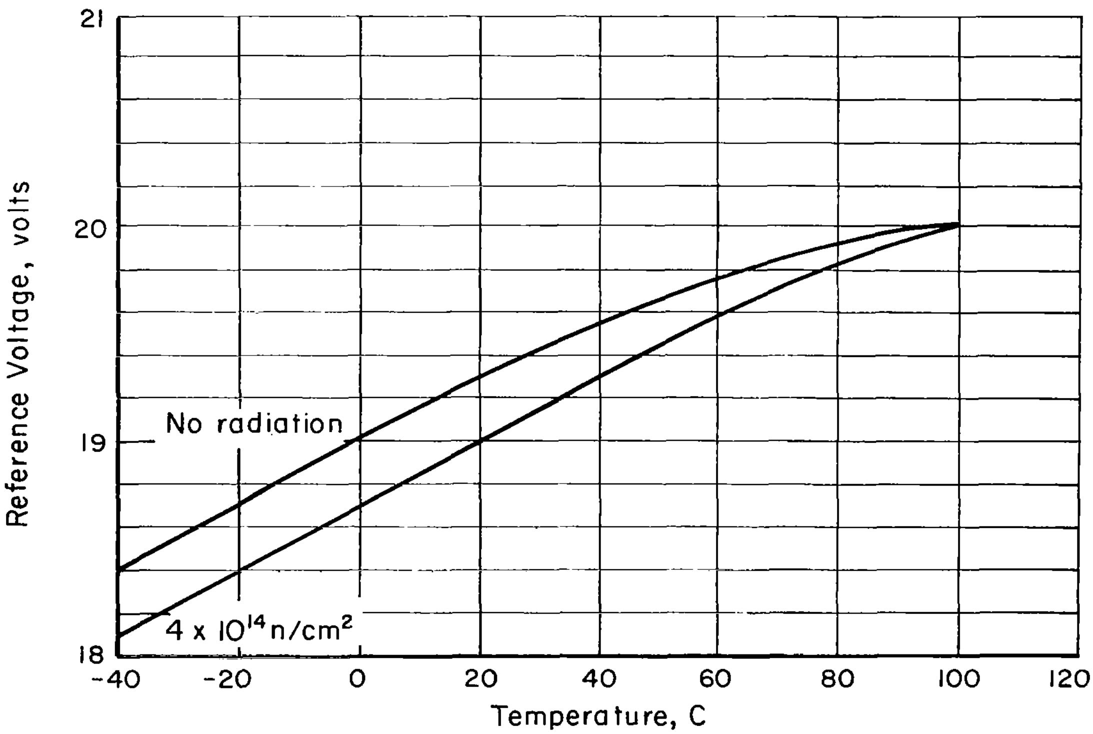


FIGURE 15. VOLTAGE-TEMPERATURE CHARACTERISTICS FOR IN968B(2)

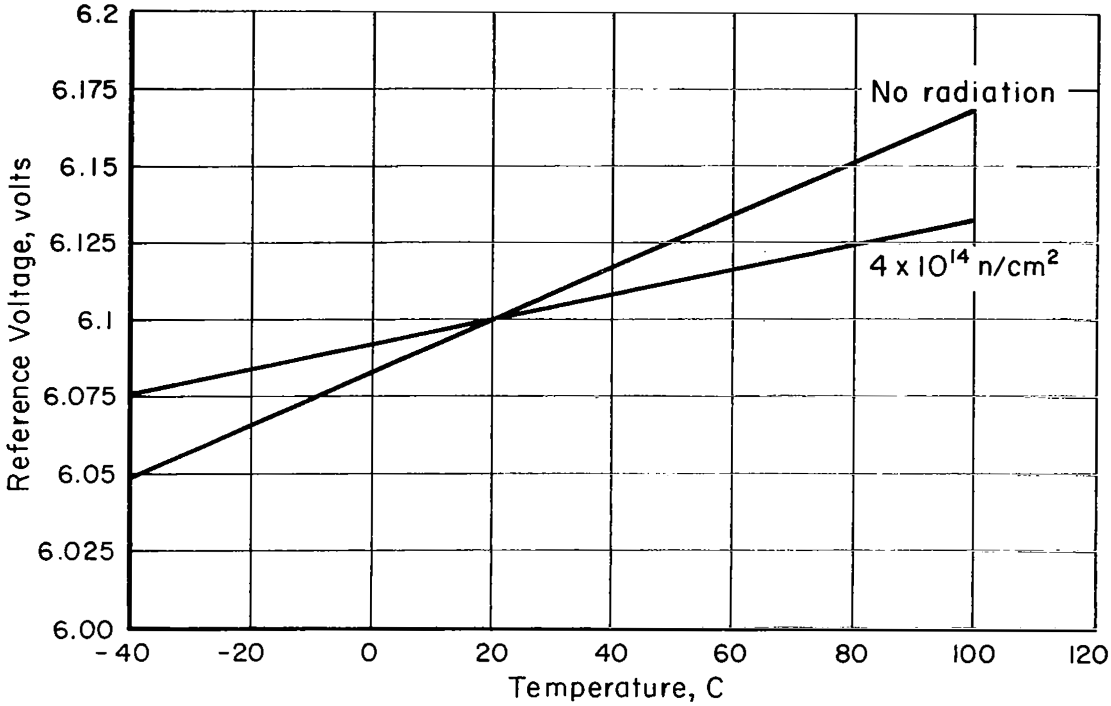


FIGURE 16. VOLTAGE-TEMPERATURE CHARACTERISTICS FOR IN829(2)

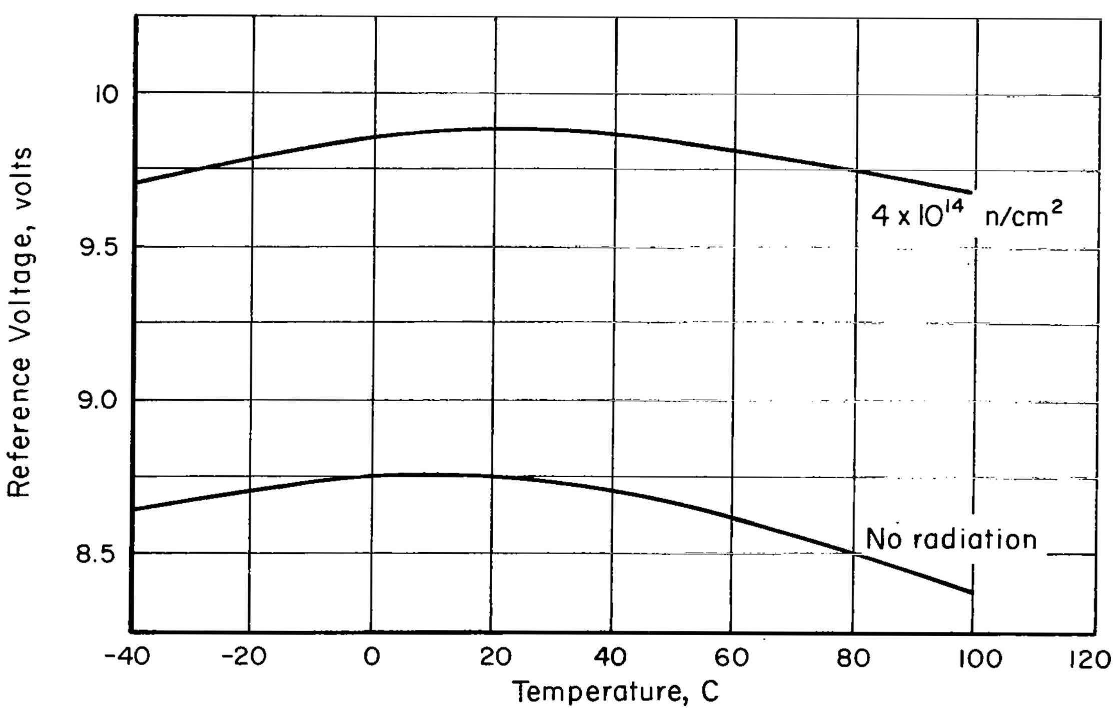


FIGURE 17. VOLTAGE-TEMPERATURE CHARACTERISTICS FOR IN939(2)

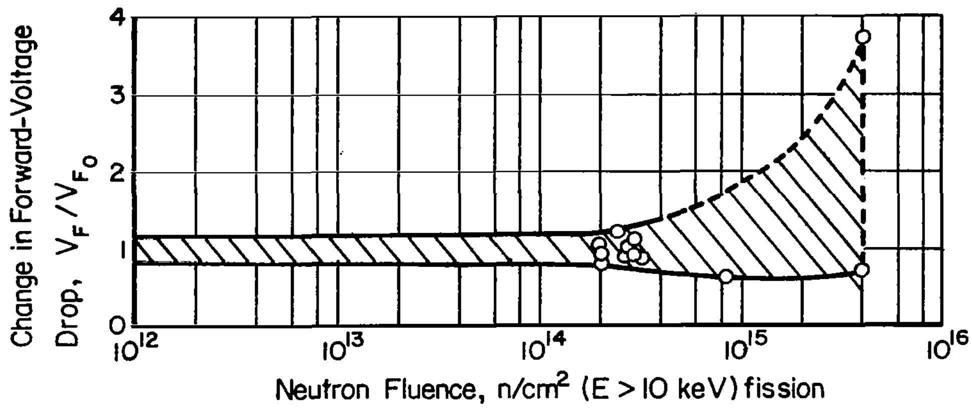


FIGURE 18. COMPOSITE OF CHANGES IN FORWARD-VOLTAGE DROP VERSUS NEUTRON FLUENCE FOR REFERENCE DIODES

12 Sets of Data

Tunnel Diodes

Tunnel diodes are majority-carrier devices which exhibit a negative resistance in their forward characteristic and may be used in various circuits including amplifier, oscillator, logic, and switching. They are less sensitive to a radiation environment than most other semiconductor devices. Gallium arsenide units have operated satisfactorily to fluences of 10^{17} n/cm^2 (E > 10 keV), while germanium units are expected to perform satisfactorily to 10^{16} n/cm^2 and silicon to 10^{15} n/cm^2.[3] Silicon units have shown a 100 percent increase in valley current at 1 to 3 x 10^{15} n/cm^2, with the increased current approaching the peak current value at 10^{16} n/cm^2 (E > 10 keV).

Study of N on P germanium tunnel diodes has shown them to be more radiation resistant by a factor of two than similar P on N devices.[4] Results of this study indicated that both types of devices would perform satisfactorily in a properly designed circuit to a fluence of 1.5 x 10^{16} n/cm^2 (E > 0.3 MeV) and 2.2 x 10^8 rads (C).

Early studies of the effect of electron radiation on tunnel diodes showed sharp increases in valley current until the negative resistance region was entirely destroyed at a fluence of 10^{17} e/cm^2 (E = 800 keV).[5] Other studies indicated similar effects from electron irradiation as a 1-MeV fluence approaches 10^{17} e/cm^2.[6]

Varactor Diodes

Varactor diodes are single-junction semiconductor devices that are used in variable-capacitance applications, their capacitance varying with applied voltage. Information available on the effects of radiation on these devices is inadequate for reaching general conclusions as to their resistance to a radiation environment. A radiation study in which this type of device was exposed to an electron fluence of 8×10^{15} e/cm^2 (E = 1.5 MeV) shows an increase in the reverse current but not of a serious degree since the greatest permanent increase in current observed was 245 nanoamperes.(1) The forward-voltage drop was essentially unchanged.

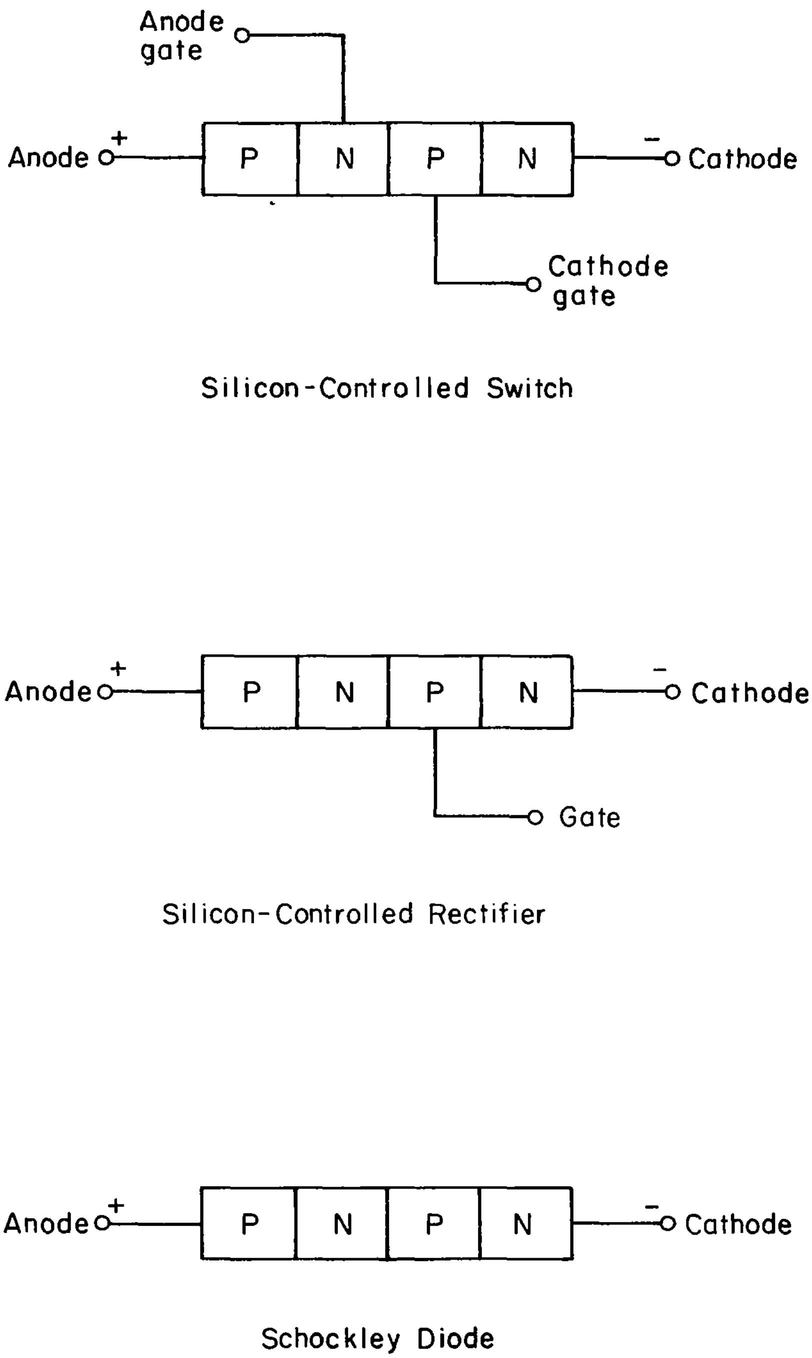
Microwave Mixer Diodes

Information on the effects of neutron and electron radiation on microwave mixer diodes indicates only minor variations in the d-c characteristics to fluences of 2.6×10^{16} n/cm^2 (E > 10 keV) and 8×10^{15} e/cm^2 (E = 1.5 MeV).(1, 7) The neutron fluence was from a reactor environment, which also included a gamma dose of 2.9×10^8 rads (C).

Silicon-Controlled Devices

Silicon-controlled devices are among the most sensitive of all electronic parts to a radiation environment. These include three basic units: the silicon-controlled rectifier (SCR), the silicon-controlled switch (SCS), and the Schockley diode. These units are all four-layer, pnpn semiconductor devices analogous to overlapping pnp and npn transistors, and they differ only in the external accessibility of the four layers through the attaching of electrical lead wires. The silicon-controlled switch has leads to all four layers of the pnpn semiconductor structure, while the silicon-controlled rectifier excludes the lead to the central n-region. The Schockley diode has leads only to the outer p- and n-layers. The structures of these devices are illustrated pictorially in Figure 19.

Exposure to radiation induces defects or bulk damage in silicon-controlled devices which reduces the current-transfer ratios of the two overlapping transistors. The reduction in transfer ratios increases the gate current, holding current, and breakover voltage required to switch these devices on or make them conduct. If the radiation fluence is great enough that the product of the transfer ratios of the two sections becomes less than one, no amount of gate current applied to a silicon-controlled switch or rectifier or increase in the voltage applied to a Schockley diode will cause them to conduct.



Silicon-Controlled Switch

Silicon-Controlled Rectifier

Schockley Diode

FIGURE 19. STRUCTURE DIAGRAMS OF SILICON-CONTROLLED DEVICES

Gate current requirements to fire a silicon-controlled rectifier increase rapidly at fluences above 2×10^{11} n/cm^2 (E > 10 keV). This is not necessarily the minimum fluence at which problems may occur with these units, since radiation-induced discontinuities have occurred at fluences as low as 1.09×10^8 n/cm^2 (E > 10 keV).(8) Complete failure where the unit fails to fire occurs at fluences as low as 10^{13} n/cm^2 (E > 10 keV). These problems indicate that the application of these devices in a radiation environment generally should be avoided if possible; if they must be used, the total fluence should not exceed 10^{11} n/cm^2 (E > 10 keV).

The application of silicon-controlled switches and Schockley diodes, being similar devices, should be approached with the same caution as that pointed out above, although data are unavailable for verification.

Schottky Barrier Diodes

The Schottky barrier diode, being a majority-carrier device, should have a relatively low sensitivity to a radiation environment. However, exposure to either ionizing or neutron radiation has resulted in the degradation of this type of device. Ionizing radiation, such as low-energy electrons, gamma rays, and X-rays, produce surface effects with a buildup of a positive space charge in the oxide and an increase in the surface velocity of planar devices. These surface effects are responsible for the degradation of the reverse current and excess forward current when the Schottky barrier diode is exposed to this environment.(9) The primary effect of neutron radiation is bulk damage, which includes carrier removal and decrease in bulk lifetime. The series resistance of the diode increases because of the carrier removal, while the decrease in bulk lifetime results in an increase in forward and reverse current.

The exposure of two different Schottky barrier diode-type devices (gold-silicon and chromium-protactinium-platinum-silicon) to a total gamma dose of 10^8 rads resulted in increases in the reverse current that varied from a nominal change to almost four orders of magnitude.(10) This total gamma dose also resulted in large variable responses in the forward characteristic at currents below 100 microamperes, with relatively small changes being experienced at higher current levels. Reactor irradiation to a neutron fluence of 10^{14} n/cm^2 resulted in negligible changes in the characteristics of these same devices.

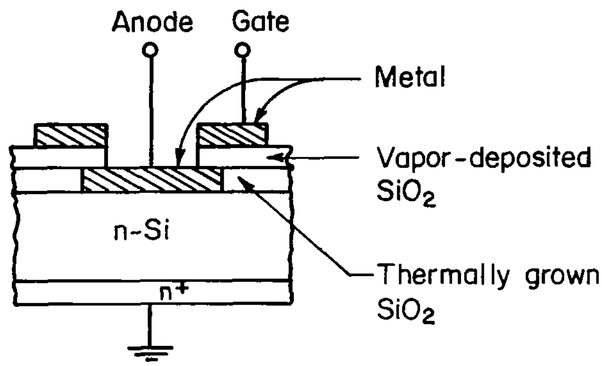
Annealing experiments following the irradiation of the above devices resulted in significant annealing at 150 C for units experiencing large changes in reverse current, while those having small increases required a temperature of 300 C.

Various physical configurations of aluminum-silicon Schottky barrier diodes were irradiated with low-energy electrons (15 to 20 keV) to a dose of 10^9 rads (SiO_2) at room temperature with their leads shorted.(9) These configurations, which are illustrated in Figure 20, include a p-n guard-ring diode, an overlap diode, and a non-overlap diode. The p-n guard-ring diode experienced no degradation in reverse current below a dose of 10^8 rad (SiO_2) and an increase of approximately one order of magnitude to 1.0 nanoampere at 10^9 rad (SiO_2). The overlap diode was more sensitive: the reverse current increased an order of magnitude at 10^8 rad (SiO_2) and approached another order of magnitude increase at $\sim 5 \times 10^8$ rads (SiO_2) for a reverse current of 100 nanoamperes. The non-overlap diode was even more sensitive to the radiation environment.

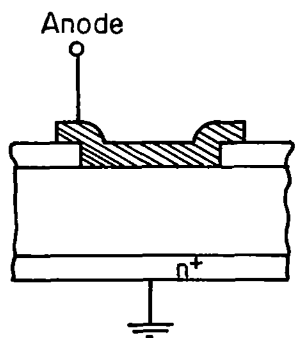
The gate-controlled diode configuration, which is also illustrated in Figure 20, was constructed as platinum-silicon devices and aluminum-silicon devices. The electron dose to which these units were subjected was 10^8 rad (SiO_2), and resulted in a large increase in reverse current. The platinum-silicon devices were considerably more sensitive to the radiation than the aluminum-silicon devices in this respect and also in the degradation of their forward characteristic, in which they experienced increases in forward current at low voltages. The forward characteristic of the aluminum-silicon units was insensitive to the low-energy electron dose of 10^8 rad (SiO_2), with any excess current from the irradiation being masked by the normal thermionic emission current of these devices. The effect of the gate voltage upon the forward and reverse currents of the gate-controlled diodes was shifted by exposure to the low-energy electron environment in such a manner as to require a more negative gate voltage to obtain a change in current similar to that prior to irradiation.

Neutron irradiation to fluences of 10^{15} n/cm^2 (E > 0.1 MeV) also resulted in large amounts of excess current at low forward voltages in the platinum-silicon devices because of recombination in the space-charge region.(9) The normal thermionic emission current of the aluminum-silicon devices again completely masked any increase that might occur in these units. An increase in the diode series resistance from carrier removal was evident in both the platinum-silicon and aluminum-silicon devices.

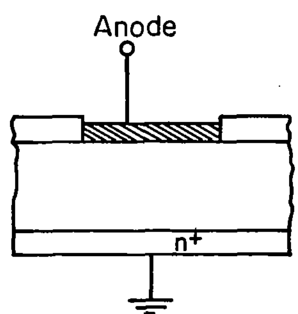
Gate-controlled diode



Overlap diode



Non-overlap diode



p-n guard ring diode

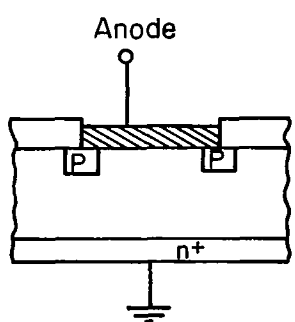


FIGURE 20. STRUCTURE OF SCHOTTKY DIODES[9]

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