SECTION 8. DIODES

8.1. INTRODUCTION

The semiconductor diode performs a large variety of electronic functions. These include rectification or "blocking", switching, photo-current generation, light emission and Zener breakdown at an electronic barrier, most commonly a diffused p-n junction (Grove, 1967). Other barriers include epitaxial and implanted junctions, the heterojunction and the Schottky barrier. Materials include silicon, germanium and all the compound semiconductors. P-n junctions form sub-elements of all integrated circuits (e.g. source/drain junctions of MOS devices), but this section will discuss mainly the discrete silicon p-n junction diode.

Unless heavy neutron irradiation is involved, rectifying action is not affected seriously by radiation; optical diodes, however, may be seriously affected (see e.g. Martin et al (1983); Eisen & Wengen (1982)).

8.2. MECHANISMS

The changes in minority-carrier lifetime, τ, and resistivity, ρ, produced in silicon by bulk radiation damage are reflected in the response of p-n junction devices to radiation. In a p-n junction, both forward and reverse I-V characteristics contain lifetime terms. For forward current:

$$I_F \propto \frac{\sqrt{\rho}}{\tau} \qquad \text{......8(i)}$$

where I_F is the forward current for a given voltage. The reverse current is composed of diffusion and generation current.

The latter is increased if τ is reduced:

$$I_{gen} \propto \sqrt{\frac{1}{\tau}} \qquad \text{......8(ii)}$$

The reverse diffusion current which flows when a diode is illuminated also contains a lifetime term:

$$I_{diff} \propto \frac{1}{\tau} \qquad \text{......8(iii)}$$

Thus, we can estimate the effects which a given amount of lifetime damage will produce although, in the case of reverse leakage current, the magnitude of surface leakage is usually greater than either of the above terms and less predictable. Carrier removal will, of course, also increase the voltage drop produced by a current flowing across the base region of a diode. The principles described above apply also to the metal-semiconductor junction diode (Schottky barrier) used in some nuclear diodes, photodiodes and integrated circuits.

"Surface effects" on several device structures (e.g. rectifier diodes and transistors) are described later. The term embraces a wide range of effects which vary with the treatment applied to p-n junctions where they meet a surface. In oxide-passivated ("planar") diodes, it is predictable that surface leakage will be increased by irradiation. Normally, the magnitude of surface effects will be determined by the ionising dose received, such dose having an ionisation, not a bulk damage effect.

8.3. EQUIVALENT FLUENCES

It is often possible to "simulate" the effect of irradiation of one particle by using another, more easily available, type of particle. This is discussed more fully under bipolar transistors. However, much of the research into this principle was performed with solar cells as test vehicles (see e.g. G.J. Brucker and B. Markow (1967); B.L. Gregory and F.L. Vook (1968); W. Rosenzweig (1962); J.R. Carter Jr. and H.Y. Tada (1977)).

Table 8(1) shows the relative effect of various particles on solar cells. In the diodes in question, a given fluence of reactor neutrons "is equivalent to" a larger fluence of 10 MeV electrons and a still larger fluence of 1 MeV electrons. In the case shown in Table 8(1), one reactor n.cm^{-2} is equivalent to 2000 normally incident 1 MeV electrons.cm^{-2}: a useful conversion when test results are compared.

This convenient principle of equivalent fluences applies to most solar cells because, given this structure, atomic displacement effects ("bulk damage") are dominant degradation mechanisms. The principle need not apply if surface or interface effects are significant, as is the case with many blocking diodes, especially those with the oxide passivated (planar) structure. Some of the data of diodes and transistors presented in this document originate from U.K. defence programmes (Martin et al (1983)). They describe devices tested in the HERALD and VIPER reactors at neutron fluence values in the range 10^{12} to 10^{13} n.cm^{-2} (E_n 10 keV). On the basis of Table 8(1), one could assume the damage-equivalent fluences for a test in a 1 MeV electron beam at 90° incidence to be 2 x 10^{15} and 2 x 10^{16} e.cm^{-2} respectively. In comparison with the exposure levels inside spacecraft (less than 10^{13} e.cm^{-2} or 300 Krad), these are very high. The reactor test data are therefore mainly useful in that they provide the design engineer with some documentary evidence of the comparative severity of radiation problems with one device type or another in the space environment and with guidance as to how to structure the evaluation of radiation at the calculated mission exposure levels.

As Van Lint(1980) says: "The most common need is to establish an upper limit for the damage produced by one particle type (using) experimental data (obtained from) another particle type". He stresses that calculation, although an approximate procedure, is a useful one.

8.4. SOLAR CELLS

The cells in solar-cell arrays on spacecraft are protected by thin cover glasses. The resistivity of the silicon base region may be 1 to 10 ohm.cm, n- or p-type, with various refinements of diode structure. When cells are exposed to space radiation, all of these factors affect their degradation. Degradation versus time predictions in a given orbit are made by a computer program in which all these factors are adjusted (Debruyn and Jensen (1983)). Other forms of optoelectronic diodes are dealt with in later sections.

TABLE 8(1) - CRITICAL PARTICLE FLUXES, ϕ_{CRIT}, REQUIRED TO PRODUCE 25% AND 50% DEGRADATION OF SHORT-CIRCUIT CURRENT UNDER AM = 0 ILLUMINATION OF 10 OHM.CM N-ON-P SILICON SOLAR CELLS (1)

	ϕ crit (25%)	Damage ratio $\frac{K\tau\ (\text{particle})}{K\tau\ (1\ \text{MeV})}$	ϕ crit (50%)	Damage ratio
10 MeV protons	8.0×10^{12}	6250	1.8×10^{13}	6666
Reactor neutrons	2.5×10^{12}	2000	6.0×10^{13}	2000
10 MeV electrons	3.0×10^{14}	16.7	8.0×10^{15}	15
1 MeV electrons	5.0×10^{15}	1.0	1.2×10^{17}	1.0
Co-60 gamma rays	1.8×10^{18}(2)	0.003	–	–

NOTES

1. Values taken from "The Solar Cell Radiation Handbook", Report No. 21945-6001-RU-00 (TRW Systems Group, Redondo Beach, Cal., USA, 28 June 1973: Fig. 3-6, pp. 3-21).

2. This fluence yields a dose of approx. 10^9 rad (Si).

8.5. LOW-POWER RECTIFIER DIODES

Low-power rectifier diodes are usually of a planar structure and exhibit low leakage before irradiation. Thus, small radiation-induced alterations in surface charge may produce noticeable effects on the measured leakage even though such leakage does not often become a serious functional hazard. A typical result of electron beam irradiation, carried out by JPL on a sample group of GE 1N4148 signal diodes, is given by Stanley et al (1976) and Price et al (1981/82). After a fluence of 10^{13} electrons.cm^{-2} of energy 2.2 MeV, an ionising dose of approx. 300 Krad (Si), the mean reverse leakage current at 15V increased from a fraction of a nanoampere to about 1 nA. However, the device did not exceed the specified value of 25 nA. Only a very small change in the forward characteristic was observed. The authors of the JPL test report comment elsewhere (Price et al (1981/82)) that diodes, when exposed to such doses as used, exhibit "inherent radiation hardness" and that consequently not many tests on diodes were performed. The above is borne out by test results from other European programmes. However, Bräunig et al (1981) also discuss elsewhere the occurrence of "mavericks", i.e. exceptionally sensitive diodes (Wagemann et al (1973)).

One U.S. manufacturer advertises a radiation-characterised form of diode, type 1N5430. This diode has a guaranteed performance after a fast neutron dosage, ϕn , of 10^{14} n.cm^{-2} ($\Sigma > 10$ keV; isotope gamma rays of the order of 10^5 rads can be assumed to accompany the neutron). Typically, the reverse current at 50V increases from 20 to 22 nA at $\phi n = 10^{14}$ cm^{-2} and 32 nA at $\phi n = 10^{15}$ cm^{-2}. Minimum and maximum limits of certain post-irradiation parameters are given in the data sheets.

Generally, low-power silicon rectifiers exposed to a fluence of 3×10^{12} reactor neutrons.cm^{-2} show a small change in forward voltage drop of the order of ±5%. Such a change can normally be neglected. On the other hand, in some tests (Eisen and Wenger (1982)), changes in reverse leakage were found to be as large as 500% if the initial leakage was low, e.g. in the 10 nA range, the post-irradiation values being in the region of 100 nA. In this case, the effect would be produced by the ionisation accompanying the reactor neutron fluxes used for testing.

It is to be expected that reverse leakage currents will be both noticeable and more severe when a diode is under a high reverse voltage or when low leakage currents may affect the circuit as, for example, in photomultiplier circuitry.

8.6. HIGH-POWER RECTIFIER DIODES

In high-power diodes, an increase in the forward voltage drop may be of greater significance than in low-power devices because power dissipation will increase noticeably. After 3 x 10^{-2} $n.cm^{-2}$ (reactor), an increase in forward voltage drop as large as 100% at 1A was observed in some power rectifiers (Eisen and Wenger (1982)). It is probable that types which exhibit a much smaller change are available.

8.7. ZENER DIODES

At reactor neutron exposures in the 10^{12} cm^{-2} range, Zener breakdown voltages do not change more than 10 mV, well within the limits of the usual commercial devices.

Bräunig et al (1981) show a similar change from a fluence of 10^{13} cm^{-2} of 2.2 MeV electrons.

8.8. LIGHT-EMITTING, PHOTO- AND NUCLEAR DIODES

These devices degrade quite strongly under particle radiation. They are discussed in detail in a later Section.

8.9. CONCLUSIONS

Although the reaction of diodes to irradiation is generally much less profound than that of transistors, semiconductor diodes have active junctions and may develop leakages or undue forward resistance when irradiated heavily under demanding stress conditions.

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Note: the information in this report is not secret, but distribution may be restricted to certain agencies.

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