SECTION 13. OPTOELECTRONIC DEVICES

13.1. INTRODUCTION

The term optoelectronic devices is taken here to mean devices which are activated by, or emit, light. Frequently, a pair of these devices are used together as a transmitter and a receiver of light signals. Optical fibres have been dealt with in a separate section, as have passive optical media. We will not discuss display devices which are unlikely to play a major part in equipment exposed to space or nuclear radiation. Most of the devices subject to exposure will be of the semiconductor type, but brief mention will also be made of light sensors of the vacuum-tube type. In general, vacuum tubes and other devices with glass envelopes are tolerant to radiation, but rarely used due to their bulkiness and high electrical power consumption and high voltage supply requirement.

Optoelectronic devices, in which the active elements are semiconductors, are frequently sensitive to radiation because the absorption or generation of light in a solid medium is often influenced by the defect structure of that medium (hence, the first studies of radiation damage were "on colour"; see section on "optical media"). For example, light-emitting diodes operate by the recombination of excess carriers via impurity centres in a III-V compound. Neutron-induced centres can interfere with this process. The detection of light in silicon usually operates by the collection of the minority carriers generated by the light. Neutron or surface damage can interfere with this collection process. The darkening of transparent coatings or encapsulations around a semiconductor chip (glass or polymer) is also a possibility. In the case of vacuum tubes, such as TV or multiplier tubes, the mechanisms of light generation and sensing are not as strongly affected by radiation damage, but one must always ensure that the transparent envelope is not darkened in the window region. A major radiation characterisation programme for visible and IR LEDs, photo-transistors and optocouplers was carried out for ESA by Crouzet in 1980 and updated in 1985.

13.2. LIGHT-EMITTING DIODES (LEDs)

When a p-n junction in a III-V semiconductor is forward biased, the carriers pass into and across the junction, and recombine near the junction. Given suitable defect centres, the recombination is accompanied by light of a photon energy slightly less than the band-gap energy of the semiconductor. The efficiency of conversion of electrical power into photon events is directly proportional to the minority carrier lifetime in the active regions of the diode. Particles can affect the light output efficiency of the system in two ways:

1. as for transistors, neutron damage reduces the minority carrier lifetime in the active regions and

2. as particles produce new defects (recombination centres), the radiation-induced defects compete for carriers with the pre-existing luminescent defects. This may further reduce the light output efficiency.

The importance of the two damage effects will vary quite strongly with the impurities used and it is not surprising therefore that some designs of light-emitting structure are found to be more affected by neutron irradiation than others. The more sophisticated epitaxial structures (often multilayer ones) are often strongly affected by a neutron exposure of 10^{12} n.cm^{-2} (1 MeV). The non-epitaxial zinc-diffused gallium arsenide diodes are less strongly affected, while Si-doped GaAs diodes are damaged in the same way as the epitaxial type. Barnes has studied neutron/gamma effects (1972) and Stanley tested LEDs using high-energy electrons (1970). JPL has also explored LEDs to 2.5 MeV electrons (1985). Thompson and Janssens (1978) showed that there is significant injection annealing of LEDs which may balance the radiation degradation. Judicious choice of forward current and duty cycle could extend the life of LEDs in the space environment.

In the photovoltaic mode, the photodiode operates on the same general principle as the solar cell. Minority carriers, generated by light, diffuse to the p-n junction and are collected. The region from which carriers can be collected is determined by the diffusion length, L, of minority carriers in the base (low-doped) region of the diode. L^2 is equal to $D\tau$, where 'τ' is the minority carrier lifetime and D is the minority carrier diffusion constant. As described earlier, particles degrade minority carrier lifetime. Thus, the fractional photovoltaic efficiency n/n_o of a diode as a function of neutron fluence can be predicted from first principles by a method similar to that described earlier for the degradation of transistors. The photovoltaic mode is useful when the signal amplitude is to reproduce the variations in light intensity. The speed of response, however, is limited by the time taken for carriers in the base to diffuse to the junction.

In the photoconductive mode, only the carriers created within the electric field of the junction (depletion region) are collected, which increases speed of response. In addition, this removes some of the dependence of the performance on minority carrier lifetime and thus reduces the effect of neutron bombardment. Some effects will still occur because leakage and series resistance are also increased by neutron bombardment and affect the light-generated signal.

According to the "SIRE" data compilation, reactor neutron fluence of about 3 x 10^{12} n.cm^{-2} (1 MeV) reduces the photo-current (presumably in the photovoltaic mode at "short circuit") of type TIL78 and other devices.

At this fluence, the photo-current was reduced by about 90%. In another device, the Ferranti MS7B, operated at open circuit (roughly equivalent to photoconductive mode), the signal decreased by 32% for the same order of neutron fluence. As the mechanisms of photodiode degradation are understood, it should theoretically be feasible to generate engineering prediction curves of performance versus time in space (or particle fluence).

13.3. PHOTOTRANSISTORS

A phototransistor consists of an npn or pnp structure designed in such a way that the base region is efficiently exposed to a light beam. The minority carriers produced constitute the signal normally supplied electrically by the base contact and, when the normal V_{CE} bias is supplied, collector current flows at a value proportional to the light intensity. The "base current" is, of course, amplified by h_{FE} (see Section 5) and neutron damage will accordingly affect the responsivity of phototransistors. The gain of a phototransistor is, in fact, directly proportional to the minority carrier lifetime in the base region (A.G. Stanley, 1970). Under neutrons, light-activated relays (thyristors, etc.) should behave in the same general way as phototransistors.

The degradation of the output current of an LS600 phototransistor after exposure to 2 x 10^{12} reactor neutrons.cm^{-2} was 80% (SIRE). Given the above direct dependence on minority carrier lifetime, it is unlikely that phototransistors of greatly improved tolerance to radiation can be found and this form of light sensor should be dispensed with when the predicted degradation cannot be tolerated. Since a phototransistor can be considered as a photovoltaic diode with a built-in amplifier, it is reasonable to assume that most signal applications, normally dealt with by the use of phototransistors, can be achieved by means of a photodiode followed by a radiation-tolerant amplifying device (junction FET, high-frequency transistor). Photosensitive field-effect transistors are obtainable, but no radiation test data are available at present.

As for photodiodes, prediction curves for phototransistors can be produced.

13.4. OPTOCOUPLERS

Optocouplers (opto-isolators) are devices which employ a light beam to achieve electrical isolation between a signal input and the rest of an electronic circuit. The usual types consist of a light-emitting diode facing a photodiode or phototransistor chip across a small thickness of an optical medium such as polymer, glass or, in some cases, air. A new series of "photologic" consists of an optical-fibre input and an electrical output, usually a logic voltage. The response of these devices to radiation damage is simply a combination of the degradation of the component parts. Thus, for example, it is not surprising that isolators employing phototransistors are more sensitive than those employing photodiodes (see earlier parts of this section).

A degradation of about 70% in the current transfer ratio (I_{in} vs I_{out}) was found after exposure of a phototransistor (type TIXL 101) to a neutron fluence of 2 x 10^{12} reactor neutrons.cm^{-2} . Because of surface effects, 10^5 rad gamma rays also produced degradation. Brucker (1978) estimates the threshold of damage to optoisolators to be in the region of 5 x 10^{10} for the photodiode types and of 10^{10} for phototransistor types. He derives these estimates from data by Barnes on light-emitters (threshold of damage 10^{11} n.cm^{-2} (14 MeV)) and some of his own data on p-i-n diodes, showing some degradation at 10^{11} n.cm^{-2} (14 MeV) by use of a factor of two for relative damage effect. Brucker (1978) thus gives a figure of 5 x 10^{10} n.cm^{-2} (14 MeV) for optoisolators, but the above explanation shows that this is very much a worst case, i.e. the fluence at which the first detectable damage is observed in quite sensitive devices. The data on the TIXL 101 shows that, for some types of optoisolators, circuits which will survive much higher levels than 5 x 10^{10} n.cm^{-2} could, in fact, be designed even with commercial devices.

13.5. IMAGING CHARGE-COUPLED DEVICES (CCDs)

These devices find application in control and stabilisation systems such as star-trackers and as imaging elements in the focal plane of camera-type instruments.

Certain scientific CCD types have a response to X-rays which is useful for astronomy, including spectroscopy. X-ray telescopes with cooled CCDs at the main focus are being adopted for several US and ESA projects (see, for example, ESA SP-1097; Lumb and Holland 1988a). Other applications of X-ray imaging are also being investigated.

Most imaging CCDs are comparatively radiation-sensitive with typical failure levels in the range of 3 to 10 kilorads. Some work has been performed on radiation-hardening and a hardened array is offered by Texas Instruments for military applications.

The most noticeable consequence of radiation damage is an increase in dark current due to interface state generation (Saks, 1980; Debusschere, 1984) and this is generally the main reason for device "failure".

For X-ray astronomy missions, a cooled CCD is used in the photon-counting mode. In this mode, the device is very sensitive to radiation-induced defects in the silicon. These defects may retain part of the signal charge, which may only consist of a few hundred electrons. As a result, the measurement of X-ray energies may be seriously affected by a total dose of a few kilorads (see, for example, J.R. Janesick 1988). However, methods of minimising this effect are being developed by ESA projects (see, for example, Lumb and Holland, 1988b).

When CCDs are used a star trackers, particle radiation can produce signals which could be mistaken for stars. An analysis of this type of interference should be made of any mission passing through radiation belts (see, for example, J. Daniels and A.D. Holland, 1987).

Using 150 kV X-rays, ^{60}Co and protons to 50 MeV, it has been found that the damage is independent of the type of radiation and only a function of total dose (Debusschere, 1984). Some initial studies, also carried out by Debusschere, evidenced that imaging CCDs can be hardened using the well-established MOS hardening techniques.

13.6. ELECTRO-OPTIC CRYSTALS

Inorganic and organic materials possessing certain types of crystal symmetry may demonstrate the electro-optic effect. Examples of this effect are bi-refringence, doubling of laser light frequency, light valve, piezoelectric and pyroelectric action and other ferroelectric effects. Little study has been performed of space radiation effects on these materials as a class. Apart from a predictable darkening of some crystals due to colour centres or radiolysis, no known pattern exists in the radiation effects to be found in the megarad range. Test data, especially for quartz, will be found in many compilations.

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