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Proton Damage in Linear and Digital Optocouplers†

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Abstract

Fundamental differences in design influence the way that linear and digital optocouplers are degraded by radiation. Linear optocouplers are more affected by current drive conditions because the detector operates in a high-injection region when the LED produces normal light output, and do not have the extra operating margin that is inherent in digital optocouplers. Although LED degradation is often the dominant degradation mechanism in space, degradation of optocouplers with improved LEDs is limited by photoresponse degradation. Phototransistor gain has a relatively minor effect except at very high radiation levels.

I. INTRODUCTION

Optocoupler failures occurred on the Topex-Poseidon spacecraft after about two years of operation. Later work in the laboratory showed that the failures were due to extreme sensitivity of LEDs within the optocouplers to displacement damage from protons [1-3]. Although earlier work had been done on displacement damage in light-emitting diodes, none of the devices studied previously had been as heavily damaged at the low radiation levels where the optocouplers failed in space [4-7]. Subsequent work has shown that LED damage varies over an extremely wide range, depending on the particular manufacturing technology [8].

This paper discusses proton degradation of linear and digital optocouplers. One obvious way to harden optocouplers is to select LEDs that are more resistant to displacement damage. A direct comparison is made of degradation of a commercial linear optocoupler from one manufacturer with a hardened version of the same device with a different LED technology. Other factors, including degradation of optical photoresponse and transistor gain are also discussed, along with basic comparisons of digital and analog optocouplers.

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Linear optocouplers are designed with somewhat different requirements than digital optocouplers, which not only affects their radiation response but also the interpretation of radiation test data.

Optocoupler degradation depends on the degradation of both III-V and silicon devices. Consequently there is some ambiguity about how to compare damage at different proton energies because the energy dependence of non-ionizing energy loss (NIEL) is different for the two materials. In addition, recent experimental data on the energy dependence of proton damage in LEDs [9] does not agree with earlier calculation of NIEL for GaAs semiconductors that was based primarily on JFETs [10], suggesting that there are unresolved issues relating to NIEL in III-V devices. We have chosen to do our experimental work with 50 MeV protons, which is near the peak in the proton energy spectrum for many earth-orbiting systems with nominal shielding thicknesses of about 2.5 mm of aluminum. This reduces the magnitude of adjustments to account for the energy dependence compared to the approach used for solar cell degradation (10 MeV equivalent damage). The lower energy is appropriate for solar cells which are typically shielded only by a thin cover glass, but not for optoelectronic parts that are typically located inside shielded enclosures, increasing the mean energy of the protons that actually arrive at the devices.

II. COMPARISON OF STANDARD AND HARDENED LINEAR OPTOCOUPLERS

Initial evaluation of linear optocouplers was done on a device that was manufactured with a diffused LED with amphoteric doping. The 880 nm LED technology was chosen by the manufacturer because it provided significantly more light output than other types of LEDs, along with lower forward voltage. However, that type of LED is extremely sensitive to displacement damage, seriously affecting the performance of the device in space. Consequently, a modified version of the linear optocoupler was designed that used a double-heterojunction LED technology (820 nm).

Samples of the two types of light-emitting diodes used in the different versions of the optocoupler were provided by the manufacturer for radiation testing. Degradation of a typical LED from the standard device is compared with degradation of a double-heterojunction LED that is used in the hardened optocouplers in Figure 1. The revised LED provides about an order of magnitude improvement compared to the normal LED. The phototransistor was the same in both the hardened and standard devices.

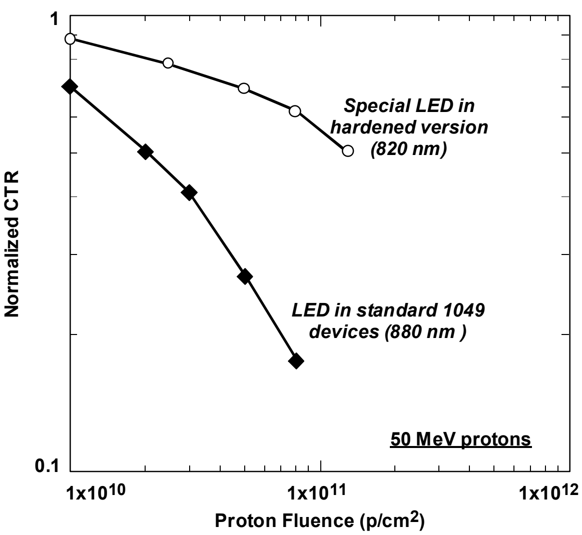

Figure 1. Degradation of the two LED technologies used in standard and hardened optocouplers.

The degradation of linear optocouplers fabricated with the two LED technologies is shown in Figure 2. The devices were irradiated with bias applied to the collector of the phototransistor, but with no forward current through the LED. Note the strong dependence of the degradation on the forward current of these analog optocouplers. Although the degree of improvement in CTR degradation is roughly what is expected from substitution of the LED, a closer examination of the results shows that there is actually less damage in the hardened device than expected from the difference in LED degradation alone. This is caused by the particular way in which analog optocouplers are designed to reduce both the variability in CTR between units and to "flatten" the strong negative temperature coefficient of the LED.

Figure 3 shows how CTR current dependence of the unhardened optocoupler changes after irradiation (the duty cycle of the measurements was low to eliminate possible interference from current-enhanced annealing [8]). The main reason for the decreased dependence on LED forward current is the deliberate operation of the phototransistor in a high injection. At low radiation levels the change in (optical) drive current as the LED degrades is small, so the operating point of the phototransistor remains near the flat region (with the normal range of LED currents). The decrease in LED output is partly compensated by the increased gain of the phototransistor as its operating point moves from high injection to the current where the gain is maximized. However, at higher radiation levels the light output of the LED is markedly reduced, and the operating point shifts to regions with steeper slope, where the falloff in CTR with current increases the amount of degradation beyond that expected from just the LED degradation.

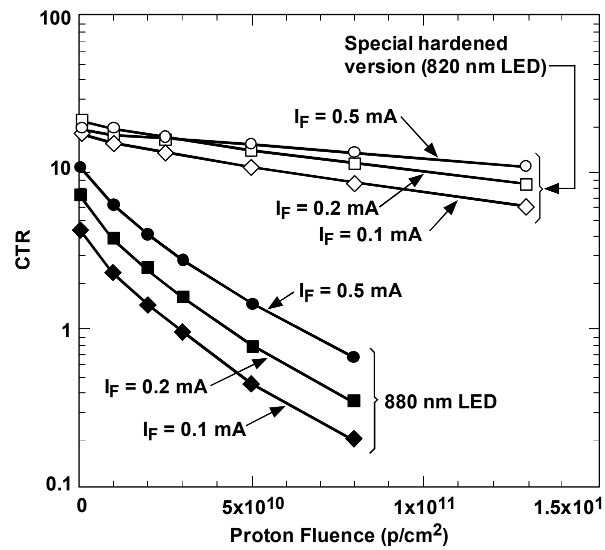

Figure 2. Degradation of standard and special versions of the OLH300 linear optocoupler.

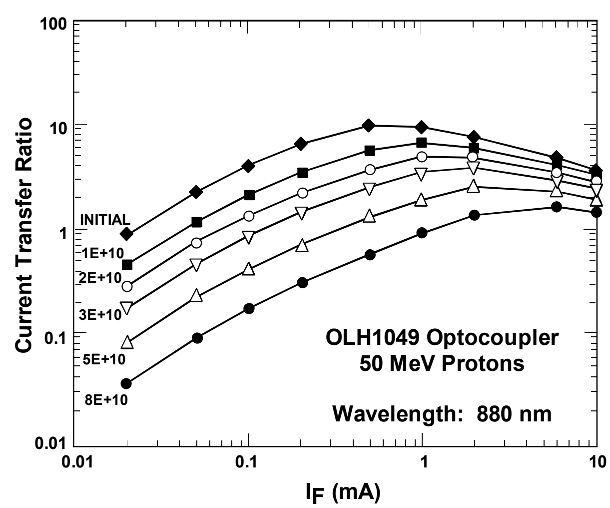

Figure 3. Degradation of the standard version of the optocoupler at various LED forward currents.

Figure 4 shows the current dependence of CTR for the improved optocouplers at various radiation levels. Initially these devices are deliberately operated well beyond the peak in the transistor characteristics (high injection region). This reduces the sensitivity to temperature effects in the LED and tightens the distribution of CTR. It also causes degradation in CTR to be less than the degradation in LED output because the reduced light output from the LED shifts operation to lower transistor current, where the transistor gain is higher. Thus, the particular way in which analog optocouplers are designed tends to mask internal changes in operating conditions until the collector current falls below the peak in the operating characteristics.

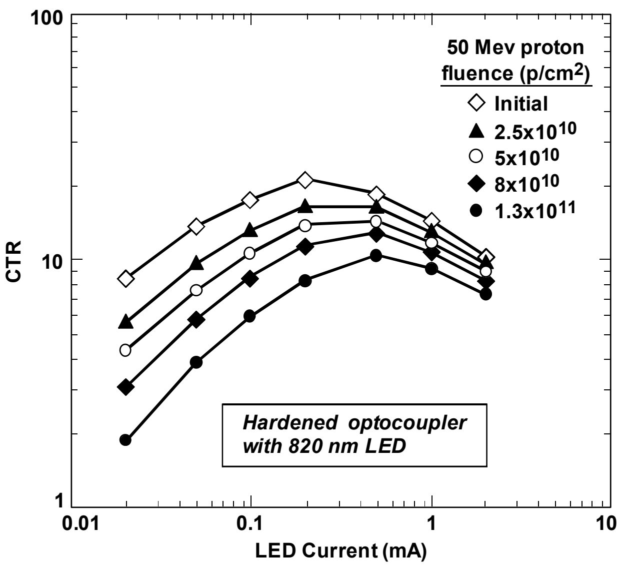

Figure 4. Degradation of the special version of the optocoupler at various LED forward currents.

As a result, linear optocouplers have a different dependence on fluence than digital optocouplers. CTR degradation in digital devices tends to track LED degradation, exhibiting large changes at low fluence levels which gradually "flatten" at higher fluences. The CTR degradation of linear optocouplers is less severe at lower radiation levels than that of digital optocouplers because the normal operating region of linear optocouplers is above the peak current region.

Some further comments are in order regarding LED degradation. Although only a limited number of LED types have been subjected to radiation testing, the evidence to date suggests that there are fundamental differences in the radiation sensitivity of two basic types of LEDs: diffused LEDs, which are fabricated with GaAs or AlGaAs (depending on wavelength); and double-heterojunction (DH) LEDs, which are fabricated with a more complex process that involves two or more layers of dissimilar semiconductor materials. Diffused LEDs are less costly to manufacture, and have very high efficiency near the wavelength where silicon has maximum responsivity (approximately 900 nm).

Figure 5 compares the degradation of four different types of LEDs from various manufacturers (the measurement current is approximately 50% of the maximum recommended operating current). Note the extreme difference between the degradation of the different LED technologies.

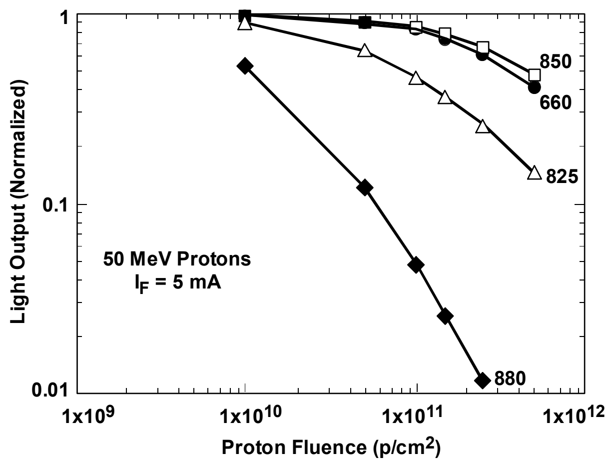

Figure 5. Degradation of several different LED technologies when they are irradiated with protons.

In addition to the difference in degradation, the two types of LED technologies also differ in the way that the damage anneals after irradiation. Damage in the diffused LEDs is affected by current flow during or after irradiation [2, 7, 10]. Substantial damage may recover when high operating currents are used, even for time periods of a few minutes. This is not only important for applications, but also needs to be carefully considered when doing radiation tests on LEDs or optocouplers. If measurements are extended into the high operating current region, a substantial amount of damage may anneal, reducing the apparent degradation when a series of stepped irradiation-and-measurement sequences are used. Although that may be appropriate for applications with high current, it may cause substantial underestimation of the damage that occurs with low forward current. Operating conditions during and after testing need to be carefully planned to take this dependence into account.

In contrast, damage in double-heterojunction LEDs exhibits only a very slight dependence on operating current. Although double-heterojunction LEDs would appear to be the best choice for optocoupler design, they are less efficient than diffused, amphoterically doped LEDs.

Optocouplers that use double-heterojunction devices must be designed with increased phototransistor gain or with lower current transfer ratio.

III. DIGITAL OPTOCOUPLERS

Digital optocouplers are intended for digital applications where the input LED is driven well beyond the active switching point, saturating the output stage. For example, Figure 6 shows the transfer characteristics of the Hewlett-Packard 6N134 optocoupler. These characteristics show the relationship where the device is functioning like a high-gain linear amplifier. The manufacturer does not guarantee performance in this region, but instead specifies that the device will function with a 10 mA load, driving the output to a guaranteed saturation voltage (with a resistive load) with the LED driven at 10 mA. This is more than a factor of three above the region where the device typically changes state, as shown in the figure, providing a large operating margin.

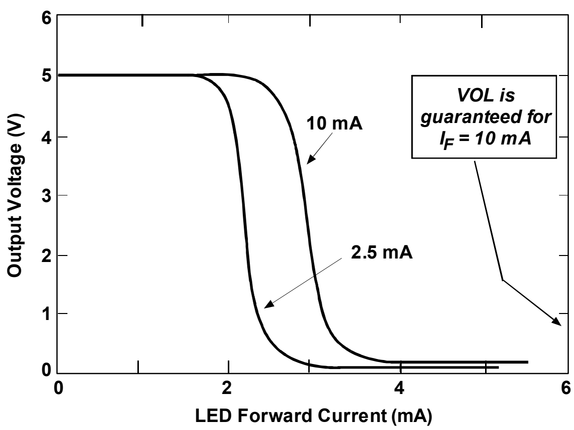

Figure 6. Transfer characteristics of a 6N134 digital optocoupler (unirradiated).

The active operating region of digital optocouplers is usually not measured for individual units. The active switching region varies considerably for different devices, and typically has a much stronger temperature coefficient that that of linear optocouplers. In most cases the transfer characteristics shift to higher LED current levels at high temperatures because of the strong negative temperature coefficient of the LED.

The CTR of unirradiated digital optocouplers depends weakly on LED current. However, for digital optocouplers with sensitive LEDs the CTR dependence on drive conditions changes after irradiation. Figure 7 shows how the CTR degrades for a digital optocoupler with a simple phototransistor detector. The recommended initial operating current of this device is 1 mA to reduce the effects of high current on LED reliability. Although this increases reliability (without considering radiation damage), operating in this region increases the sensitivity of the device to radiation because the LED output shifts the phototransistor to low operating currents. The change in CTR dependence on operating current is more severe for most digital optocouplers after they are irradiated compared to linear optocouplers.

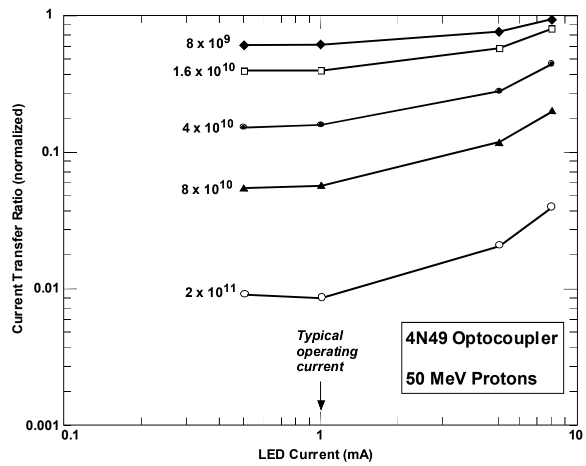

Figure 7. CTR dependence of the 4N49 optocoupler after various levels of proton irradiation

IV. PHOTOTRANSISTOR DEGRADATION

Linear optocouplers and some simplified digital optocouplers use basic phototransistors as detectors, although many digital optocouplers use more complex amplifier stages. Phototransistor gain degradation is one factor that contributes to CTR degradation in basic optocouplers, and that factor still remains when LEDs with improved radiation performance are used.

Figure 8 shows how protons degrade the gain of typical phototransistors. Five volts was applied between the collector and emitter during irradiation; the base region was left floating to simulate typical optocoupler applications. Measurements after irradiation were made in the conventional way, evaluating the transistor by applying a base current and measuring the resulting collector current just as for a normal transistor. One transistor is from a digital optocoupler and the other is from an analog optocoupler. In both cases very little degradation occurs until relatively high radiation levels are reached. These results were taken at a constant collector current (1 mA for the 4N49, and 100 µA for the transistor from the analog optocoupler). Far less degradation occurs when the phototransistors are irradiated to equivalent total dose levels with cobalt-60 gamma rays, so that the damage is dominated by displacement effects.

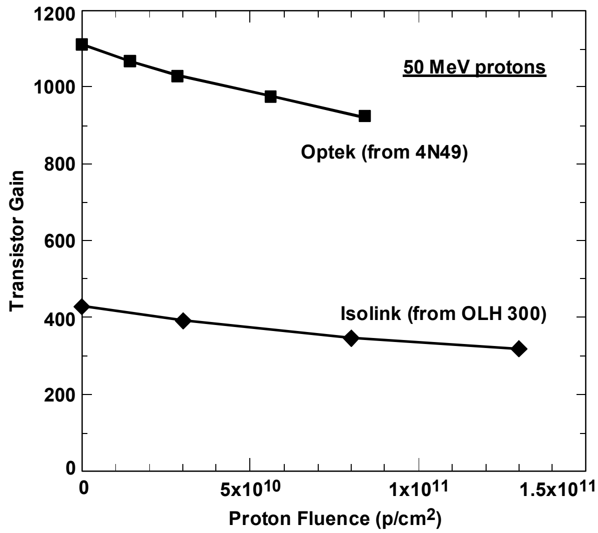

Figure 8. Gain degradation of phototransistors used in two different types of optocouplers.

Although discrete transistors are usually operated at fixed current, when phototransistors are used in an optocoupler the degradation of the LED light output will steadily reduce the operating current when the optocoupler is irradiated. Thus, the dependence of the transistor degradation on operating current must also be taken into account.

Figure 9 shows how the current dependence of phototransistor gain is affected by radiation. As shown in the figure, at a fluence of 3 x 10^{10} p/cm^2 the decrease in gain due to the shift in operating

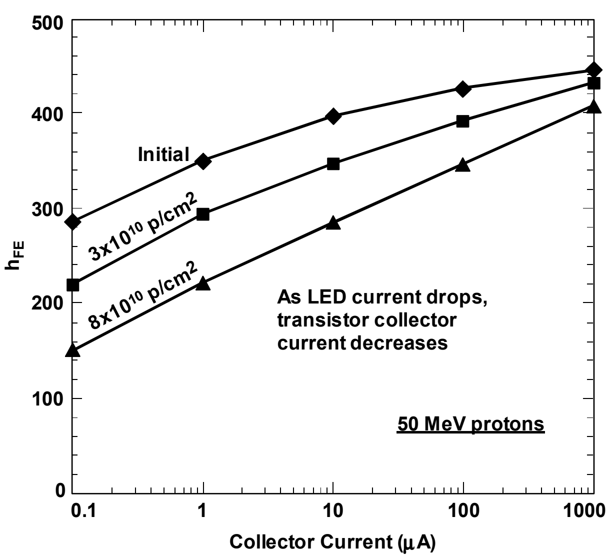

Figure 9. Dependence of phototransistor gain on operating current (transistor from an analog optocoupler process).

characteristics is comparable to the decrease in gain due to radiation. This can have a significant effect on the overall degradation of CTR. For example, the optical power of the 880 nm LED used in the standard linear optocoupler falls by about a factor of two at 3 x 10^{10} p/cm^2 (see figure 1). This lowers the operating current, and increases the degradation in CTR.

V. Optical Photoresponse Degadation

Selecting LEDs that are more resistant to radiation and modifying the detector circuit to reduce the dependence of CTR on transistor gain results in optocouplers with far less degradation to proton displacement damage than conventional optocouplers that operate at 880 nm. However, if conventional silicon photodetectors are used, there will still be significant degradation of the optical photoresponse. Most photodetectors use a high/low p-n junction that allows some light be collected by diffusion. Photoresponse degradation is affected by wavelength because the optical absorption depth depends on wavelength. At 880 nm, the "1/e" absorption depth in silicon is approximately 46 µm, while at 700 nm the absorption depth is only 5.6 µm. Some of the optical carriers will be collected within the depletion region, which is approximately 2 µm for typical photodetectors with lightly doped substrates. However, a large fraction of the light is collected by diffusion, particularly for longer wavelengths. The minority carrier diffusion length L_n in a p-substrate is

$$L_n = [D\tau]^{1/2} \qquad (1)$$

where D is the diffusion constant, and τ is the minority carrier lifetime. The diffusion length is reduced as the minority carrier lifetime degrades from radiation [11]. The diffusion length must be approximately three times greater than the absorption length in order to collect nearly all of the carriers. Measurable degradation occurs when the diffusion length falls below that threshold condition.

Figure 10 shows the photoresponse of silicon detectors from three different optocoupler technologies (the photoresponse was measured at the wavelength used in the optocoupler application). Note that there is about an order of magnitude difference in the fluence at which significant degradation occurs, which correlates with the wavelength. The dashed lines show calculations of photoresponse based on a model for solar cell degradation [12]. There is close agreement between the calculations and experimental data for the three devices at 50 MeV.

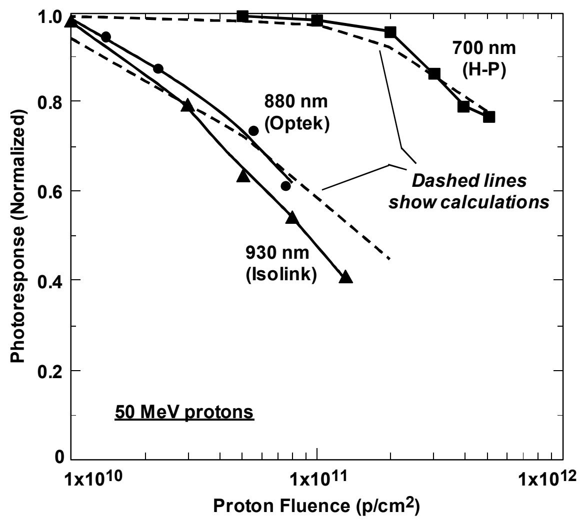

Figure 10. Degradation of optical photoresponse for detectors from three different optocoupler technologies.

Photoresponse measurements were also made on a discrete phototransistor that can be used over a wide range of wavelengths. The phototransistor was connected as a diode, measuring optically induced photocurrent in the base-collector junction. These results are shown in Figure 11. They are in general agreement with the results for optocoupler detectors used in Figure 10. Note that the degradation is much greater at longer wavelengths, in agreement with the assumption that the degradation is dominated by changes in minority carrier diffusion length.

The results in Figures 10 and 11 suggest that there is an upper limit to the radiation level for silicon-based detector technologies that corresponds to the inherent limitations of photoresponse. That limit can be adjusted upward by selecting LEDs with shorter wavelengths. However, conventional photodetectors have reduced optical sensitivity when short-wavelength optical sources are used, and thus it is necessary to trade off radiation hardness and CTR.

Other types of silicon detectors are available that do not depend on collection of photo-induced current from diffusion. We evaluated proton damage in a P-I-N detector at various wavelengths in order to compare its response to the damage that was observed in the photodiodes. The P-I-N detector was reverse biased at -5 V, which was sufficient to fully deplete the i-region of this device.

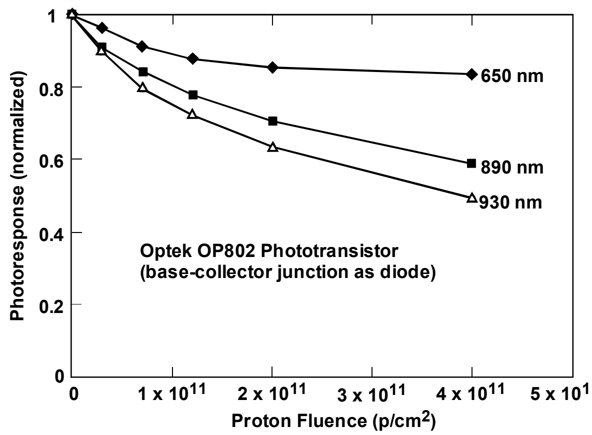

Figure 11. Degradation of the photoresponse of a general-purpose phototransistor at various wavelengths.

It is intended for applications with voltage between 5 and 20 volts. The degradation of photoresponse of the P-I-N detector is shown in Figure 12, using the same scale as that used for phototransistor degradation in Figure 10. Far less degradation occurred for the P-I-N detector, particularly at longer wavelengths. This illustrates that alternative detector technologies can improve optocoupler performance even further, more consistent with the improved performance of double-heterojunction LEDs.

Although the photoresponse of the P-I-N detector was relatively immune to displacement damage, the leakage current increased far more after proton irradiation than the leakage current of conventional photodiodes.

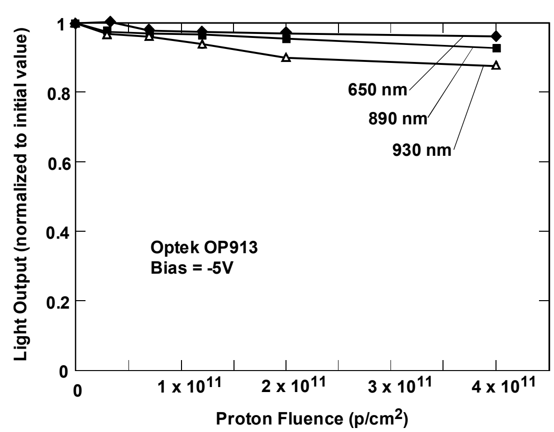

Figure 12. Degradation of the photoresponse of a P-I-N detector at various wavelengths.

VII. Discussion

Three underlying factors contribute to optocoupler degradation. All three factors are affected by displacement damage, and it is important to do radiation tests with high-energy protons, not just gamma rays, in order to determine how optocouplers will survive in typical space environments.

The most important factor is LED degradation. As noted in earlier work [1-3], certain types of LED technologies are extremely sensitive to displacement damage. However, it is possible to select optocouplers with double-heterojunction LEDs that are inherently more resistant to displacement damage. This typically will increase the radiation hardness by an order of magnitude or more. One must keep in mind however that optocouplers are hybrid devices. The specifications usually do not include the wavelength or basic technology of the LEDs. Some manufacturers purchase LEDs from external suppliers, and have little knowledge or control of the LED technology that they use other than their operation within the electrical specifications of the overall optocoupler. Variations in LED technology and supplier can cause optocoupler hardness to vary over a wide range, limiting the value of archival radiation test data.

Although one would normally expect transistor gain degradation to be important, typical phototransistors in modern devices have relatively narrow base regions which reduce their sensitivity to displacement damage. They also are relatively resistant to ionization damage. Even though gain degradation is the least important factor, the current dependence of transistor gain will add to the CTR degradation as the LED output degrades. That factor is particularly important for optocouplers with LEDs that are highly sensitive to displacement damage because the light output decreases so much at low radiation levels, forcing the phototransistor into a region with lower gain.

The third factor, optical photoresponse, has not received sufficient attention. For optocouplers with improved LED hardness, optical photoresponse is the largest contributor to CTR degradation, which is evident by comparing the LED degradation in Figure 1 with photoresponse degradation in Figures 10 and 11. Photoresponse degradation depends on wavelength because the absorption coefficient is wavelength dependent. It is possible to design structures with epitaxial layers that reduce the effective absorption depth. However, that design approach also reduces responsivity and efficiency. There are also alternative detector technologies with less degradation (see Figure 11) but it is likely that the photoresponse of conventional silicon photodetectors will be the limiting factor in the radiation performance of most optocouplers.

Radiation can also affect light transmission through the coupling material. That mechanism has not been important in any of the optocouplers that we have evaluated to date.

In summary, this paper has discussed proton degradation in two basic types of optocouplers. By selecting improved LED technologies, it is possible to use optocouplers at equivalent total dose levels of 20 krad(Si) or more in environments that are dominated by protons. With improved LEDs, photoresponse degradation is the most important factor in optocoupler degradation. Optocouplers that operate at shorter wavelength are less affected by photoresponse degradation because the light is absorbed in much shallower regions. That provides an inherent advantages for optocouplers that operate in the visible range (approximately 700 nm) compared to those that operate near the peak in silicon responsivity (900 nm).

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Abstract. Factors are discussed that contribute to degradation of optocouplers. Test results are compared for hardened and unhardened versions of a linear optocoupler. Photoresponse degradation is shown to be the limiting factor for optocouplers with conventional silicon detectors and integrated amplifiers.