Relative Degradation of Near Infrared Avalanche Photodiodes from Proton Irradiation

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Abstract:

InGaAs and Ge avalanche photodiodes are compared for the effects of 63-MeV protons on dark current. Differences in displacement damage factors are discussed as they relate to structural differences between devices.

INTRODUCTION & BACKGROUND

There continues to be a strong interest in the use of avalanche photodiodes (APDs) as space-borne optical communications data receivers. APDs are an attractive receiver choice for photon starved communications applications, because their internal gain mechanism can improve signal to noise ratio. The choice of APD for a particular application requires an advantageous combination of several factors, including high quantum efficiency, high frequency response, low noise, and high gain [1]. Radiation-induced changes in dark current are important to quantify, because dark current changes are an important component of such figures of merit as signal to noise ratio and noise equivalent power (NEP). The total spectral noise current of an unilluminated APD is given by:

$$i_n = \left[2q\left(I_{ds} + I_{db}M^2F\right)B\right]^{1/2} \qquad (1)$$

where I_{ds} is the unmultiplied surface dark current, I_{db} is the gain-multiplied bulk dark current, M is the gain, F is the excess noise factor, and B is the noise bandwidth [2]. Total dark current (I_d) is related to the parameters in (1) by:

$$I_d = I_{ds} + MI_{db} \qquad (2)$$

The receiver must also be appropriate for the laser wavelength being used. In previous work we presented gamma and 51-MeV proton results for several silicon APD structures, including a near IR-enhanced Si APD appropriate for 1064nm systems [3]. Silicon detectors have a long-wavelength responsivity cutoff at 1.1 μm, which corresponds to the wavelength of its bandgap. Therefore, detectors made from materials with higher absorption coefficients at long wavelengths are necessary for near infrared applications [4]. This paper discusses proton and gamma radiation degradation in Ge and InGaAs APDs suitable for wavelengths of 1300 and 1550 nm.

EXPERIMENTAL PROCEDURE

Two APDs were selected for the study, an InGaAs APD from Hamamatsu (G8931-03), and a germanium APD from Judson (J16A-18A-R100U). The InGaAs APD has an active area diameter of 30μm, and the Ge APD has an active area diameter of 100μm. Both are high-speed APDs, with cutoff frequencies of approximately 2 GHz and 1.5 GHz, respectively. The quantum efficiency of both devices is approximately 0.7 at 1300nm.

Four samples of the InGaAs APD were irradiated at Crocker Nuclear Laboratory, UC Davis, using 63-MeV protons to a fluence of 2×10^{12} p/cm^2. The devices were irradiated and characterized for changes in total dark current (I_d) (leakage current measured at operational voltages under unilluminated conditions), under a constant reverse bias. The voltage was that required for a pre-irradiation gain of approximately 10, and was approximately 0.95 V_{BR} (breakdown voltage) for these APDs. The mean value was 68.5V. One additional sample was irradiated under bias at the Jet Propulsion Laboratory's Cobalt-60 facility to a cumulative dose of 269 krad(Si) [1.04 Mrad(InGaAs)] to compare proton and gamma radiation effects.

Three samples of the Ge APD were irradiated to 2×10^{12} p/cm^2 at CNL. During testing it was determined that similar changes in dark current occurred in biased and unbiased samples. Therefore, only one of the three Judson devices was irradiated under bias, using a voltage that was approximately 0.9 V_{BR} (mean value of 30.9V); this corresponded to a pre-irradiation gain of approximately 3. All three devices were characterized at 0.9 V_{BR}. An additional sample was irradiated under bias using Cobalt-60 gamma radiation to a cumulative dose of 269 krad(Si) [1.01 Mrad(Ge)].

All irradiations were conducted at room temperature. Pre- and post-irradiation characterization was done at 25°C using a thermoelectric cooler (TEC). The temperature of the TEC modules was stable to within ±0.1°C. Characterizations were completed within five minutes after each irradiation to minimize annealing affects.

EXPERIMENTAL RESULTS

The InGaAs APDs had an average pre-irradiation dark current (I_{do}) of 5.6nA (at M = 10). Figure 1 shows changes in dark current (I_d) as a function of 63-MeV proton fluence. At the final cumulative fluence of 2×10^{12} p/cm^2, the APD dark current increased to a mean value of nearly 1 μA. Changes in dark current increased linearly with fluence at a rate of approximately 4×10^{-10} nA cm^2/proton. If this value is adjusted for M = 1, it is similar to the damage factor observed by H. Ohyama, et al. [5] for an InGaAs pin photodiode

subjected to displacement damage from 1-MeV neutrons. Very little annealing was observed following irradiation. After one month of unbiased annealing at room temperature, the average reduction in dark current was only 80nA (approximately 8 percent).

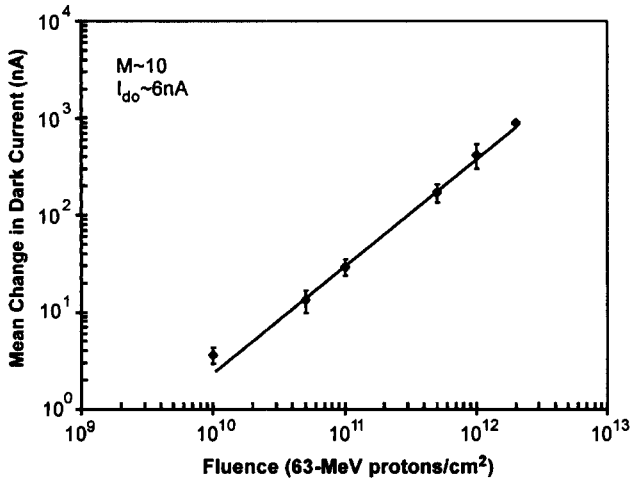

Fig. 1 Mean changes in dark current in the Hamamatsu InGaAs APD.

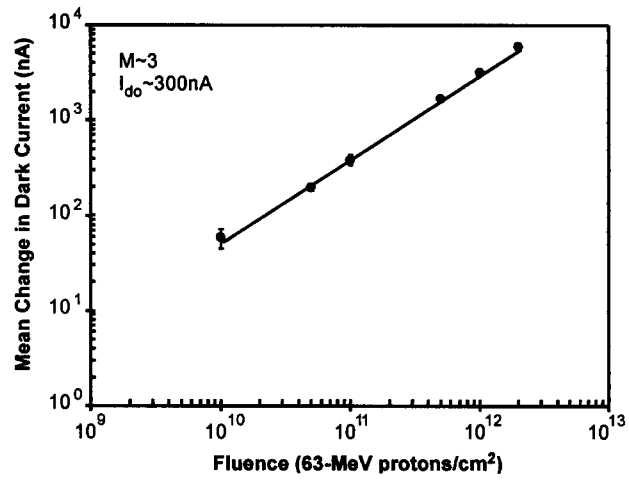

Fig. 2 Mean changes in dark current in the Judson Ge APD.

The Ge APDs had a pre-irradiation dark current of 299nA (at M = 3). Figure 2 shows the mean change in dark current for this device as a function of fluence. It was also linear over the entire fluence range. The damage factor was approximately 3.5 x 10^{-9} nA cm^2/proton. The mean value at 2 x 10^{12} p/cm^2 was approximately 6 μA. Unlike the InGaAs APDs, this device showed significant annealing while unbiased at room temperature, showing a 50% reduction in dark current after several hours (Fig. 3).

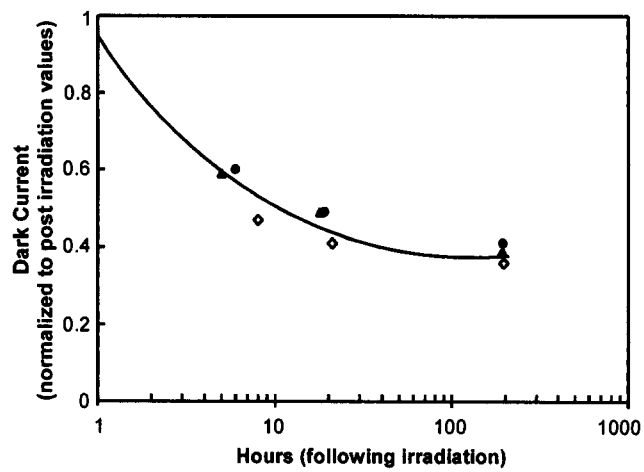

Fig. 3 Dark current reductions during unbiased room temperature annealing of the Ge APD.

Analysis

A. Bulk Damage

Previous work with Si APDs [3] showed that proton-induced increases in APD dark current were primarily due to displacement damage in the depletion region bulk material. Furthermore, because carriers generated in the depletion region are multiplied via the internal APD avalanche mechanism, such dark current increases were also gain multiplied. In order to confirm that our 63-MeV proton results are due to displacement damage in the InGaAs and Ge bulk regions, Co-60 gamma testing was performed in order to determine if ionization damage was a significant contributor to the dark current increases.

When comparing 63-MeV proton and Co-60 damage, we expect that the displacement damage ratio will be related to nonionizing energy loss (NIEL), and that the displacement damage due to proton and gamma radiation will be linear with respect to fluence [6, 7]. As can be seen from Fig. 4 and Fig. 5, there is a non-linearity to the Co-60 data that indicates a total ionizing dose (TID) effect may also be involved. For the InGaAs APD, this effect appears to saturate below 100 krad(Si)(equivalent) and may be contributing to the slight departure from linearity of the InGaAs proton data at 1 krad(Si)(equivalent). Nevertheless, TID appears to be responsible for only a very small fraction of the total increases in dark current in both APD technologies.

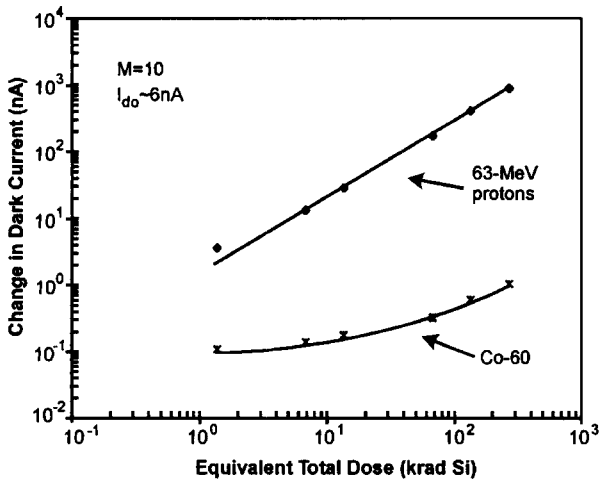

Fig. 4 Comparison of results for Hamamatsu InGaAs APD.

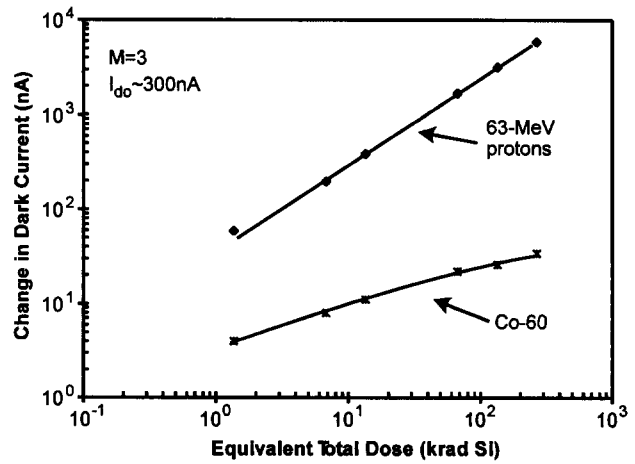

Fig. 5 Comparison of results for Judson Ge APD.

B. Structural Differences

In comparing the InGaAs and Ge results, it is important to note that changes in dark current due to displacement damage in detector depletion regions have been found to be directly proportional to the volume of these regions [3, 8]. In order to achieve very high quantum efficiency, the thicknesses of photodiode absorption regions are on the order of $1/\alpha$, where α is the optical absorption coefficient. However, in order to minimize transit time effects and maximize frequency response, absorption regions are kept as narrow as possible without sacrificing too much quantum efficiency [4, 9]. InGaAs APD depletion region thicknesses from 2.5 to 7μm are common [9-10], and high speed Ge APDs have depletion regions ranging from several microns to over 100μm, depending on the wavelength for which they are being optimized [4]. Although optimized for high speed at 1300nm, the responsivity of the Ge APD at 1550nm is about 0.9 A/W. This suggests that the active absorption depth (spanning the depletion region and deeper material where carriers are transported via diffusion) may be close to $1/\alpha$, which for Ge at 1550nm is around 100μm. For this reason, carriers contributing to dark current may be generated in a volume of bulk material that is around 2 orders of magnitude larger in the Ge APD than in the InGaAs APD. If we correct our damage factors for M=1, the ratio of the Ge and InGaAs factors is also approximately 2 orders of magnitude. A large difference in volume also explains why I_{do} (for M=1) is nearly two orders of magnitude higher in the Ge APD.

Relatively high dark current and noise does not prohibit the use of an APD. In application, it is undesirable for the noise of the system amplifier to exceed the detector noise. In light of this, Ge APDs can be used in applications where amplifier noise is relatively high, in environments with high electro-magnetic interference, for example [2]. Ge APDs can also be cooled to temperatures as low as 77K to reduce dark current and noise, as is the case in photon-counting applications [11].

C. Reduction of V_{BR}

An additional concern for any APD is the reduction of V_{BR} from radiation damage. We evaluated samples of the InGaAs and Ge APDs for changes in breakdown voltage as a function of proton fluence, measuring V_{BR} with a curve tracer under unilluminated conditions at 25°C. No change in V_{BR} was observed in the Ge APDs. The InGaAs APDs did show a 1V drop in V_{BR} by 2×10^{12} p/cm^2. Irradiations were continued (in an unbiased mode) to 5×10^{12} p/cm^2; V_{BR} was measured at a reverse current of 10 μA. Figure 6 shows V_{BR} as a function of fluence for the InGaAs APD; there is a 0.5V drop in V_{BR} per 1×10^{12} p/cm^2.

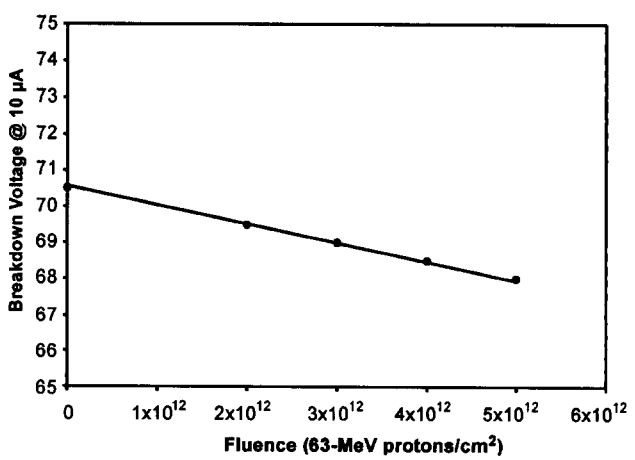

Fig. 6 Changes in breakdown voltage for the InGaAs APD.

Although this effect is not extreme, it could be a factor in a system where the APD was biased for a high, fixed gain prior to irradiation. Because depletion region doping levels in InGaAs APD depletion regions are fairly high ($5 \times 10^{15}/cm^3$)[9,10], it is unlikely that carrier removal is responsible for the effect. It is more likely that displacement damage is affecting the functionality of guard rings which are often used to control APD surface currents caused by the junction curvature effect [4], and that this caused the drop in V_{BR}.

Discussion

We have compared 63-MeV proton and Co-60 gamma radiation results for Ge and InGaAs APDs, suitable for applications at 1.3 and 1.55 μm. Dark current changes in these devices appear to be dominated by displacement damage in the bulk material. It is suspected that the higher dark current prior to irradiation and higher displacement damage factor observed with the Ge APD is due to a larger active volume, compared to the InGaAs APD. We note that the importance of dark current levels, before or after irradiation, depends entirely on the application and system noise requirements.

Wide variations in APD device structure exist. For example, InGaAs APDs use an InP substrate, separate multiplication (InP) and absorption (InGaAs) regions, and an InGaAsP transition region to control charge buildup at the heterojunction interfaces. However, there are different InGaAs APD fabrication approaches, including mesa structures and planar structures with various styles of guard rings [9-12]. Previous work [3] has shown that structural differences can have a large effect on the radiation responses of Si APD technologies, and bulk and surface damage can have varying degrees of dominance depending on structure.

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