Comparison of the Effects of 51-MeV Protons on Differing Silicon Avalanche Photodiode Structures

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Abstract

Different silicon avalanche photodiode structures are compared for the effects of 51-MeV protons on dark current and responsivity. Large differences in depletion widths coincided with differences in sensitivity to dark current increases and responsivity degradation.

INTRODUCTION

The ongoing interest in space-based light detection and ranging (LIDAR) experimentation continues to create a demand for highly sensitive and radiation tolerant photodetectors. Avalanche photodiodes (APDs) are often chosen for LIDAR systems due to their low noise and high gain compared to conventional detectors. For space applications requiring high sensitivity, radiation-induced changes in device parameters such as responsivity and dark current need to be quantified so that intensity dependent data are correctly interpreted. Limited radiation testing of APDs has been done previously [1], however radiation effects on differing avalanche photodiode structures have not been widely researched. This study examines two different silicon avalanche photodiode structures: a conventional APD from Advanced Photonix and an IR-enhanced APD from Perkin Elmer. Results for a third device type from Pacific Silicon will be included in the final paper.

EXPERIMENTAL PROCEDURE

Two silicon APD structures were studied to determine how proton and gamma radiation affect their characteristics: the RCA Type C30954E "reach through" structure by Perkin Elmer, and the 036-70-62-531 by Advanced Photonix. Both are high speed APDs with active area diameters of 0.8 and 0.9 mm, respectively. However, there is an important dissimilarity. The reach through structure is enhanced for near infrared wavelengths, and has similar responsivity at 800nm and 1 micron. The Advanced Photonix APD has a more typical responsivity curve, for a silicon detector, which peaks at 800nm and falls off rapidly for longer wavelengths. The IR-enhanced APD has a much larger active collection depth because of the long absorption depth near the silicon bandgap edge.

The APDs were irradiated at UC Davis using 51-MeV protons. Samples of the Advanced Photonix device were irradiated with Cobalt-60 gamma rays in order to compare proton and gamma radiation effects. All devices were irradiated and evaluated under reverse bias. Pre-irradiation gain was approximately 100 for the Advanced Photonix device and 200 for the Perkin Elmer device. 800nm LED's were the light source for responsivity measurements. 800nm is near the peak of the responsivity curves for these detectors and close to 815nm, a water absorption line that is important for certain LIDAR atmospheric studies. The IR-enhanced structure was also evaluated at 1064nm, and that data will be presented in the final paper along with data on un-biased irradiations and annealing. Three samples of each device were tested at 800nm. Irradiations were conducted at room temperature, and pre- and post- irradiation characterization was done at 22C.

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EXPERIMENTAL RESULTS

Large increases in dark current (I_d) were observed in both structures. Pre-irradiation dark currents were approximately 40nA (Perkin Elmer) and 4nA (Advanced Photonix). After a fluence of 10^{12}p/cm^2, I_d in both devices was observed to increase by two orders of magnitude above pre-irradiation values. However, post-irradiation I_d was an order of magnitude higher in the reach through structure (Fig. 1). An analysis of the device properties and mechanisms responsible for this difference is presented later in the summary.

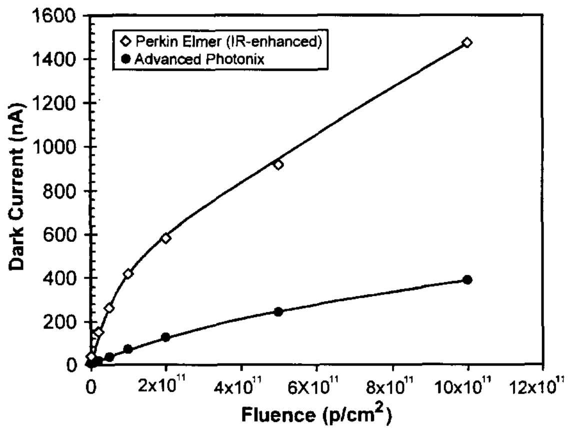

Fig. 1 Comparison of the increase in dark current from 51-MeV protons for the Perkin Elmer and Advanced Photonix APDs.

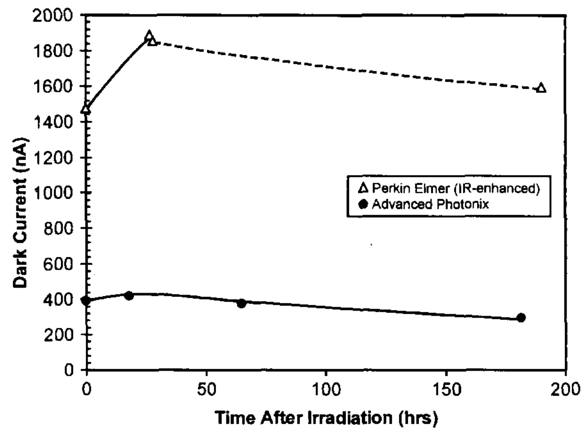

Fig. 2 Comparison of unbiased annealing data for dark current in the Perkin Elmer and Advanced Photonix APDs

Due to timing restrictions, the APDs in our study were irradiated at two different dose rates, with the last three doses having a rate ten times that of lower doses. This may contribute to the apparent non-linear relationship between dark current and fluence that we observed at higher doses. It is also important to note that we did not adjust the gain after each dose to match pre-irradiation values, but rather maintained a constant bias throughout testing that matched operational voltages. Degradation in the gain may also contribute to the bend in the data at high fluences.

After one day of unbiased annealing (unbiased annealing was required by project specifications), I_d increased 28 percent in the Perkin Elmer APD and 8 percent in the Advanced Photonix APD. A similar effect was reported by Swanson et al. [1] who observed a 33 percent increase in I_d 28 minutes after irradiation in APDs tested with electrons and gamma radiation. After the initial increase, the dark current slowly decreased (slight recovery was observed two hours after the initial Perkin Elmer annealing measurements). After one week, the Advanced Photonix dark current was 25 percent less than its post-irradiation value, and the Perkin Elmer dark current was still 8 percent above its post-irradiation value (Fig. 2).

Responsivity changes in the two devices were dissimilar as well. The responsivity of the Perkin Elmer APD decreased consistently with fluence, losing 70 percent by 10^{12}p/cm^2. The responsivity of the Advanced Photonix APD did not decrease significantly until $2x10^{11}$p/cm^2 and only a 40 percent loss was observed after 10^{12}p/cm^2 (Fig. 3). Losses were greater at 1064nm and will be discussed further in the complete paper.

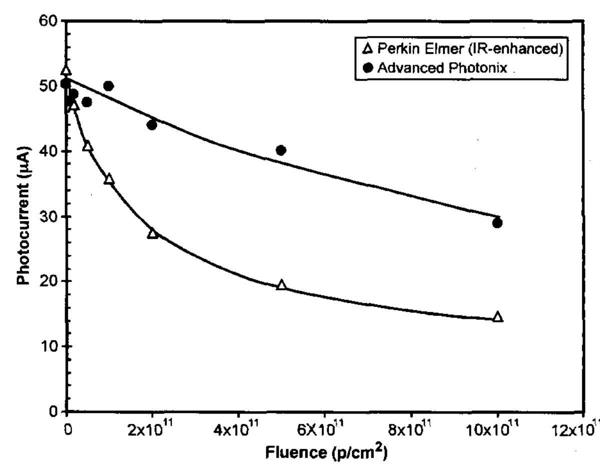

Fig. 3 Comparison of responsivity at 800nm after irradiation with 51-MeV protons

Total dose irradiation of the Advanced Photonix APD was done at the Jet Propulsion Laboratory, using Co^{60} gamma rays at 50 rad(Si)/s. Comparison of the effects of proton and gamma radiation was used to determine the dominant mechanism responsible for the large shifts in device parameters observed with protons. Although both types of radiation cause ionization damage, gamma radiation primarily causes ionization, while protons produce both ionization and displacement effects.

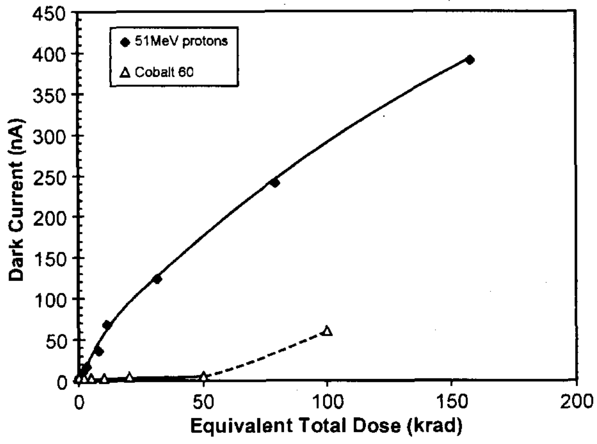

Fig. 4 Comparison of radiation-induced increases in dark current from 51-MeV protons and Co^{60} in the Advanced Photonix APD

Fig. 4 compares dark current data from representative Advanced Photonix devices irradiated with protons and gamma rays. The biasing and temperature conditions were identical in both test situations. Compared to the 51-MeV proton data, no appreciable increase in dark current was observed with Co^{60} until 100 krad(Si). However, at the equivalent total dose, the proton data showed a dark current nearly five times that of the Co^{60} data at 100 krad(Si). This indicates that displacement damage (bulk damage) was the major radiation effect observed with protons and that ionization (surface effects) was far lower. No decrease in responsivity was observed when the Advanced Photonix APD was subjected to gamma rays.

ANALYSIS

Spreading resistance measurements were used to determine the doping profiles of the two APD structures (Fig.'s 5 and 6). The lightly doped, near intrinsic region of the Perkin Elmer APD is approximately 130 microns deep, compared to the 25 micron depth of the Advanced Photonix APD. Note also that the carrier concentration of the i-region of the Perkin Elmer device is more than a factor of 10 lower. The depletion region volumes for the two structures are $6.5 \times 10^{-5} cm^2$ (Perkin Elmer) and $1.3 \times 10^{-5} cm^2$ (Advanced Photonix). This difference can be explained because the Perkin Elmer device is enhanced for wavelengths up to approximately 1 micron. Since the 1/e absorption depth of photons at 1 micron in silicon is over 200 microns (compared to approximately 15 microns at 800nm), a depletion region approaching this depth is necessary to achieve efficiency at long wavelengths [2].

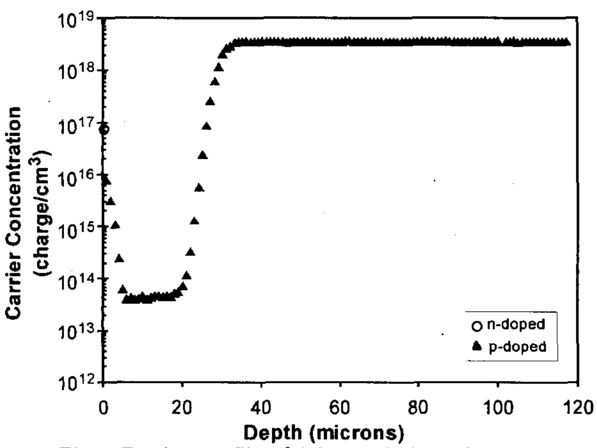

Fig. 5 Doping profile of Advanced Photonix APD

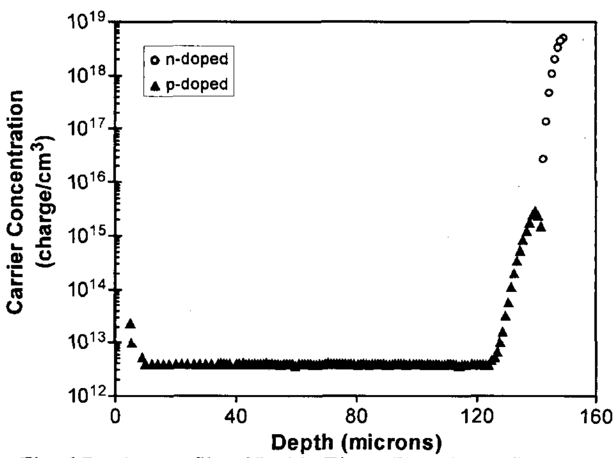

Fig. 6 Doping profile of Perkin Elmer (IR-enhanced) APD

Our data show irradiation from 51-MeV protons causing dark current increases of two orders of magnitude in the two silicon APDs studied. Kalma and Hardwick [3] observed similar dark current changes in fully depleted silicon PIN diodes after irradiation with neutrons. Because APDs operate in a fully depleted mode, this is an appropriate comparison. Previously, leakage current increases in neutron irradiated silicon devices have been attributed primarily to the creation of carrier generation centers in the depletion region bulk by displacement damage. Our data agrees well with calculations of dark current changes (ΔI_d) based on the displacement damage coefficients for silicon depletion regions of Srour, et al. [4] according to

$$\Delta I_d / V = q n_i \phi / 2K_{gn} \qquad (1)$$

where V is the depletion region volume, n_i is the intrinsic carrier density, ϕ is the neutron fluence, and K_{gn} is the damage coefficient. After applying the appropriate NIEL ratios [5,6] and correcting for APD gain, our $\Delta I_d / V$ from 51-MeV protons are within a factor of 2 of that reported by Kalma and Hardwick in silicon PIN diodes after neutron irradiation.

As is evident from Eq. 1, ΔI_d from displacement damage is directly proportional to depletion region volume. Bulk dominated dark current can also be considered to be gain multiplied. The depletion region volume of the Perkin Elmer APD is 5 times greater than the Advanced Photonix APD, and the Perkin Elmer device was operated at a gain twice that of the Advanced Photonix device. The combined effects of the differences in gain and depletion region depth explain the order of magnitude difference in ΔI_d after irradiation. The low doping levels in the i-regions will be affected by carrier removal [7] at higher fluences, and that will be discussed in the complete paper.

The fact that no increase in dark current was observed with Co^{60} until 100 krad(Si) confirms that the increase after proton irradiation is primarily due to bulk damage. We attribute the relatively small increase in dark current after 100 krad(Si) of total dose to displacement damage from Compton electrons produced by gamma ray irradiation (this will be discussed further in the full paper). Since no change in responsivity occurred due to gamma radiation, our observed degradation of responsivity with proton irradiation can also be attributed to displacement damage, due to its well known effect of reducing minority carrier lifetime [8,9]. A discussion relating the difference in depletion depth to the differing responsivity losses of the two structures will be presented in the final paper.

It is evident that care must be used when choosing an APD structure for sensitive space applications. Note that these detectors may be used with light levels as low as several femtowatts and have peak responsivites of 50 to 60 A/W. We observed a ΔI_d of over 1μA in the Perkin Elmer structure after 10^{12} p/cm^2. For space applications requiring light levels near the lower limit of these detectors, 1μA shifts in dark current would be quite significant. There appears to be a trade off between high responsivity at long wavelengths and sensitivity to bulk damage due to the necessarily long depletion width.

CONCLUSION

There is a continuing need for highly sensitive detectors in space applications. This study examines two avalanche photodiode structures with very different internal structures. Decreased responsivity and increased dark current were observed after irradiation with 51-MeV protons for both devices. However, the long-wavelength-enhanced "reach through" structure with the wider depletion region showed a much larger sensitivity to dark current and responsivity changes.

Comparison of proton and gamma ray data indicate that radiation-induced increases in dark current are due primarily to displacement damage in the depletion region and are therefore directly proportional to the volume of this region. Because silicon detectors intended for long wavelength applications require wide absorption regions in order to efficiently collect light, there is a trade off between the desire for high gain in the near infrared and sensitivity to bulk damage in the depletion region which leads to decreased responsivity and increased dark current. For near IR applications, it may be desirable to chose a detector with a smaller depletion region and sacrifice some initial responsivity at wavelengths near 1 micron for the sake of decreasing vulnerability to bulk damage.

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