Mesa-isolated InGaAs avalanche photodiode damage by ionizing radiation

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ABSTRACT

InGaAs avalanche photodiodes (APDs) fabricated from epitaxial material by etching detector mesas and encapsulating the etched mesas under bisbenzocyclobutene (BCB) resin were irradiated by Co-60 gamma-rays to assess their sensitivity to a total ionizing dose of 200 krad(Si). A low-excess-noise APD design with a multi-stage avalanche gain region was tested. Ninety-six identical 20-μm-diameter APDs were characterized to assess the response of the design to ionizing radiation. The APDs were not under bias during irradiation. Damage to the APDs was characterized by measuring the change in room temperature dark current following irradiation, at a reverse bias for which the average avalanche gain is $M=10$. No significant increase of dark current was observed following gamma irradiation: the average increase was 5% and the standard deviation for the measurement was 10%.

Keywords: avalanche photodiode, APD, InGaAs, radiation damage, total ionizing dose, gamma-ray

1. INTRODUCTION

Avalanche photodiodes (APDs) are photodetectors that can be regarded as the semiconductor analog of photomultiplier tubes (PMTs). One important difference is that APDs don’t have a photocathode that is physically separate from their current gain medium; another difference is that the multiplication process in an APD is normally bi-directional, so it has different statistics than the uni-directional gain process of a PMT. Linear-mode APDs don’t typically operate with as much gain as PMTs, but InGaAs APDs are attractive for near infrared (NIR) applications between 950 – 1700 nm that require modest amounts of gain (~10×) and fast rise time (<200 ps) because they have much higher quantum efficiency at the long wavelength end of this band than the available PMTs (typically 80% at 1550 nm versus a few percent). APDs are also valued for their compact size, rugged monolithic format, and amenability to wafer scale mass production. The compact and mechanically simple form, light weight, and long operational lifetime of APDs make them well suited to space applications where failed components cannot be replaced, and the value risked by component failure is very high.

Prior studies of radiation damage to InGaAs APDs have identified displacement damage as the dominant mechanism, but investigation of total ionizing dose (TID) effects has been limited to small sample sizes. A prior study published by Becker and Johnston assessed the response of planar diffused junction InGaAs APDs with InP multipliers to both proton and gamma radiation, and found them to be much more sensitive to non-ionizing energy loss (NIEL) than total ionizing dose (TID), with little increase in dark current for a TID up to 269 krad(Si).1 Displacement damage was also found to dominate the increase in dark current observed for etched mesa grown junction InGaAs APDs with InAlAs multipliers in a proton damage study reported by Williams et al.2 However, Becker and Johnston reported TID data from one device each of two different planar APD designs, and no direct measurement of TID effects was made by Williams et al. on the etched mesa APDs. Here we report new TID measurements on a ninety-six device sample of etched mesa grown junction APDs.

InGaAs APDs can be built in a variety of different ways, and differences in device structure and composition could potentially result in different radiation damage characteristics. Planar diffused junction InGaAs APDs are formed by patterned diffusion of a dopant into the surface of an epitaxially-grown semiconductor wafer. Commonly, the anode of a planar APD is formed by dopant diffusion, and the patterned area of the anode diffusion defines the lateral edges of the diode junction. In contrast, both the anode and cathode doping of an etched mesa grown junction APD are part of the original epitaxial wafer structure, and the lateral extent of the APD junction is defined by physically etching away the...
surrounding epitaxial material. Although all InGaAs APDs absorb the optical signal in a layer of In_{0.53}Ga_{0.47}As – the composition that is lattice-matched to the InP substrate – either InP or In_{0.52}Al_{0.48}As may be used for the other epitaxial layers, including that in which avalanche multiplication occurs.

Radiation damage to an APD manifests as an increase in dark current which increases the shot noise of the detector, degrading sensitivity. Both planar and mesa APDs suffer dark current leakage through the center of the junction (“bulk leakage”) and are susceptible to additional leakage at the perimeter. In general, displacement damage is expected to increase bulk leakage, whereas cumulative exposure to ionizing radiation is most likely to affect perimeter leakage, because the dielectric materials which might trap charge generated by ionizing radiation contact the perimeter of the APD junction.

Displacement damage, quantified by non-ionizing energy loss (NIEL), results when heavy particles like protons or ions knock atoms in the semiconductor out of their lattice sites, leaving behind vacancies and interstitials whose associated energy states act as mid-bandgap traps. The increase in trap density results in an increase in generation-recombination (G-R) dark current due to the traps’ function as non-radiative recombination centers that reduce minority carrier lifetime; the increase in trap density can also increase dark current from trap-assisted tunnel leakage in regions of the junction where the electric field is high enough to drive quantum tunneling of electrons out of occupied valance band states into nearby unoccupied conduction band states. Both Becker and Johnston\textsuperscript{1} and Williams et al.\textsuperscript{2} report that the increase in dark current observed following irradiation by protons tracks closely with calculated NIEL.

In other semiconductor devices such as field effect transistors (FETs), cumulative damage from ionizing radiation, quantified by TID, is associated with the build up of charge trapped in dielectric layers. Dielectric materials typically contact the junction of both planar and mesa APDs at the perimeter. The junction of a planar APD intersects the wafer surface at the edge of the anode diffusion, where a set of guard rings is used to prevent edge breakdown by shaping the depletion region in a way that avoids concentrating the electric field, and by breaking up the potential drop between the anode and surrounding material into multiple small steps. The wafer surface between guard rings is typically protected under a dielectric surface passivation layer. Charge generated by ionizing radiation and trapped in the surface passivation layer of a planar APD could potentially degrade the performance of its guard rings because the ideal guard ring spacing depends upon the surface charge density between rings; degradation of guard ring performance could increase perimeter leakage by increasing the peak electric field at the edge of the APD, which is the driving force for perimeter leakage. Similarly, the mesa sidewall which defines the edge of the junction of an etched mesa APD is typically clad by a dielectric encapsulant meant to protect the sidewall from environmental humidity and chemical contamination that could increase the surface recombination velocity (thereby increasing G-R leakage), lower the dielectric strength of the sidewall, or chemically convert the exposed semiconductor into a more conductive material. Ionizing radiation could promote undesirable chemical changes at the mesa sidewall by breaking chemical bonds. However, unlike displacement damage, mechanisms by which ionizing radiation might damage InGaAs APDs remain speculative. The purpose of the

![Figure 1: Simplified structural diagram of the etched mesa InGaAs APDs.](image-url)
The experiment reported here was to look for evidence of TID effects in a larger sample set of InGaAs APDs, to better quantify the response of such devices to ionizing radiation.

2. EXPERIMENTAL PROCEDURE

2.1 APD Test Samples

A simplified structural diagram of the etched mesa InGaAs APDs is shown in Figure 1. Bisbenzocyclobutene (BCB) resin encapsulating the APD mesa, and metal contacts deposited on top of the APD mesa, are not drawn in Figure 1. Also, the fine structure of the multiplication layer is not shown in Figure 1. This APD design uses a repeating pattern of p- and n-type doping, and changes in alloy composition between InAlAs and (InAlAs)_{2}(InGaAs)_{2-1}, in its multiplier to modulate carrier energy and impact-ionization rate. Engineering the impact-ionization process inside the multiplier narrows the statistical distribution of the avalanche gain, greatly reducing the excess multiplication noise of the APD.

The APDs were processed from material grown by molecular beam epitaxy (MBE) on 2-inch n-type InP substrates. The total thickness of the epitaxial film is about 3.6 μm; during operation, the depleted volume of the diode junction spans approximately 2.78 μm between the heavily doped anode and cathode layers. Approximately 6 μm of contact and interface metal is deposited on top of the APD mesa. Not including thin layers of Ti, Cr, Pt, and Pd used variously to promote metal adhesion, block intermixing, and promote solder wetting, the majority of the metal stack includes a 1 μm Au contact pad, 2 μm of Ag acting as a spacer to raise the contact metal above the surrounding BCB, and 3 μm of In solder. The InP substrate is thinned to 350 μm and the detector structure is designed for back-illuminated operation (i.e. illumination through the substrate), but in this experiment, the devices were irradiated from above rather than through the substrate.

APDs were fabricated from the epitaxial material in an 8-mask process. First, epitaxial material outside the active area of each detector was removed by wet chemical etching, to expose the conductive n-type substrate. The n-type substrate serves as a common electrical contact to the cathode side of all APDs on the wafer. Next, 20-μm-diameter Au pads were deposited over the active area of each detector to make electrical contact to the anode side of the diode. In the same lift-off step, a ring contact was deposited on the exposed InP substrate outside the detector active area to make contact to the cathode side of the diode. APD mesas just wider than the anode contact pads were then formed by a second wet process.

Figure 2: InGaAs APDs (grey chip) mounted in a Gel-Pak® carrier (black square), fixtured with TLD arrays at the perimeter of the carrier.
chemical etch, and the pristine mesa sidewalls were chemically treated to terminate the exposed surface of the semiconductor crystal with bonds that have energy states outside the bandgap of the semiconductor. The purpose of the chemical passivation step is to reduce the density of mid-gap traps at the surface, thereby lowering perimeter leakage. The chemically passivated mesa sidewalls were then encapsulated under photo-patterned BCB resin. Following cure of the BCB, Ag under-bump metal (UBM) was patterned over the anode contact pads to raise the height of the metal stack above the lip of the surrounding BCB, and provide a solder wetting layer. Next, the substrate was thinned to 350 μm and polished, and a broad-band anti-reflection coating was patterned on the back side of the substrate, opposite the APDs. Supplementary Au cathode contacts were then patterned on the back side of the substrate, outside the active area of each detector. Finally, In bump solder was patterned over the UBM on the front side of the wafer. With this last step, the electrical contacts of the APDs were prepared for flip-chip bonding to either readout electronics or to submounts with wire bond pads.

2.2 Gamma-Ray Exposure

All ninety-six APD arrays were formed on a single semiconductor die, which was temporarily mounted in a Gel-Pak® chip carrier. The chip carrier was fixture for testing with four CaF₂ thermoluminescent dosimeter (TLD) arrays placed in proximity to the APD samples prior to irradiation (Figure 2). Each TLD array consisted of four TLDs per array. Gamma-ray irradiation of the samples was conducted using the Sandia National Laboratory (SNL) Gamma-ray Irradiation Facility (GIF) 190 kilocurie Co₆₀ source providing primary photon energies of 1.17 and 1.33 MeV. The TLD arrays and APD sample were placed in a Pb-Al container (cover not shown) in order to attenuate scattered low-energy photons since the presence of these photons in the incident spectrum can cause dosimetry errors. The container assured that lower energy photons (< 1 MeV) were attenuated or absorbed in the container walls. Low energy photons are created by Compton scattering of the Co₆₀ gamma-rays within the source structure or within materials that lay between the source and the irradiated device, as well as within materials that lie beyond the device but contribute to backscattering. The container also prevented unwanted exposure of the sample device to sustained periods of room lighting. The temperature in the vicinity of the sample ranged from 22.2-24.6°C. The glow-curve readings of the sixteen individual TLDs and computation of the resulting dose and dose rate statistics were performed by International Photonics Consultants (IPC) in conjunction with the SNL Radiation Metrology Laboratory (RML).

![Avalanche Gain and Dark Current vs. Reverse Bias](image)

**Figure 3:** Semi-log plots of avalanche gain (left-hand axis) and room temperature dark current (right-hand axis) versus reverse bias, for a typical APD from the study.
2.3 Dark Current Measurement

Room temperature current-voltage (I-V) characteristics were collected by probe-testing the APDs on a Cascade Microtech M150 probe station, mounted in a custom dark box. Twenty-four APDs were contacted at a time by a custom low-leakage Celadon probe card interfaced to an HP 4155A semiconductor parameter analyzer through an Agilent E5250A switch matrix.

Accurate measurement of changes in APD dark current is complicated by the steep slope of an APD’s gain and dark current as functions of reverse bias, and by the sensitivity of these characteristics to changes in series contact resistance. Figure 3 is a semi-log plot of avalanche gain (left-hand axis) and dark current (right-hand axis) as functions of reverse bias. The data in Figure 3 is typical of one of the ninety-six 20-μm-diameter APDs measured for this study, at room temperature. These APDs are typically operated at avalanche gains from M=10 to 40, corresponding to a reverse bias of approximately 60 V. Both avalanche gain and dark current increase rapidly with reverse bias near the normal operating point of the APD, and have vertical asymptotes at the avalanche breakdown voltage \( V_{br} \) – behavior that is approximated by the empirical relation:

\[
M \approx \left(1 - \frac{V - IR}{V_{br}}\right)^{-n},
\]

where \( V \) is the reverse bias applied to the APD’s terminals, \( I \) is the current through the junction, \( R \) is an effective resistance that includes the series contact resistance of the APD, and \( n \) is a fit parameter that varies with diode design. The chief difficulty is that annealing of the APD’s electrical contacts by current flow during operation, or variations in the quality of contact between probe tip and APD contact pad over repeat probings, can result in changes in \( R \) which shift the gain and dark current characteristics as functions of the applied reverse bias. Variations in \( R \) which are unrelated to radiation effects can lead to significant differences in repeat measurements of dark current at a given applied reverse bias, and sensitivity to such variations in \( R \) increases for reference points further up the gain curve.

The measurement error introduced by variations in \( R \) can be addressed in three ways. First, APD contacts should be burned-in by a sustained period of operation, prior to collection of any data; this minimizes contact annealing effects. Second, collection of data from larger samples helps to distinguish radiation response from measurement error. Lastly, the measurement reference point should be defined as a fixed voltage offset from the breakdown voltage, rather than as a fixed reverse bias applied to the APD terminals. The reason a voltage offset relative to breakdown is a better point of reference is that avalanche gain, avalanche breakdown, and dark current are all physically determined by the electric field strength inside the APD junction. Measurement of the reverse bias applied to the APD’s terminals at which the APD enters avalanche breakdown is a surrogate for measuring both \( R \) and the breakdown field. A given avalanche gain is obtained at a constant offset in electric field strength relative to the breakdown field, which maps to a constant offset in terminal voltage relative to the terminal breakdown voltage. For the devices in this study, an average avalanche gain of M=10 was obtained at a 2.4 V offset from the terminal breakdown voltage.

3. EXPERIMENTAL RESULTS

3.1 Gamma-Ray Dosimetry

The averaged total dose and dose rate are summarized and shown in Table 1. RML TLD reading estimates were based on random uncertainties in TLD responses at Co\(^{60}\) energies and are reported at the 1-sigma level. At Co\(^{60}\) energies, the Dose (Si) is calculated as Dose (Si) = Dose (CaF\(_2\)) x 1.02. Conversion to the SI unit of radiation absorbed dose is the Gray (Gy) where 1 Gy = 100 rad.

Table 1. Co-60 Gamma-Ray (> 1 MeV) Irradiation of Voxel APDs.
3.2 Change of Dark Current

For ninety-six samples, the average room temperature dark current at M=10, 2.4 V below the breakdown voltage, was 20.3 ± 1.7 nA prior to irradiation and 21.3 ± 1.5 nA afterwards. If dark current measurements before and after irradiation are subtracted for each APD, prior to averaging the differences, the average increase in dark current was 1.0 ± 2.1 nA. In 31/96 cases, the dark current measured after irradiation was lower than the measurement prior to irradiation.

4. ANALYSIS AND DISCUSSION

The increase of an APD’s dark current resulting from radiation exposure is a problem to the extent that it degrades the sensitivity of the optical receiver of which the APD is a component. APDs are always used in conjunction with amplifiers, so photoreceiver sensitivity depends both upon the shot noise on the APD’s dark current and upon amplifier noise. APD and amplifier noise are uncorrelated, so in the approximation of white noise spectra, the spectral intensity of the current noise, referred to the input of the amplifier is:

\[ S_{\text{receiver}} = S_{\text{APD}} + S_{\text{amp}} \text{ [A}^2\text{/Hz]} \] (2)

where

\[ S_{\text{APD}} = 2qM^2FI_{\text{primary}} \] (3)

and \( S_{\text{amp}} \), the input-referred noise of the amplifier, is typically in the range of \( 10^{-24} \) to \( 10^{-22} \) A\(^2\)/Hz for commercial transimpedance amplifier (TIA) chips designed for bandwidths in the ~MHz to ~GHz range. In Eq. (3), \( q \) is the elementary charge, \( F \) is the excess noise factor (a function of \( M \), and dependent upon APD design),\(^{5,6} \) and \( I_{\text{primary}} \) is the unmultiplied current, including dark current. The contribution to \( I_{\text{primary}} \) of the APD’s dark current is normally estimated as the gain-normalized dark current measured at the APD’s terminals, or about 2 nA for the APDs in this study, when they are operated at M=10. For the APDs in this study, \( F=2.1 \) at \( M=10 \), such that \( S_{\text{APD}} \approx 1.3\times10^{-25} \text{ A}^2\text{/Hz} \).

The dark current of the APDs tested in this study would need to increase by about an order of magnitude before the shot noise contribution from amplified dark current at \( M=10 \) was comparable in magnitude to the spectral intensity of typical TIA noise sources. In fact, the observed increase in dark current is about 5%, and smaller than the standard deviation of the measurement, whether one examines the increase in the average dark current or the average increase in dark current.

5. CONCLUSIONS

A ninety-six detector sample of etched mesa grown junction APDs exhibited negligible increase in dark current following exposure to a 200 krad(Si) TID of gamma-rays. The large sample size helped limit experimental error caused by changes in series resistance unrelated to TID effects. These results confirm the finding by previous studies on smaller sample sets that InGaAs APDs are significantly more susceptible to displacement damage than to TID effects.

REFERENCES


