InAs Avalanche Photodiode with Improved Electric Field Uniformity

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A new class of avalanche photodiodes (APD) characterized by exclusive electron impact ionization and known as electron avalanche photodiodes (e-APD), have received considerable attention recently due to their ideal gain and excess noise characteristics. HgCdTe, the first material system in which exclusive electron impact ionization was demonstrated, has been the subject of substantial research and development for applications requiring mid and long wavelength infrared photodetectors with high sensitivity, including remote gas sensing, light detection and ranging (LIDAR), and both active and passive imaging. More recently, InAs has also been shown to demonstrate exclusive electron impact ionization and has subsequently come under intense study. Although InAs APD's have not yet reached the multiplication gains achievable in HgCdTe, the advantages inherent to III-V materials, including mature device fabrication and improved compositional uniformity, make InAs APD's particularly attractive for mid-infrared focal plane arrays (FPA). Here, we report a significant, ~5x, increase in the room temperature multiplication gain for InAs APD's, as compared to the state-of-the-art at 10 V reverse bias.

One of the biggest impediments to further improving the performance of InAs APDs appears to be the high unintentional background doping inherent to InAs, which results in a non-uniform electric field strength in the multiplication region. Simulated electric field profiles (Fig. 1) show a strong dependence on background doping concentration; even for an optimistic dopant concentration of 5×10^{14} cm^{-3}, the field is highly non-uniform. Such field non-uniformity limits the amount of gain that is achievable before undesirable band-to-band tunneling current begins to dominate. Background doping in InAs has previously been reported to be n-type even when SIMS data showed an order of magnitude more acceptor impurities than donor impurities.[1] We attribute the anomalous n-type doping to amphoteric native defects, which act as multiply ionizable donors in undoped InAs.[2] In order to mitigate the undesirable effects of this background doping, we present a proof-of-concept layer structure (Fig. 2) with a graded p-type doping profile designed to improve the electric field uniformity (Fig. 3), resulting in an increased multiplication gain by a factor of ~5 at 9.25 V reverse bias; further optimization of the doping profile should allow for even higher multiplication gains.

All samples were grown by solid-source molecular beam epitaxy (MBE) in an EPI Mod. Gen II system on n-type sulfur doped (100) InAs substrates. Mesa diodes ranging in diameter from 50 to 350 μm were defined by wet etching using H_3PO_4:H_2O_2:H_2O (1:1:1), followed by a 30 second dip in H_2SO_4:H_2O_2:H_2O (1:8:80) and subsequent passivation with SU-8 to reduce surface leakage current.[3,4] Bulk dominated dark current was verified by measuring dark current for various diode sizes and observing a linear dependence on area. Due to the extremely small band-gap of InAs, good Ohmic contacts were formed using unannealed Ti/Au (20/150 nm). Phase-sensitive detection, similar to ref. 5, is used to measure the multiplication gain and excess noise factor.

By leveraging an improved doping profile and the reduced background doping achievable with MBE growth, we demonstrate devices with minimal excess noise (Fig. 4) and a representative multiplication gain (Fig. 5) of ~70 at 9.25 V reverse bias – the highest gain reported thus far by a factor of ~5 for an InAs APD operated below 10 V reverse bias.

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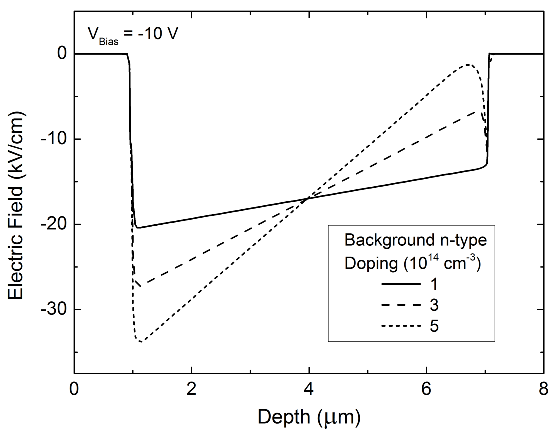

Fig. 1. Simulated electric field profiles for three different background doping concentrations at a reverse bias of 10V. Even for an optimistic background doping of 5x10^{14} cm^{-3}, the electric field profile is highly non-uniform.

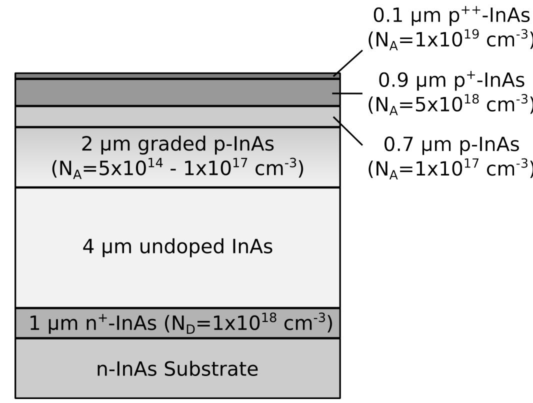

Fig. 2. Proof-of-principle InAs APD layer structure. The graded p-type doping profile is designed to improve electric field uniformity in the multiplication region.

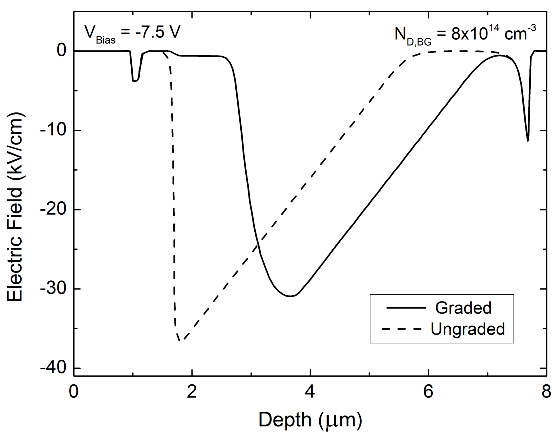

Fig. 3. Simulated electric field profiles at a reverse bias of 7.5V for the layer structure shown in Fig. 2, and a similar structure without the graded p-type doping. The background doping is taken to be n-type with a concentration of 8x10^{14} cm^{-3}. Further improvement to the electric field uniformity could be achieved by optimization of the graded p-type doping layer.

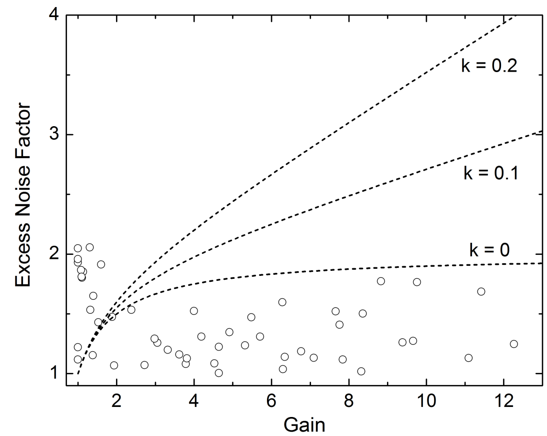

Fig. 4. Excess noise factor measured at room temperature on 70 μm diameter diodes with the layer structure shown in Fig. 2. The dashed lines represents McIntyre's local field model for different values of k, the hole to electron ionization coefficient ratio.

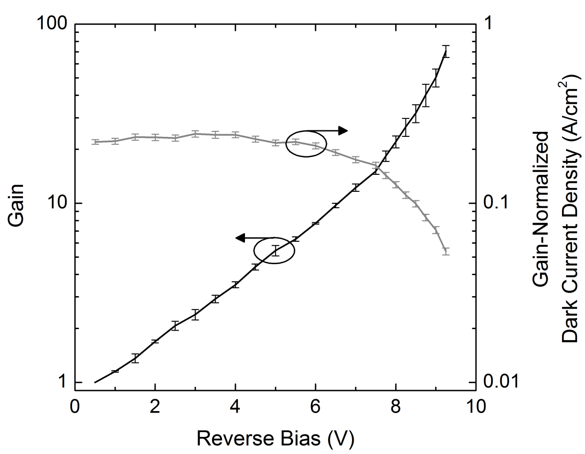

Fig. 5. Avalanche gain (black line) and gain-normalized dark current density (grey line) measured at room temperature on 70 μm diameter diodes with the layer structure shown in Fig. 2. The values shown are the average from multiple devices, and the error bars represent the sample standard deviation. A gain of ~70 is realized at the record low reverse bias of 9.25V for an InAs APD.