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Enhanced low-noise gain from InAs avalanche photodiodes with reduced dark current and background doping

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We reduced the room temperature dark current in an InAs avalanche photodiode by increasing the p-type contact doping, resulting in an increased energetic barrier to minority electron injection into the p-region, which is a significant source of dark current at room temperature. In addition, by improving the molecular beam epitaxy growth conditions, we reduced the background doping concentration and realized depletion widths as wide as 5 μm at reverse biases as low as 1.5 V. These improvements culminated in low-noise InAs avalanche photodiodes exhibiting a room temperature multiplication gain of ~80, at a record low reverse bias of 12 V. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4757424]

Over the past decade, InAs avalanche photodiodes (APD) have been shown to exhibit electron-dominated avalanche multiplication,[1,2] significant gain at low biases and electric fields,[3] near ideal excess-noise characteristics,[4] and gain-independent bandwidth.[5] InAs possesses several advantages compared to other APD materials, including strong optical absorption extending into the mid-infrared, inherent compositional uniformity, and mature high-yield III-V device fabrication. These characteristics make InAs APDs attractive for a wide range of applications including chalcogenide fiber-based and free-space optical communications, remote gas sensing, 3D laser detection and ranging (LIDAR), and both active and passive imaging. However, the performance of state-of-the-art InAs APDs is currently limited by excessive dark current and unintentional background doping concentrations, which restrict the practical operating temperatures and limit achievable multiplication gains.[6] We demonstrate significantly enhanced performance by reducing the dark current and background doping concentration, culminating in high room temperature multiplication gains up to ~80 at a low reverse bias of 12 V, which corresponds to an ~3× improvement in gain over previously reported InAs APDs tested under similar conditions.[3,7]

The need for wide multiplication regions in InAs APDs, necessitating low background doping concentrations, has been thoroughly established in previous reports.[3,7] The combination of a relatively weak field-dependence of the electron ionization coefficient and the onset of band-to-band tunneling at relatively low electric fields in InAs results in larger multiplication gains being achievable for thicker multiplication regions. However, capacitance-voltage (C-V) measurements have previously indicated that depletion widths are limited to ~4 μm below 10 V reverse bias, which corresponds to active background doping concentrations in the 7×10^{14}–$2 \times 10^{15}\,\mathrm{cm}^{-3}$ range.[3,7] The source of this high active background doping is still unclear, but is possibly due to a combination of amphoteric native defects[8] that act as donors in nominally undoped InAs, as well as dicarbon deep-donors.[9] Dicarbon deep-donors are expected to be present in higher concentrations in material grown by metal-organic chemical vapor deposition (MOCVD) than that grown by molecular beam epitaxy (MBE), due to the inescapable presence of carbon-containing molecules in the former.

Samples in this study were grown in an EPI Mod. Gen. II MBE system on n-type sulfur-doped (100) InAs substrates. Silicon and beryllium were used as n- and p-type dopants, respectively. Three approaches for reducing background-doping concentrations were explored. First, growth was performed at a relatively high substrate temperature of ~500 °C in order to minimize impurity sticking. Second, a relatively high growth rate of 1 μm/h was chosen to reduce the concentration of any impurities that might incorporate. Finally, dopant cells were cooled to idle temperatures (350 °C) during i-region growth in order to eliminate parasitic incorporation of dopant species leaking around the closed MBE source shutters, due to the well-established arsenic drag effect.[10]

As shown in Fig. 1, two separate sample structures were investigated. The ungraded structure contains 6 μm of nominally intrinsic (i) material surrounded by n^+ and p^+ claddings doped at $1 \times 10^{18}\,\mathrm{cm}^{-3}$ and $5 \times 10^{18}\,\mathrm{cm}^{-3}$, respectively, whereas for the graded structure, in place of the 6 μm i-region is a 4 μm i-region followed by a 2 μm graded p^- region and a 0.7 μm uniform p^- region. The graded structure was designed to reduce the peak electric field strength by grading the doping profile; for reasons that will be discussed below, this structure exhibited reduced dark currents resulting in improved current stability at higher multiplication gains. Both structures contain a 0.1 μm-thick p^{++} contact layer, the effects of which will also be discussed below.

Circular mesa diodes ranging in diameter from 100 to 350 μm were fabricated using photolithography and wet etching in a 1:1:1 solution of phosphoric acid (86%), hydrogen peroxide (30%), and deionized water, followed by a 30 s dip in a 1:8:80 solution of sulfuric acid (96%), hydrogen peroxide (30%), and deionized water and immediate passivation with SU-8 photoresist to reduce surface leakage current.[11,12]

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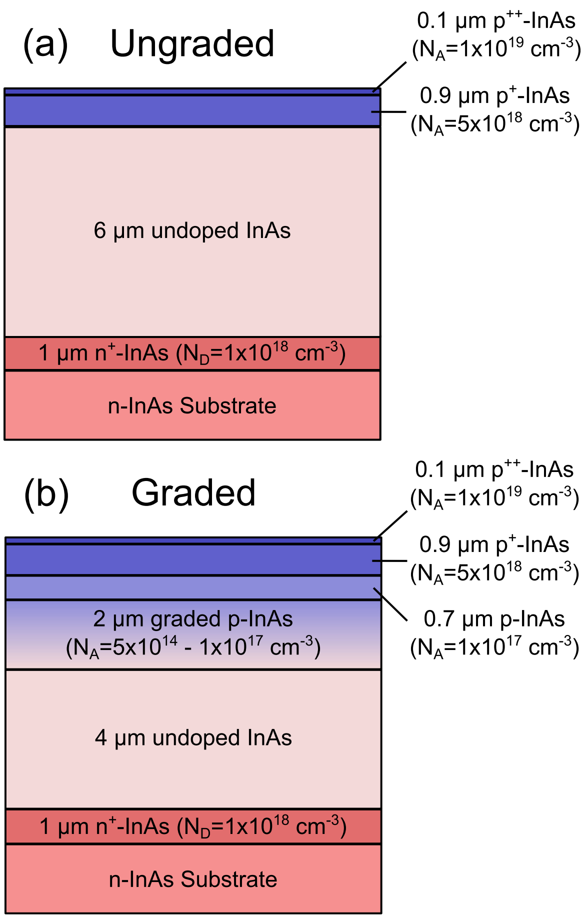

FIG. 1. Schematic cross-sections of the (a) ungraded and (b) graded structures investigated.

Top Ohmic contacts were then formed with unannealed Ti/Au (20/150 nm) deposited by electron-beam evaporation. Bulk-dominated leakage current, which is essential for practical applications, was verified by measuring dark current for various diode diameters and observing a linear dependence on area, which confirmed the effectiveness of the SU-8 surface passivation.

Fig. 2 shows depletion widths versus reverse bias determined using C-V characterization (120 K) and the known relative dielectric constant of 14.6 for InAs.[13] Results from previous reports[3] are also shown for comparison. Depletion widths as large as 5 μm were observed at the low reverse bias of 1.5 V, which corresponds to a background doping concentration below $2\times10^{14}\,\mathrm{cm}^{-3}$, which is significantly lower than previous reports.[3,7]

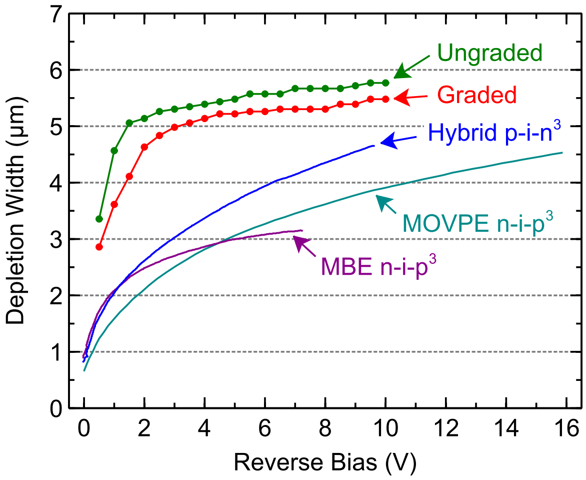

FIG. 2. Depletion width versus reverse bias determined by capacitance-voltage measurements at 120 K for the ungraded and graded structures, with three samples reported in Ref. 3 shown for comparison. The ungraded and graded structures exhibited rapid depletion of the i-region at a rate corresponding to background doping concentrations below $2\times10^{14}\,\mathrm{cm}^{-3}$—significantly lower than previous reports.

As noted above, the large dark currents historically observed in InAs APDs near room temperature limit practical devices to cryogenic operating temperatures. Previous studies have shown that the dark currents in SU-8 passivated, bulk-dominated devices[7] exhibit Arrhenius activation energies of ~0.4 eV near room temperature, which is slightly larger than the InAs bandgap, an indication that diffusion current dominates the dark current characteristics. Significantly, in contrast to an ideal diode in which dark current saturates at reverse biases above ~3 q/kT, in InAs APDs minority electrons from the p-region that diffuse into the i-region undergo multiplication, resulting in a dark current density that increases with reverse bias. Thus, it is crucial to minimize electron injection from the p-region contact, as confirmed by observations of reduced dark current for samples containing an AlAsSb electron blocking layer near the p-type contact.[14] An alternative approach, which does not increase growth and etch complexity, is to simply increase the p-doping at the p-type contact. This increases the energetic barrier to thermionic emission of minority electrons into the p-region. For an increase in contact-layer p-doping from $5\times10^{18}\,\mathrm{cm}^{-3}$ to $1\times10^{19}\,\mathrm{cm}^{-3}$, numerical inversion of the Fermi-Dirac integral, assuming the effective valance band density of states of $6.6\times10^{18}\,\mathrm{cm}^{-3}$, predicts an increase in barrier height of ~1 kT at room temperature, resulting in a ~3× decrease in gain-normalized dark current density.

As shown in Fig. 3, the ungraded and graded structures, which incorporate highly doped p-type contact regions, exhibited a significant reduction in gain-normalized dark

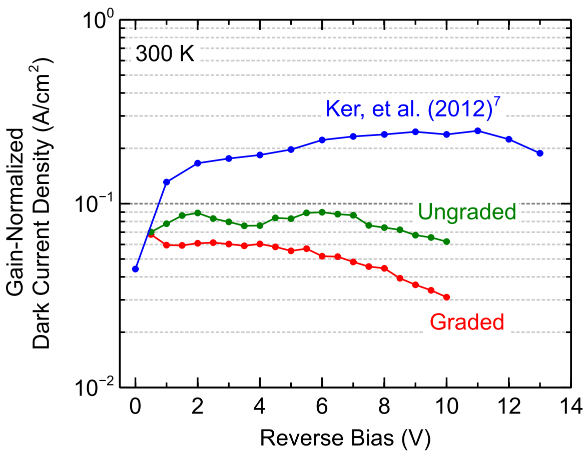

FIG. 3. Representative room-temperature gain-normalized dark current densities for the ungraded and graded structures compared with recent results from Ref. 7. The graded structure exhibited a significant, ~3×, improvement due to high p-doping in the top contact and a thick p-region which reduced thermally injected electron diffusion into the multiplication region.

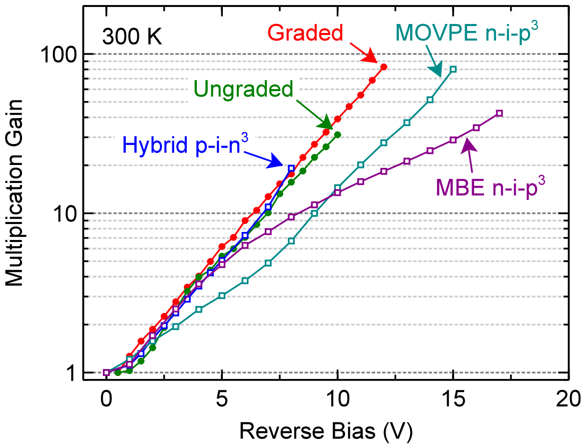

FIG. 4. Measured room temperature multiplication gain versus reverse bias for the ungraded and graded structures compared to the best previously reported results found in Ref. 3. The reduced background doping in the ungraded and graded structures resulted in increased gain at a given bias, and the reduced dark current allowed stable low-noise amplification at higher biases, culminating in a peak gain of ~80 at 12 V reverse bias.

current density compared to recently reported results[7] from otherwise similar devices. The reduction in dark current of the graded structure, as compared to the ungraded structure, is attributable to the increased p-region thickness, which is expected to reduce the number of electrons injected from the p-type contact that successfully diffuse to the i-region and experience multiplication. Further reduction in dark current is expected for even higher top-contact p-doping, but the downward slope of the gain-normalized dark current density for the graded structure in Fig. 3 implies that other forms of dark current that do not undergo multiplication, such as hole diffusion from the n-region, are significant in this device.

Room temperature multiplication gain versus reverse bias measurements for the ungraded and graded structures are shown in Fig. 4, along with comparable results from the literature.[3] The low background doping concentrations present in the ungraded and graded structures resulted in increased gain at a given bias, when compared to similar devices with higher background doping concentrations. In addition, the decreased dark current allows stable operation at high gains, culminating in measured gains as high as ~80 at a record low reverse bias for an InAs APD of 12 V. As shown in Fig. 5, noise characteristics of these devices remain near ideal due to the electron-dominated impact ionization, as established in previous reports.[15]

In conclusion, we reduced the dark current and background doping concentrations in InAs APDs. This resulted in a ~3× increase in the measured room temperature multiplication gain at 12 V reverse bias, as compared with the current state-of-the-art for InAs APDs, while maintaining low excess noise characteristics.

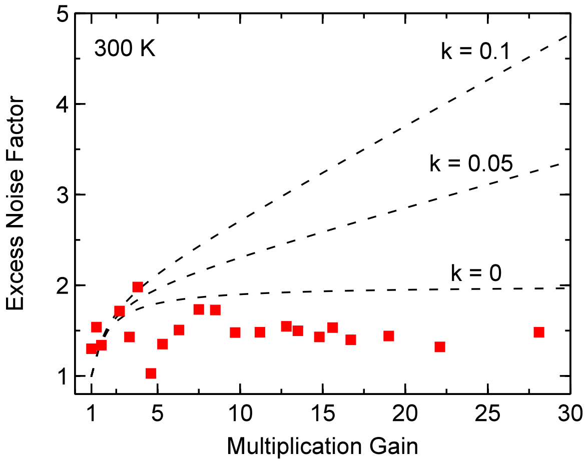

FIG. 5. Representative graded structure excess noise factor versus multiplication gain measurements taken at room temperature (filled squares), compared to McIntyre's local field model[16] for different values of k, the hole to electron ionization coefficient ratio (dashed lines). The extremely low noise characteristics observed are consistent with McIntyre's history-dependent model for electron-dominated impact ionization,[17] as previously reported for HgCdTe and InAs based APDs.[15,18]

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