Reducing III-V avalanche photodiode noise through the introduction of boron

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Avalanche photodiodes (APDs) are important for applications requiring detectors with high sensitivity at elevated bandwidths, such as communications and laser radar. III-V APDs are advantageous for these applications due to the existence of robust fabrication processes for III-V devices, compositional uniformity, and compositional control over cutoff wavelengths. However, impact ionization gain is a stochastic process that results in an excess noise factor, F, which increases with the multiplication gain, M, and reduces the signal-to-noise ratio. Despite intense activity over the past >40 years, InAs is one of the only III-V materials/alloys that has been found to exhibit intrinsically low excess noise.[1] Consequently, much recent effort has focused on artificially reducing excess noise though heterojunction band engineering with conventional materials.[2] For example, digital alloy, or short period superlattice, growth can reduce excess noise,[3] but this approach is only effective in a limited set of material systems.[4]

Highly-mismatched alloys have been proposed as a path towards bulk materials with intrinsically low noise as the addition of the highly-mismatched element perturbs the conduction band (nitrogen, boron) or valence band (bismuth), which theoretically should suppress impact ionization in that band.[5,6] This is exciting as it could provide a universal approach for reducing the impact ionization noise of III-V materials. Unfortunately, the addition of nitrogen into (In)GaAs was found to *increase* the excess noise factor.[7] By contrast, we report for the first time that the introduction of boron not only *reduces* the excess noise, but also *increases* the strength of impact ionization initiated by electrons, potentially increasing the achievable levels of multiplication for a given applied electric field.

All-BGaInAs p-i-n APDs (structures shown in Fig. 1a) were grown by solid-source molecular beam epitaxy (MBE) in an EPI Mod. Gen II system with boron, gallium, and indium compositions lattice-matched to the n-type Si-doped (100) GaAs substrates with 400-nm and 800-nm thick intrinsic regions. As shown in Fig. 1b, excellent lattice-matching and crystal quality were evident in (224) high-resolution X-ray diffraction (HR-XRD) reciprocal space mapping (RSM) of a p-i-n structure with an 800-nm thick intrinsic region. Room-temperature photocurrent, dark current, and excess noise measurements were performed on 100 and 150-µm diameter devices with a 543-nm He-Ne continuous wave laser. As seen in Fig. 2, low dark currents and strong photoresponse were obtained for both $B_{0.01}Ga_{0.97}In_{0.02}As$ and $B_{0.03}Ga_{0.91}In_{0.06}As$ p-i-n diodes with a 400-nm intrinsic region, resulting in clear avalanche multiplication beginning at ~15 V reverse bias. As shown in Fig. 3a, the excess noise factor decreased with increasing boron concentration compared to a GaAs p-i-n with an i-region of 0.5 µm;[8] the addition of just 1% boron reduced the noise by suppressing $k = \beta/\alpha$ compared to GaAs. Increasing the boron incorporation to 3% decreased the k-factor further, suggesting that increasing the boron incorporation could further decrease device noise. Impact ionization coefficients for electrons, α, and holes, β, were determined using the method similar to Yuan *et al.*[9] While highly mismatched alloys like dilute-nitrides and -borides were theorized to suppress the electron-initiated impact ionization coefficient due to perturbation in the conduction bandedge,[5,6] we observed an increase in the electron-initiated ionization coefficient and a decrease in the hole ionization coefficient compared to GaAs[10] (Fig. 3b).

Here we demonstrate the potential for engineering low-noise APDs with the addition of boron into conventional III-V materials. The result is a materials approach that simultaneously reduces the excess noise factor by suppressing the k-factor *and* increases the strength of α, potentially enabling a new class of APDs that produce higher gains with lower excess noise.

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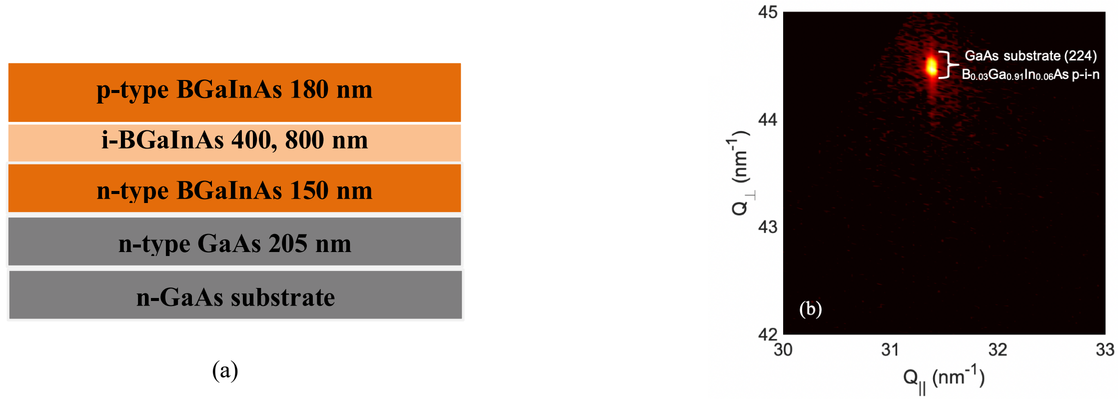

Fig. 1 (a) Layer structures of the all-BGaInAs p-i-n diodes. (b) Representative (224) high-resolution X-ray diffraction (HR-XRD) reciprocal space map (RSM) of an all-$B_{0.03}Ga_{0.91}In_{0.06}As$ p-i-n with an 800 nm i-region showing excellent lattice-matching and crystal quality.

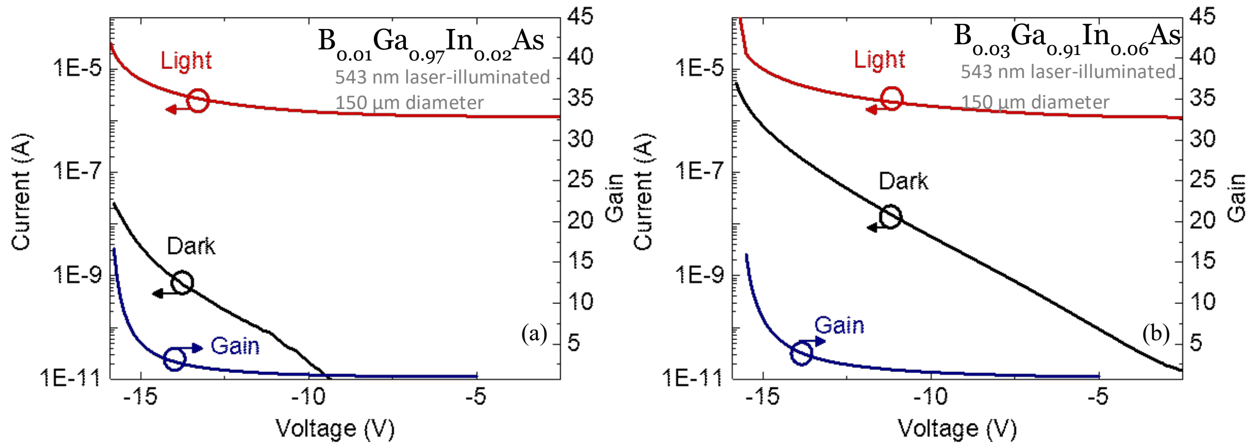

Fig. 2 300K dark and light current-voltage characteristics and multiplication gain for (a) $B_{0.01}Ga_{0.97}In_{0.02}As$ and (b) $B_{0.03}Ga_{0.91}In_{0.06}As$ p-i-n APDs with a 400-nm intrinsic region, grown lattice-matched to GaAs. Both exhibited strong optical response relative to the dark current, with clear avalanche multiplication gain beginning at -15V, indicating BGaInAs alloys are excellent candidates for APDs.

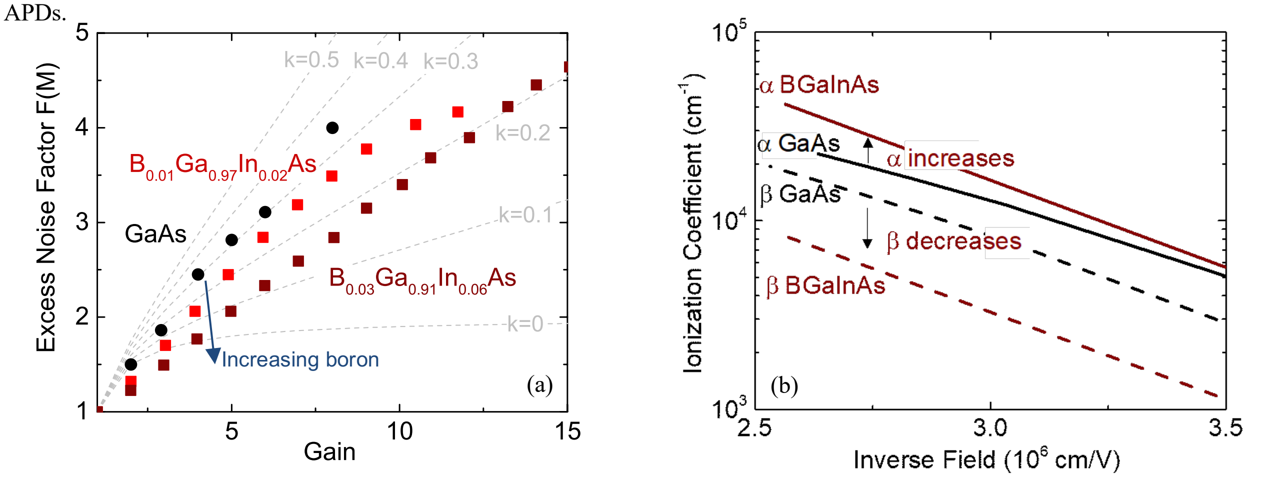

Fig. 3 (a) Measured 300K excess noise factor versus multiplication gain (solid squares) with calculations with McIntyre's model for different *k* factors (blue dashes). The *k*-factor of 400-nm intrinsic region BGaInAs APDs improved *monotonically* with increasing boron concentration, with a 1.5× reduction observed at 3% B as compared to a GaAs APD with an 500-nm intrinsic region.[8] (b) The impact ionization coefficient for electrons (α) in $B_{0.03}Ga_{0.91}In_{0.06}As$ increased compared to GaAs,[10] while the impact ionization coefficient for holes (β) decreased. This resulted in both a decrease in the excess noise factor, as well as an increase in the achievable multiplication gain at a given electric field.