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Experimental evaluation of impact ionization in dilute nitride GaInNAs diodes

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The anomalous behavior of impact ionization in dilute-nitride GaInNAs photodiodes with a range of nitrogen content below 4% is investigated. The ratio of hole- and electron-initiated ionization coefficients, $k = \beta/\alpha$, is enhanced by a factor up to ~ 4 with increasing nitrogen content. The absolute ionization coefficients are suppressed by up to two orders of magnitude at low electric fields in samples with 3% N. The narrow band gap, suppressed impact ionization, and increased breakdown voltage characteristics of GaInNAs make it a suitable material for use as part of a composite collector in GaAs-based heterojunction bipolar transistors. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4819846>]

The dilute nitride Ga(In)NAs is an interesting material system due to its anomalously large reduction in energy band gap with the addition of a small fraction of nitrogen (N).^{1,2} A band anticrossing (BAC) interaction between the localized N states and the extended conduction-band (CB) states of GaNAs has been predicted to lead to a splitting of the CB into two subbands known as $E_{-}(k)$ and $E_{+}(k)$.² The downward shift of the lower subband, $E_{-}(k)$, not only accounts for the reduction of the fundamental band-gap energy of GaAs, but also for the increase of the electron effective mass, m_e^* , due to the strong non-parabolicity of the lower subband. GaInNAs is preferred over GaNAs for thick bulk structures grown on GaAs to minimize the tensile strain introduced by the small substitutional N atoms; hence lattice matching to GaAs can be achieved with appropriate In and N compositions. Since the effects of In on the N energy level and of N on the valence band (VB) offset in GaInNAs are known to be negligible,² it may be reasonable to assume that both GaNAs and GaInNAs alloys share similar electronic transport properties.

Low-noise and high-gain avalanche photodiodes (APDs) are usually based on material with dissimilar electron (α) and hole (β) ionization coefficients, and with the avalanche gain being initiated by the more readily ionizing carrier.³ Adams suggested that the modified conduction band of dilute nitrides would hinder electrons from reaching sufficient energy to impact ionize, leading to a very small α and hence low noise for hole-initiated avalanche gain in dilute nitride APDs.⁴ However, excess noise measurements on a GaNAs p - i - n APD containing 0.75% N by Kinsey *et al.* showed no apparent evidence of suppression of α , as the ratio of ionization coefficients, $k = \beta/\alpha$, based on McIntyre's local model,³ was found to be close to that of GaAs.⁵

In this letter, we investigate the electron impact ionisation rate in GaInNAs alloys from the measurements of

breakdown voltages (V_b), electron-initiated avalanche gain (M_e) and excess noise factor (F_e) on a series of GaInNAs p^+ - i - n^+ diodes with N compositions in the range of 1% to 3.8%. The diode structures used in this study were grown on (100)-oriented, n^+ GaAs substrates by conventional solid-source molecular beam epitaxy (MBE) as described in an earlier publication.⁶

Table I shows the nominal i -layer thickness, In and N compositions of the GaInNAs samples studied in this work. Wafers A to E have similar layer structure, consisting of a 500 nm p^+ GaAs top cladding, 50 nm p^+ GaInNAs, undoped GaInNAs i -region with thickness specified in Table I, 50 nm n^+ GaInNAs, and n^+ GaAs bottom cladding and buffer layer on n^+ GaAs substrate. Wafer F consists of a GaInNAs n^+ - i - p^+ structure designed to be complementary to the GaInNAs p^+ - i - n^+ in wafer D. Uniform In concentration across the wafer was confirmed by secondary ion mass spectrometry (SIMS) measurements. Analysis of the X-ray diffraction (XRD) rocking curves across wafers B and C showed a gradual decrease in the N concentration and a change from tensile to compressive strain corresponding to a small lattice mismatch from -7×10^{-4} to 2×10^{-3} with increasing radial distance from the center of wafer.

Mesa diodes with variable diameters (50–400 μm) and top optical access windows were fabricated using a standard process for GaAs. The unintentional background doping in the i -region of each sample was determined from the capacitance-voltage (C-V) profiles of the devices, which is typically in the order of 10^{15} cm^{-3} as shown in Table I. Wafer E was grown under non-optimal conditions and required postgrowth thermal annealing at 850 °C to reduce its high unintentional background doping level⁷ from mid 10^{16} cm^{-3} to $\sim 1 \times 10^{15} \text{ cm}^{-3}$.

A phase-sensitive lock-in detection technique was used to extract the electron photocurrent generated by illuminating the p^+ GaAs top optical window of a reverse-biased device with a focused laser beam spot. Based on the absorption coefficients of doped GaAs given in Ref. 8, nearly 100% and

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TABLE I. Nominal i -layer thickness (w), composition, and unintentional background doping density (UID) of the GaInNAs structures studied in this work. Also shown are the wafer positions at which measurements were taken, *i.e.*, center (“c”), edge (“e”), or from center to edge (“c-e”) of wafer. All wafers are as-grown, except for wafer E which is annealed at 850 °C.

Wafer	A	B	C	D	E	F
w (nm)	1000	400	400	800	1000	800
Wafer position	c	c-e	c-e	e	c	e
In (%)	3.0	8.0	10.0	10.0	10.0	10.0
N (%)	1.0	3.0	3.8	~3.0	3.8	~3.0
UID ($\times 10^{15} \text{ cm}^{-3}$)	1.0	3.0	3.0–4.5	3.0	1.3	7.0

98.3% of the total absorbed light generates carriers within the top 550-nm p^+ cladding layer at a laser wavelength of 442 and 532 nm, respectively. When the reverse-biased device is illuminated in such a way, the photo-generated minority electrons diffuse and get swept across the GaInNAs p^+-i-n^+ depletion region by the electric field. At sufficiently high fields, impact ionization by the injected electrons results in a measurable gain in photocurrent represented by M_e . Using a longer laser wavelength at 785 nm or 1064 nm, electron-hole pairs are photo-generated in the GaInNAs absorber instead of the GaAs top cladding layer, and the resulting avalanche gain is represented by M_{mix} . A linear extrapolation of the primary photocurrent is used to correct for a small increase in the carrier collection efficiency due to the increasing depletion width and peak electric field with reverse bias. The avalanche gain or multiplication factor (M) is the ratio of the multiplied and primary photocurrent. The avalanche excess noise of the GaInNAs devices with a range of N compositions was measured using a phase-sensitive, transimpedance amplifier-based noise measurement system based on the method by Li *et al.*⁹ The system has a center frequency of 10 MHz and a stable effective noise power bandwidth of 5.43 MHz for device junction capacitances up to 100 pF.

In wafer C, the N fraction decreases gradually from 3.8% at the center to 2.6% at the edge of wafer, while the In fraction remains constant at 10%. This makes it a suitable material for the investigation of the breakdown voltage of GaInNAs p^+-i-n^+ devices as a function of change in band-gap energy (E_g) induced by N. E_g at a particular wafer position was determined from the room-temperature photoluminescence peak. The measured E_g vs. N fraction in wafer C is in good agreement with E_- (minimum of the lower subband) calculated from the BAC model¹⁰ for $\text{Ga}_{1-x}\text{In}_x\text{N}_y\text{As}_{1-y}$ with $x = 3y$

FIG. 1. Breakdown voltages across wafer C as a function of direct band gap.

(GaAs lattice-matching condition), although it deviates by up to 10% from the experimental E_- data by Skierbiszewski¹¹ for N fraction in the range of 1 to 3%. V_b was calculated by extrapolating the inverse multiplication factor ($1/M$) versus reverse-bias voltage to zero, based on Miller’s empirical formula.¹²

Fig. 1 shows that V_b decreases with E_g as the N fraction varies from the edge to the center of wafer C. This behavior is anomalous compared to other semiconductors where there is a general trend of V_b increasing with E_g .¹³ In III–V semiconductors with bandgaps $E_g \geq 1$ eV, where α and β are of similar magnitude, a detailed study showed that V_b scaled with a zone-averaged conduction band energy $\langle E \rangle$, due to both the distribution of energetic carriers throughout the Brillouin zone and to electron-phonon scattering by the deformation-potential interaction.¹³ The addition of N to GaAs splits the conduction band throughout the Brillouin zone.¹⁴ The net effect on $\langle E \rangle$ is small (since the energy of isolated nitrogen states is ~ 1.7 eV which is close to the value of $\langle E \rangle \sim 1.8$ eV for GaAs^{2,13}) and is found to be insufficient to account for the measured variation of V_b . Hence avalanche breakdown in GaInNAs is controlled by different factors than other semiconductors of similar bandgap. A suppression of α such that $\beta \gg \alpha$ (as suggested by Adams⁴) would reduce avalanche feedback leading to a higher breakdown voltage. We therefore measured the multiplication noise characteristics to obtain information on the ratio β/α .

Figs. 2(a) and 2(b) compare the excess noise of electron-initiated multiplication for the GaInNAs devices with thinner and thicker i -regions, respectively. Also included in Fig. 2 are data for GaAs p^+-i-n^+ diodes with comparable i -region

FIG. 2. Excess noise factor against electron-initiated multiplication for GaInNAs p^+-i-n^+ structures with i -region thickness, (a) $w = 0.4 \mu\text{m}$, (b) $w = 0.8$ and $1.0 \mu\text{m}$, and a range of N fractions. The lines are predictions from McIntyre’s noise model with k increasing from 0 to 1.1 in steps of 0.1 as described in Ref. 3. The star symbols are the experimental results for a GaAs p^+-i-n^+ with comparable i -region thickness by Li *et al.*^{9,15}

thickness (w) measured by Li *et al.*^{9,15} It is evident from Fig. 2 that $k = \beta/\alpha$ of GaInNAs is very similar to that of GaAs for N fractions $\leq 2.0\%$. The $w = 0.4 \mu\text{m}$ p^+-i-n^+ devices at the edge of wafer B, which contain 2.0% N, gave a k value ($k = 0.4$) similar to that of a slightly thinner GaAs p^+-i-n^+ diode,¹⁵ as well as that of a slightly thicker GaAs p^+-i-n^+ diode with 0.75% N reported by Kinsey *et al.*⁵ Wafer A with $w = 1.0 \mu\text{m}$ and 1.0% N gave $k = 0.5$, which is close to the $k = 0.6$ of a GaAs diode with $w = 1.13 \mu\text{m}$.⁹

In contrast, for N content $\geq 3.0\%$ the excess noise increases for both thin and thick GaInNAs structures as shown in Fig. 2, with an approximately two-fold increase in k compared with GaAs. For small values of multiplication, the ionization rate ratio k exceeds 1, i.e., lower noise would be realized with hole-initiated multiplication. The reduction in asymmetry of α and β compared to GaAs causes an increase in feedback in the current multiplication process. This results in a more abrupt avalanche breakdown with $\alpha(V_b) = \beta(V_b) \approx 1/w$ when $k = 1$, and significant multiplication occurs only at high fields close to breakdown.

Plotting $M-1$ versus electric field on a semilog scale allows evaluation of the onset of avalanche gain at very low M values. Fig. 3 compares the multiplication initiated by electrons (M_e) and by mixed carriers (M_{mix}) for the GaInNAs p^+-i-n^+ samples as well as a GaAs p^+-i-n^+ diode (grown at a typical GaInNAs growth temperature of 450°C) with i -region thickness around $1 \mu\text{m}$, as a function of electric field. It is clear from Fig. 3 that there is a reduction in M_e of sample A with 1% N compared with that of the GaAs diode, shifting V_b by $\sim 8\%$. The reduction in the onset of M_e is more pronounced in the as-grown (D) and annealed (E) samples with N $\geq 3.0\%$, where M_e is up to two orders of magnitude lower than that of the GaAs at a given electric field, resulting in a shift of V_b by 37%. In the absence of high-quality complementary GaInNAs n^+-i-p^+ structures for most of the samples, M_{mix} instead of pure hole-initiated multiplication (M_h) was obtained to provide a glimpse of the hole ionization rate. The change of M_{mix} relative to M_e in Fig. 3

FIG. 3. Multiplication factor minus 1 as a function of electric field for the GaInNAs devices from as-grown A, D, and 850°C -annealed E samples, compared with that of a $w = 1 \mu\text{m}$ GaAs p^+-i-n^+ structure grown at $\sim 450^\circ\text{C}$. The symbols represent pure electron-initiated multiplication (M_e) for all the samples except F, which has pure hole-initiated multiplication (M_h). The accompanying dashed lines represent mixed electron- and hole-initiated multiplication (M_{mix}). M_{mix} was obtained at a laser wavelength of 785 nm for the GaAs and A samples, and at 1064 nm for D and E.

indicates that the hole-to-electron ionization coefficient ratio, $k = \beta/\alpha$, varies from $k < 1$ to $k > 1$ with increasing In and N fractions. This is confirmed by the $M_h - 1$ curve of the n^+-i-p^+ devices of sample F in Fig. 3.

To assess the effect of ionization rate asymmetry on the breakdown voltage, we calculated V_b for a p^+-i-n^+ diode with $w = 1 \mu\text{m}$ as a function of change in α and β relative to those of GaAs (α_{GaAs} , β_{GaAs}) in Fig. 4 using the parameterization for GaAs reported in Ref. 16, which was derived from McIntyre's local model assuming uniform electric field. The parameterization produces a good fit to the $M_e - 1$ data of the GaAs diode in Fig. 3. If β is unchanged, then a reduction of α by a factor of > 10 would be required to reproduce the increased breakdown voltage for GaInNAs with 3.8% N (sample E, $V_b \approx 42 \text{ V}$), corresponding to an increase in k to > 10 . This exceeds the value obtained from experiment (Fig. 2), confirming that a change in ionization rate asymmetry is not sufficient to explain our experimental results.

α and β can be separately estimated for GaInNAs with $\sim 3.0\%$ N using samples D and F which are complementary p^+-i-n^+ and n^+-i-p^+ structures with an i -region thickness of around 750 nm as determined from C-V measurements. Neglecting small differences in the dimensions, background doping or alloy content in the two samples, we can determine α and β from measurements of M_e and M_h using the well-known formulae given in Ref. 17. Fig. 5 shows that α and β of GaInNAs are lower than GaAs by a factor approaching two orders of magnitude at low fields. The value of $k = \beta/\alpha$ for GaInNAs is approximately 2 at low fields and approaches unity at high fields, while for GaAs it varies from 0.6 to 0.8 over the given field range.

The parametrized expressions for α and β obtained from the $\text{Ga}_{0.90}\text{In}_{0.10}\text{N}_{0.03}\text{As}_{0.97}$ devices in this work are as follows:

$$\alpha = 2.0 \times 10^7 \text{ m}^{-1} \exp[-(6.95 \times 10^7 / E)^{2.40}], \quad (1a)$$

$$\beta = 6.3 \times 10^6 \text{ m}^{-1} \exp[-(5.10 \times 10^7 / E)^{3.20}], \quad (1b)$$

where E denotes electric field in V m^{-1} . As evident in Fig. 5, Eqs. (1a) and (1b) give good fits to the experimental data over the electric field range of $300\text{--}440 \text{ kV/cm}$. Using

FIG. 4. Breakdown voltages for a p^+-i-n^+ diode with $w = 1 \mu\text{m}$ as a function of change in α and β relative to those of GaAs, i.e., $\alpha/\alpha_{\text{GaAs}}$ and $\beta/\beta_{\text{GaAs}}$, calculated using the parameterization for GaAs in Ref. 16 based on the McIntyre's local model.

FIG. 5. α (solid symbols) and β (open symbols) as a function of inverse electric field for 3.0% N GaInNAs devices calculated from the measured M_e and M_h of samples D and F, respectively. The accompanying solid and dashed lines are the parametrized α and β . Also shown are α (solid line) and β (dashed line) for GaAs from Ref. 16 for comparison.

Eq. (1), we were able to predict $M_e - 1$ for wafer C containing 3.0% N, with a reasonably good fit to the experimental data.

Using excess noise and photomultiplication measurements, we have shown that the ionization rate ratio $k = \beta/\alpha$ increases with N content $>2\%$ in dilute GaInNAs alloys, by a factor approaching 4 at low fields for 3.0% N. This large variation is accompanied by more than an order-of-magnitude reduction in both α and β compared to GaAs, leading to an increased avalanche breakdown voltage. A large suppression of α was predicted by Adams⁴ based on the strong enhancement of electron scattering by the N levels and from the nitrogen-induced splitting of the CB which would impede the progressive gain in energy of the electrons when the energy gap exceeded the available phonon energy. However, the large reduction we observe in β was not predicted because the intrinsic random alloy scattering from N atoms,¹⁸ which limits the electron mobility has been shown to leave the hole mobility relatively unaffected.¹⁹ Also, calculations considering the zone-averaged conduction band energy $\langle E \rangle$, predict no decrease in β due to the influence of N on the band structure. One possibility is that the decrease in β at higher N content is due to extrinsic factors arising from macroscopic inhomogeneity of N content,²⁰ ionized impurity scattering,²¹ and residual lattice mismatch.²² The same extrinsic factors can be expected to influence α but it is possible that the large change observed in the ionization rate ratio $k = \beta/\alpha$ could be increased if the extrinsic factors could be identified and reduced.

In conclusion, because β as well as α is strongly reduced by the inclusion of N content $>2\%$ in dilute GaInNAs alloys, the ionization rate ratio $k = \beta/\alpha$ is only reduced by a factor 4. This may be due to unexpectedly large scattering caused by extrinsic factors arising from macroscopic inhomogeneity of N content which, unless removed, prevents the significant increase of ionization asymmetry such that $k \gg 1$ which would be required for low-noise multiplication of holes in avalanche-photodiodes. Alternatively, with the combination of narrow band gap, suppressed impact ionization and increased breakdown voltage, the GaInNAs material may have potential for use in the composite collector of GaAs-based heterojunction bipolar transistors (HBTs).

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