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Excess Noise Measurement in $In_{0.53}Ga_{0.47}As$

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***Abstract*—The excess noise due to impact ionization has been measured explicitly for the first time in $In_{0.53}Ga_{0.47}As$. By using a phase sensitive detection technique, the noise due to avalanche current was determined even in the presence of high tunneling currents. The excess noise due to pure electron injection measured on a series of thick $In_{0.53}Ga_{0.47}As$ p^+-i-n^+ diodes suggests large electron to hole ionization coefficient ratio between 3.7 at electric field of 310 $kV \cdot cm^{-1}$ to 5.3 at 260 $kV \cdot cm^{-1}$. Excess noise was also measured at fields as low as 155 $kV \cdot cm^{-1}$ suggesting that significant impact ionization occurs at these low fields. The multiplication and excess noise calculated using published ionization coefficients and ignoring dead space effects, gave good agreement with the experimental data for mixed and pure electron injection.**

***Index Terms*—Avalanche photodiodes, excess noise factor, impact ionization, $In_{0.53}Ga_{0.47}As$, ionization coefficients, multiplication.**

I. Introduction

THE $In_{0.53}Ga_{0.47}As$, lattice-matched to InP or $Al_{0.48}In_{0.52}As$, is used as the absorption layer in separate-absorption-grading-multiplication avalanche photodiodes (APDs), which are widely utilized in receiver modules of optical fiber communication systems. The field across the $In_{0.53}Ga_{0.47}As$ layer is usually kept low to minimize dark current and suppress carrier multiplication. However, low field impact ionization in $In_{0.53}Ga_{0.47}As$ that has been modeled [1] and demonstrated experimentally [2]–[4] due to the weak field dependence of the electron ionization coefficient at electric fields as low as 155 $kV \cdot cm^{-1}$, is a cause of concern since it has detrimental effect on the excess noise performance of APDs [5]–[7]. Impact ionization in $In_{0.53}Ga_{0.47}As$ also causes hole feedback in InP-based n-p-n heterojunction bipolar transistors (HBTs) with $In_{0.53}Ga_{0.47}As$ collectors [8], thereby leading to early device breakdown while in high electron mobility transistors, it can give rise to current instability, hysteresis, high gate current, and kink effect due to trapping of holes [9].

The field dependence of impact ionization coefficients, α for electrons and β for holes, in $In_{0.53}Ga_{0.47}As$ derived using photomultiplication measurements on p-i-n structures [4], [10]–[12] have shown large α/β ratios, indicating that the excess noise for $In_{0.53}Ga_{0.47}As$ will be low if the multiplication is electron initiated. However, the absolute values of α and β are in wide disagreement. Ng *et al.* [4] reported high values of α at fields below 200 $kV \cdot cm^{-1}$ corroborating those previously reported by [2], [3] deduced from measurements on n-p-n HBTs with $In_{0.53}Ga_{0.47}As$ base and collector layers. β derived from p-n-p HBT measurements [13], [14] and photomultiplication measurements [4], [10]–[12] did not show any low field ionization, but Ng *et al.* [4] reported marginally lower values of β. The determination of α at low field in p-i-n and HBT structures is fraught with complications. Movement of the depletion edge with voltage, photon recycling effects and leakage currents need to be corrected for and can mask the presence of avalanche multiplication at low values. The presence of avalanching at relatively low fields can be confirmed unambiguously, however, from additional noise above the shot noise power in the excess noise measurement. In addition, measurement of excess avalanche noise can be used to determine the α/β ratio if the dead space is negligible and the variation in the field across the avalanche region is small so that the assumption of constant α/β ratio holds.

To date, no explicit characterization of excess noise on $In_{0.53}Ga_{0.47}As$ has been reported. In this work, we report excess noise measurement due to pure electron and mixed carrier injection on a series of $In_{0.53}Ga_{0.47}As$ avalanche regions with thickness from 4.8 down to 1.8 μm to unambiguously determine the α/β ratio between fields of 260–310 $kV \cdot cm^{-1}$ and demonstrate the presence of significant ionization at fields as low as 155 $kV \cdot cm^{-1}$.

II. Experimental Details

Three $In_{0.53}Ga_{0.47}As$ p^+-i-n^+ diodes were grown by metal–organic vapor phase epitaxy on n^+ (100) InP substrates. The p^+ and n^+ InP claddings are 0.5 μm thick. These diode structures were fabricated into circular mesa structures with diameters of 50, 100, 200, and 400 μm by optical lithography and chemically etched using HBr-based etchants. Top annular contacts were deposited to allow optical access. Capacitance–voltage characteristics gave values for active i-region widths, w of approximately 1.8, 3.3, and 4.8 μm for the three p^+-i-n^+ diodes.

Pure electron initiated photomultiplication was achieved by focusing light from a 542-nm He–Ne laser onto the top InP p^+ cladding layer. The absorption coefficient of InP at this wavelength is approximately 9.7×10^4 cm^{-1} [15], hence 99% of the incident light is absorbed within the 0.5-μm p^+ cladding layer, giving pure electron injection. Measurements were also performed using a 1520-nm wavelength He–Ne laser. There is very weak absorption of light at this wavelength for InP [16], hence most of the incident light was absorbed in the $In_{0.53}Ga_{0.47}As$ i-region, to give a mixed carrier injection profile.

To obtain the multiplication factor, the photocurrent was normalized to the photocurrent at a bias voltage that was sufficient to ensure full carrier collection. No correction for the increase in injected photocurrent with reverse bias due to depletion edge

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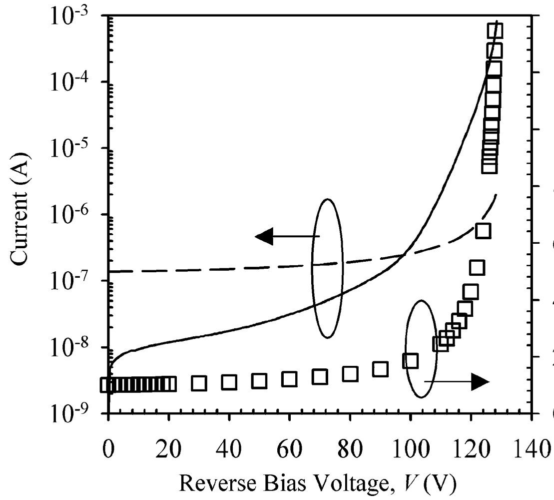

Fig. 1. Reverse dark current (solid line), photocurrent (dashed line), and pure electron initiated multiplication factor (□) versus reverse bias voltage for a 200-μm diameter p^+-i-n^+ diode with $w = 4.8$ μm.

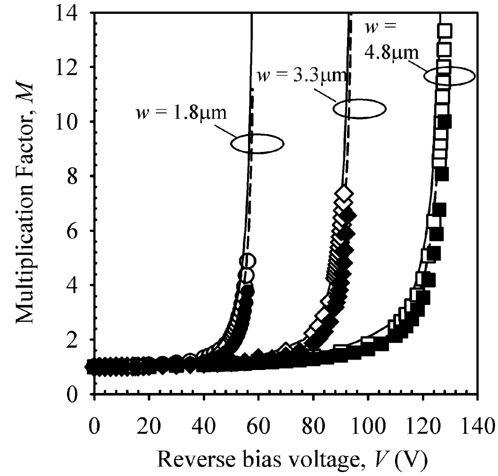

Fig. 2. Measured M_e (open symbols) and $M_{\rm mix}$ (closed symbols) for w of 1.8 μm (○, ●), 3.3 μm (◇, ◆), and 4.8 μm (□, ■). Calculated results using local model are represented by solid lines for pure injection and by dashed lines for mixed injection.

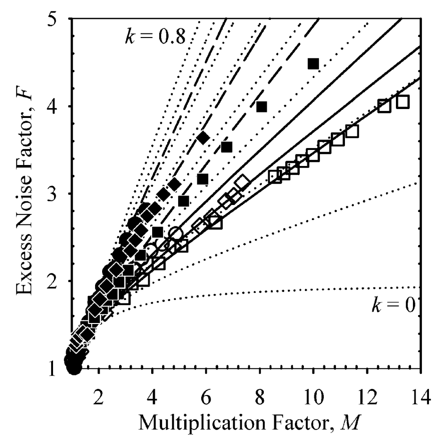

Fig. 3. Measured F_e (open symbols) and $F_{\rm mix}$ (closed symbols) with w of 1.8 μm (○, ●), 3.3 μm (◇, ◆), and 4.8 μm (□, ■). Calculations using local model are represented by solid lines for pure injection and dashed lines for mixed injection. Dotted lines are calculated from (1) for various k values from 0 to 0.8 in steps of 0.1.

movement was necessary as modeling of capacitance–voltage characteristics showed negligible depletion edge movement in the diodes.

The current–voltage characteristics and the multiplication–voltage characteristics of the 200-μm diameter mesa structure with $w = 4.8$ μm are shown in Fig. 1. Below 200 $\mathrm{kV \cdot cm^{-1}}$, leakage currents are mainly due to bulk recombination-generation processes. At high fields, tunneling current dominates the total leakage current prior to avalanche multiplication leading to breakdown. These high tunneling currents, especially in thinner structures, make it difficult to directly measure the multiplication and excess noise factors. Hence, measurements were carried out using phase-sensitive detection that is able to isolate photocurrents from the total current even when leakage currents are two to three orders of magnitude higher than the total photocurrents at high fields. The excess noise factor F was determined from noise power measurements using a technique described by Li *et al.* [17]. The noise measurement system has a center frequency of 10 MHz and a bandwidth of 4.2 MHz. Two lock-in amplifiers were used to measure the photocurrent and multiplication noise.

The pure electron initiated multiplication factor M_e, using the 542-nm laser, and the mixed carrier initiated multiplication factor $M_{\rm mix}$, using the 1520-nm laser, are shown in Fig. 2. Measurements at different laser intensities gave similar characteristics confirming the measurements are independent of excitation power.

The excess noise factor due to pure electron injection F_e and mixed carrier injection $F_{\rm mix}$ determined from noise power measurements for the three layers, are shown in Fig. 3. Although multiplication measurement is still possible, excess noise measurement on thinner $In_{0.53}Ga_{0.47}As$ layers could not be carried out due to the high tunneling leakage currents, which raises the noise floor even with the use of modulated light. McIntyre's local model predictions [18] of excess noise due to pure electron injection, as a function of multiplication is expressed as

$$F(M_e) = kM_e + \left(2 - \frac{1}{M_e}\right)(1 - k) \qquad (1)$$

where $k = \beta/\alpha$. $F_e(M_e)$ for various k values are plotted in Fig. 3 for comparison.

The parameterized expression of α and β reported by Ng *et al.* [4] were used in a local impact ionization model [18] to calculate the multiplication and excess noise for pure electron and mixed injection assuming an ideal p^+-i-n^+ diode profile. The results, shown as solid and dashed lines, respectively, are compared to the experimental data in Figs. 2 and 3.

III. Discussion and Conclusion

$M_{\rm mix}$ is marginally lower than M_e confirming that $\alpha > \beta$. The measured F_e increases with decreasing w, falling within the vicinity of the curves of $k = 0.19$ and $k = 0.27$. In the thinner devices, with increasing high fields, k approaches unity, which leads to increased carrier feedback and subsequently higher avalanche noise. The measured $F_{\rm mix}$ is higher than F_e with fitted k values ranging from 0.33 to 0.65 as w decreases. The mixed carrier initiated multiplication at 1520-nm wavelength results in higher excess noise level compared to that from pure electron injection as w decreases because with strong absorption of light at 1520-nm wavelength, the exponential distribution of photocarriers generated across the $In_{0.53}Ga_{0.47}As$ avalanche region results in proportionally more photogenerated holes created in the thinner devices which contribute to greater fluctuation in the avalanche process.

Good agreement was achieved between the multiplication and excess noise calculated using published ionization coefficients [4] and the experimental data of this work. Assuming negligible dead space effect, the local model is able to predict the α/β ratio from the excess noise measurement on the bulk $In_{0.53}Ga_{0.47}As$ diodes to be between 3.7 at the measured device breakdown fields of 310 kV $\cdot$ cm^{-1} to 5.3 at 260 kV $\cdot$ cm^{-1}, confirming results from [4]. For the thickest structure, M as low as 1.35 with associated F of 1.26 can be determined accurately suggesting the presence of impact ionization at a field of 155 kV $\cdot$ cm^{-1}. However, it is not possible to determine the α/β ratio accurately at these low fields.

The excess noise performance due to 1520-nm illumination in the 4.8 μm structure is already comparable to the typical noise performance of commercial $In_{0.53}Ga_{0.47}As$–InP APDs exhibiting $0.4 < k < 0.5$. Having a thicker low-doped structure of $w = 8$ μm is predicted to give noise corresponding to $k = 0.15$ with almost negligible tunneling prior to breakdown. Provided speed and operating voltage is not a critical factor, bulk $In_{0.53}Ga_{0.47}As$ p-i-n's may be used as low noise APDs at telecommunication wavelengths.

REFERENCES

[1] J. Bude and K. Hess, "Thresholds of impact ionization in semiconductors," *J. Appl. Phys.*, vol. 72, no. 8, pp. 3554–3561, Oct. 1992.

[2] D. Ritter, R. A. Hamm, A. Feygenson, and M. B. Panish, "Anomalous electric field and temperature dependence of collector multiplication in InP/$Ga_{0.47}In_{0.53}As$ heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 60, no. 25, pp. 3150–3152, Jun. 1992.

[3] C. Canali, C. Forzan, A. Neviani, L. Vendrame, E. Zanoni, R. A. Hamm, R. J. Malik, F. Capasso, and S. Chandrasekhar, "Measurement of the electron ionization coefficient at low electric fields in InGaAs-based heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 66, no. 9, pp. 1095–1097, Feb. 1995.

[4] J. S. Ng, C. H. Tan, J. P. R. David, G. Hill, and G. J. Rees, "Field dependence of impact ionization coefficients in $In_{0.57}Ga_{0.43}As$," *IEEE Trans. Electron Devices*, vol. 50, no. 4, pp. 901–905, Apr. 2003.

[5] J. S. Ng, C. H. Tan, J. P. R. David, and G. J. Rees, "Effect of impact ionization in the InGaAs absorber on excess noise of avalanche photodiodes," *IEEE J. Quantum Electron.*, vol. 41, no. 8, pp. 1092–1096, Aug. 2005.

[6] J. N. Hollenhorst, "A theory of multiplication noise," *IEEE Trans. Electron Devices*, vol. 37, no. 3, pp. 781–788, Mar. 1990.

[7] N. Duan, S. Wang, X. G. Zheng, X. Li, N. Li, J. C. Campbell, C. Wang, and L. A. Coldren, "Detrimental effect of impact ionization in the absorption region on the frequency response and excess noise performance of InGaAs-InAlAs SACM avalanche photodiodes," *IEEE J. Quantum Electron.*, vol. 41, no. 4, pp. 568–572, Apr. 2005.

[8] J. J. Chen, G. Gao, J. Chyi, and H. Morkoc, "Breakdown behavior of GaAs/AlGaAs HBTs," *IEEE Trans. Electron Devices*, vol. 36, no. 10, pp. 2165–2172, Oct. 1989.

[9] R. T. Webster, C. Wu, and A. F. M. Anwar, "Impact ionization in InAlAs/InGaAs/InAlAs HEMTs," *IEEE Electron Device Lett.*, vol. 21, no. 5, pp. 193–195, May 2000.

[10] T. P. Pearsall, "Impact ionization rates for electrons and holes in $Ga_{0.47}In_{0.53}As$," *Appl. Phys. Lett.*, vol. 36, no. 3, pp. 218–220, Feb. 1980.

[11] F. Osaka, T. Mikawa, and T. Kaneda, "Impact ionization coefficients of electrons and holes in (100)-oriented $Ga_{1-x}In_xAs_yP_{1-y}$," *IEEE J. Quantum Electron.*, vol. QE-21, no. 9, pp. 1326–1338, Sep. 1985.

[12] J. Urquhart, D. J. Robbins, R. I. Taylor, and A. J. Moseley, "Impact ionization coefficients in $In_{0.53}Ga_{0.47}As$," *Semicond. Sci. Technol.*, vol. 5, pp. 789–791, May 1990.

[13] D. Buttari, A. Chini, G. Meneghesso, E. Zanoni, D. Sawdai, D. Pavlidis, and S. S. H. Hsu, "Measurements of the InGaAs hole impact ionization coefficient in InAlAs/InGaAs pnp HBTs," *IEEE Electron Device Lett.*, vol. 22, no. 5, pp. 197–199, May 2001.

[14] N. Shamir and D. Ritter, "Low electric field hole impact ionization coefficients in GaInAs and GaInAsP," *IEEE Electron Device Lett.*, vol. 21, no. 11, pp. 509–511, Nov. 2000.

[15] D. E. Aspnes and A. A. Studna, "Dielectric functions and optical parameters of Si, Ge, GaP, GaAs, GaSb, InP, InAs, and InSb from 1.5 to 6.0 eV," *Phys. Rev. B*, vol. 27, no. 2, pp. 985–1009, Jan. 1983.

[16] F. R. Bacher, J. S. Blakemore, J. T. Ebner, and J. R. Arthur, "Optical-absorption coefficient of In(1-x)Ga(x)As/InP," *Phys. Rev. B*, vol. 37, no. 5, pp. 2551–2557, Feb. 1988.

[17] K. F. Li, D. S. Ong, J. P. R. David, G. J. Rees, R. C. Tozer, P. N. Robson, and R. Grey, "Avalanche multiplication characteristics in thin GaAs p^+-i-n^+ diodes," *IEEE Trans. Electron Devices*, vol. 45, no. 10, pp. 2102–2107, Oct. 1998.

[18] R. J. McIntyre, "Multiplication noise in uniform avalanche diodes," *IEEE Trans. Electron Devices*, vol. ED-13, no. 1, pp. 164–168, Jan. 1966.