Article:

Ng, B.K., David, J.P.R., Rees, G.J. et al. (3 more authors) (2002) Avalanche multiplication and breakdown in AlxGa1-xAs (x < 0-9). IEEE Transactions on Electron Devices, 49 (12). pp. 2349-2351. ISSN 0018-9383

https://doi.org/10.1109/TED.2002.805570

Avalanche Multiplication and Breakdown in $Al_xGa_{1-x}As$ $(x < 0.9)$

B. K. Ng, J. P. R. David, G. J. Rees, R. C. Tozer, M. Hopkinson, and R. J. Airey

***Abstract*—Measurements carried out on thick $Al_xGa_{1-x}As$ $(x < 0.9)$ diodes showed that the ionization coefficients of $Al_xGa_{1-x}As$ become widely different when $x \geq 0.63$ and are virtually independent of x for $x \geq 0.72$. A strong dead space effect is also observed in thick $Al_xGa_{1-x}As$ structures with $x \geq 0.6$. The breakdown voltage is found to increase at a slower rate with x when $x > 0.63$.**

***Index Terms*—$Al_xGa_{1-x}As$, avalanche breakdown, avalanche multiplication, impact ionization, ionization coefficients.**

I. Introduction

Avalanche multiplication in $Al_xGa_{1-x}As$ $(x \leq 0.6)$ is relatively well characterized [1]–[7]. In this alloy range the electron and hole ionization coefficients, α and β respectively, decrease with x and the α/β ratio $(1/k)$ in bulk material approaches unity as x increases [6]. By contrast, very little is known about the behavior for $x > 0.6$. We have recently investigated the avalanche behavior in $Al_{0.8}Ga_{0.2}As$ [8] and found that its ionization coefficients are very different in magnitude such that its α/β ratio deviates markedly from the trend observed in $Al_xGa_{1-x}As$ $(x \leq 0.6)$. These results are somewhat surprising and indicate that it is not appropriate to extrapolate the avalanche behavior of $Al_xGa_{1-x}As$ $(x > 0.6)$ from that of material with $x \leq 0.6$. It is therefore of interest to investigate the avalanche behavior in $Al_xGa_{1-x}As$ with $x > 0.6$.

II. Experiment

A series of ten $Al_xGa_{1-x}As$ homojunction p-i-n/n-i-p structures with nominal i-region thickness, w, of 1 μm ($w = 0.8$ μm for $x = 0.6$) and x ranging from 0.4 to 0.9 were used in this study. Two $Al_{0.8}Ga_{0.2}As$ layers reported previously [8] are included here for completeness. All p-i-n (n-i-p) structures were grown by conventional solid-source molecular beam epitaxy on n^+ (p^+) (100) oriented GaAs substrates. The p-i-n (n-i-p) structures comprise a thin n^+ (p^+) GaAs buffer, an n^+ (p^+) $Al_xGa_{1-x}As$ cladding layer, an undoped $Al_xGa_{1-x}As$ i-region, a p^+ (n^+) $Al_xGa_{1-x}As$ cladding layer and a thin p^+ (n^+) GaAs cap. The p^+ and n^+ cladding layers were nominally between 0.5 μm and 1 μm thick and were doped with Be and Si respectively to levels of 1–2 $\times$ 10^{18} cm^{-3}. Table I lists the aluminum fractions, the breakdown voltages (V_{bd}) and the parameters obtained from modeling the capacitance–voltage profiles of the layers.

All layers, except P70a, had windows etched in the substrate so that both electron and hole initiated multiplication characteristics, M_e and M_h respectively, can be measured on the same diode. Excitation light from a laser source was focused to a small spot ($\sim$10 μm) on either the top or back cladding layer of the diodes to inject carriers into the high field regions. An increase in the primary photocurrent prior to avalanche multiplication was corrected using the method of Woods *et al.* [9]. Excess noise measurements were performed at a center frequency of 10 MHz and a noise effective bandwidth of 4.2 MHz, as described by Li *et al.* [10].

Manuscript received July 15, 2002. This work was supported by EPSRC (U.K.) and by the Nanyang Technological University, Singapore, through a scholarship to B. K. Ng. The review of this brief was arranged by Editor M. Anwar.

The authors are with the Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, U.K. (e-mail: bkng@ieee.org; j.p.david@sheffield.ac.uk).

Digital Object Identifier 10.1109/TED.2002.805570

TABLE I
Measured Parameters of the $Al_xGa_{1-x}As$ Diodes

Layer ID	Diode type	Measured x	Modeled results: Doping ($\times10^{15}$ cm^{-3}) Cladding $p = n$	Modeled results: Doping i-region	Modeled results: w (μm)	V_{bd} (V)
P40	*p-i-n*	0.36	403	3.050	0.801	38.46
P50	*p-i-n*	0.47	447	5.991	0.773	39.39
P60	*p-i-n*	0.61	1799	0.815	0.839	42.41
P65	*p-i-n*	0.63	684	0.875	0.943	49.19
P70a	*p-i-n*	0.73	1435	1.700	1.047	55.02
P70b	*p-i-n*	0.72	1688	1.996	1.113	56.45
P80	*p-i-n*	0.80	1400	0.480	1.024	53.58
N80	*n-i-p*	0.81	1640	0.505	1.011	52.64
P90	*p-i-n*	0.89	998	0.582	1.038	54.49
N90	*n-i-p*	0.88	1173	0.825	0.855	46.39

Virtually pure carrier injection was achieved by illuminating the $Al_{0.4}Ga_{0.6}As$ and $Al_{0.5}Ga_{0.5}As$ diodes with 542 nm light from a HeNe laser, since more than 97% of this incident light [11] is absorbed in the 1 μm thick cladding layers. For the $Al_xGa_{1-x}As$ diodes with $x \geq 0.6$, 442 nm light from a HeCd laser was used. Such light is strongly absorbed (>98%) in the cladding layers of diodes with $0.6 \leq x \leq 0.8$ and pure carrier injection is ensured. The multiplication characteristics of the $Al_xGa_{1-x}As$ $(x > 0.6)$ diodes under strongly mixed carrier injection condition were also investigated using weakly absorbed 542 nm light.

III. Results and Discussions

Fig. 1 shows the typical M_e and M_h of layers P50, P60, P65, P70b, P80, and P90. For $x < 0.61$, M_e and M_h are observed to converge as x increases, consistent with previous investigations [6]. By contrast there is a significant difference between M_e and M_h of the $Al_xGa_{1-x}As$ diodes with $x \geq 0.63$. M_e and M_h of P90 appeared slightly closer than those of P70b and P80 because of a slightly contaminated injection conditions resulting from the 442 nm light. Multiplication characteristics similar to those of P90 are also observed in N90. The multiplication characteristics from mixed carrier injection (M_{mixed}), resulting from top illumination with 542 nm light, for $x \geq 0.63$ lie between those of M_e and M_h, as expected. It is also noted that $M_e > M_h$ in all layers, indicating that $\alpha > \beta$ for all x. The conventional local model [12] was used to extract the ionization coefficients from the multiplication characteristics of the $Al_xGa_{1-x}As$ diodes. The layers P40, P50, and P65 have relatively low cladding doping levels (Table I) and the depletion regions extend considerably into the cladding layers. Consequently, the nonideal electric field profiles of these layers were taken into account when calculating the ionization coefficients.

Fig. 2(a) and (b) depict the ionization coefficients for $x \leq 0.61$ and $x \geq 0.63$ respectively. The parameterized coefficients of $Al_{0.8}Ga_{0.2}As$ [8] are shown in both Fig. 2(a) and (b) for comparison. The coefficients obtained for $x \leq 0.61$ are in qualitative agreement with those reported previously [6]. It can be seen from Fig. 2 that α decreases with increasing x for $x \leq 0.61$ but remains virtually constant for all higher x. On the other hand, while β also decreases slightly with increasing x up to $x = 0.61$, it suffers a sudden large drop at $x = 0.63$, beyond which it changes very little. Consequently, the α/β ratio approaches unity as x increases from 0.36 to 0.61 but becomes much greater than unity for

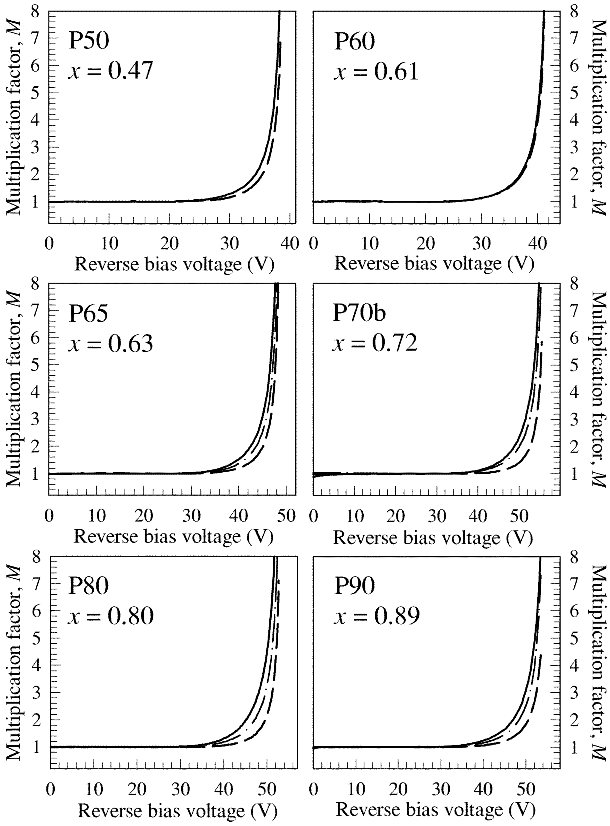

Fig. 1. (Solid lines) $\boldsymbol{M_e}$ and (dashed lines) $\boldsymbol{M_h}$ of back-etched $Al_xGa_{1-x}As$ p-i-n diodes. (Dot-dashed lines) $\boldsymbol{M_{mixed}}$ measured using 542 nm light for P65, P70b, P80, and P90 are also shown.

$x \geq 0.63$. As a result the α/β ratios in $Al_xGa_{1-x}As$ with $x \geq 0.63$ are found to be larger than those of most other III–V materials.

The excess noise characteristic of each alloy composition from pure electron injection is shown in Fig. 3. The excess noise of P40 and P50 correspond to $k = 0.7$ and $k = 0.6$ respectively and are in good agreement with the α/β ratios deduced from the ionization coefficients. In the case of P60 a lower excess noise, corresponding to $k = 0.4$, is obtained and appears to contradict the value of $\alpha/\beta \approx 1$ deduced from photomultiplication measurements. This apparent disagreement is due to nonlocal dead space effects which have become significant in a $w \approx 0.8$ μm $Al_{0.6}Ga_{0.4}As$ structure [13]. The excess noise of the $Al_xGa_{1-x}As$ $(x \geq 0.63)$ diodes is even lower and corresponds to $0.15 \leq k \leq 0.3$. These results broadly corroborate the α/β ratios extracted from photomultiplication measurements. Although the α/β ratio is almost constant in $Al_xGa_{1-x}As$ $(x \geq 0.63)$, the excess noise is seen to fall with increasing x. This suggests that the nonlocal effects in 1 μm thick $Al_xGa_{1-x}As$ $(x \geq 0.63)$ diodes are also significant and increase with x. We believe the increasing significance of dead space in $Al_xGa_{1-x}As$ $(x \geq 0.63)$ follows from the increase in threshold energy for impact ionization with x.

Allam [14] showed that the breakdown voltage in wide gap semiconductors scales linearly with a Brillouin-zone-averaged energy gap, $\langle E_{ind.} \rangle$, given by

$$\langle E_{ind.} \rangle = \frac{1}{8}(E_\Gamma + 3E_X + 4E_L) \tag{1}$$

where E_Γ, E_X and E_L are the conduction-band energies at the Γ, X and L extrema, measured from the valence band edge. When E_Γ is

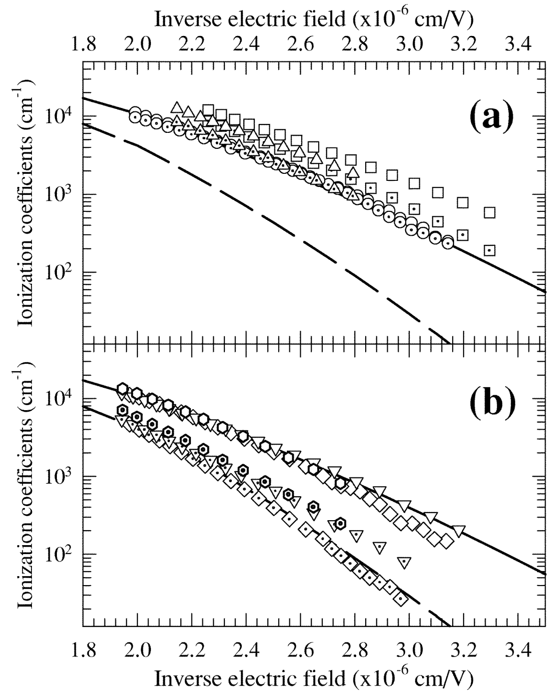

Fig. 2. (Open symbols) $\boldsymbol{\alpha}$ and (dotted symbols) $\boldsymbol{\beta}$ deduced from the $Al_xGa_{1-x}As$ diodes with (a) $\boldsymbol{x = 0.36}$ (□), 0.47 (△), 0.61 (○), and (b) $\boldsymbol{x = 0.63}$ (hexagon), 0.72 (◇), 0.89 (▽). For $\boldsymbol{x = 0.80}$, the parameterized $\boldsymbol{\alpha}$ (solid line) and $\boldsymbol{\beta}$ (dashed line) reported in [8] are used.

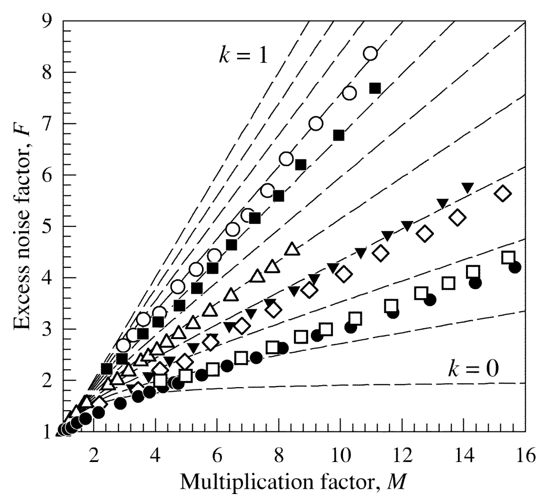

Fig. 3. Excess noise factor measured in P40 (○), P50 (■), P60 (△), P65 (▼), P70 (◇), P80 (●), and P90 (□) from electron initiated multiplication. Dashed lines are McIntyre's local prediction for $\boldsymbol{k = 0}$ to $\boldsymbol{1}$ in steps of 0.1.

particularly large such that it has a negligible effect on the high-field transport, a modified zone-average energy [14] ignoring E_Γ given by

$$\langle E_{ind.} \rangle_m = \tfrac{1}{7}(3E_X + 4E_L) \tag{2}$$

is used instead. A phenomenological relation given by

$$V_{bd} = 45.8(\langle E_{ind.} \rangle - 1.01) \tag{3}$$

is found to predict accurately the breakdown voltage of 1 μm structures of several wide gap semiconductors. To test the phenomenological expression in (3), V_{bd} of ideal $Al_xGa_{1-x}As$ diodes with $w = 1$ μm are plotted as a function of x in Fig. 4. The ionization coefficients of Plimmer *et al.* [6] and those deduced in this work are used calculated the values of V_{bd} for $x \leq 0.3$ and $x \geq 0.36$ respectively. The predictions of V_{bd} from the work of David *et al.* [1] and from (3) are

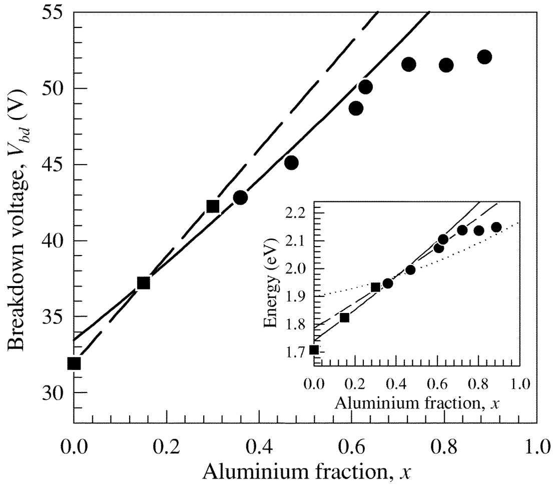

Fig. 4. Comparison of the $\boldsymbol{V}_{bd}$ of 1 $\boldsymbol{\mu}$m $Al_xGa_{1-x}As$ diodes, calculated using $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ deduced in this study (●) and those of Plimmer *et al.* (■) [6], with David's (dashed line) [1], and Allam's (solid line) [14] predictions. Inset shows the equivalent average energies corresponding to the calculated $\boldsymbol{V}_{bd}$ of 1 $\boldsymbol{\mu}$m $Al_xGa_{1-x}As$ diodes in Allam's expression [14] plotted against $\boldsymbol{x}$. $\langle \boldsymbol{E}_{ind.} \rangle$ (solid line), $\langle \boldsymbol{E}_{ind.} \rangle_m$ (dashed line) and $\boldsymbol{E}_X$ (dotted line) as a function of $\boldsymbol{x}$ are also shown in the inset.

also included in Fig. 4 for comparison. The values of $\langle E_{ind.} \rangle$ in (3) for various x are computed using (1).

While the calculated V_{bd} of the $Al_xGa_{1-x}As$ $(x \leq 0.47)$ diodes are in qualitative agreement with the empirical expression of David *et al.* [1], a better agreement is achieved with Allam's expression for x up to ~0.63. However, the calculated V_{bd} departs from both predictions and increases at a slower rate with x for $x > 0.63$. The results suggest that the additional improvement in the potential breakdown performance of $Al_xGa_{1-x}As$ devices obtained from increasing x saturates at around $x = 0.63$. The equivalent average energies corresponding to the calculated V_{bd} of 1 μm $Al_xGa_{1-x}As$ diodes in Allam's expression are plotted as a function of x in the inset of Fig. 4. The variation of $\langle E_{ind.} \rangle$, $\langle E_{ind.} \rangle_m$ and E_X with x are also shown. The average energy required to produce the calculated V_{bd} in (3) is identical to that of $\langle E_{ind.} \rangle$ for $x < 0.63$, but approaches $\langle E_{ind.} \rangle_m$ for $x = 0.72$ and tends toward E_X when $x > 0.72$. This suggests that the Γ-valley may have become unimportant in determining the V_{bd} of $Al_xGa_{1-x}As$ when $x > 0.63$ and that even the influence of the L-valleys on V_{bd} becomes decreasingly important for $x > 0.72$.

IV. Conclusion

The ionization coefficients of $Al_xGa_{1-x}As$ are found to converge as x increases from 0.36 to 0.61 but become very different at higher x, resulting in a large α/β ratio in $Al_xGa_{1-x}As$ with $x \geq 0.63$. Excess noise measurements corroborated the observation of large α/β ratios in $Al_xGa_{1-x}As$ $(x \geq 0.63)$ and revealed a strong dead space effect in thick $Al_xGa_{1-x}As$ diodes with $x > 0.6$. The breakdown voltage of 1 μm $Al_xGa_{1-x}As$ diodes is found to vary linearly with the zone-averaged energy for $x < 0.63$, but increases more slowly with x when $x > 0.63$. The results suggest that the dependence of V_{bd} on the Γ- and L-valleys of $Al_xGa_{1-x}As$ diminishes when $x > 0.63$.

References

[1] J. P. R. David, J. S. Marsland, H. Y. Hall, G. Hill, N. J. Mason, M. A. Pate, J. S. Roberts, P. N. Robson, J. E. Sitch, and R. C. Woods, "Measured ionization coefficients in $Ga_{1-x}Al_xAs$," in *Proc. 1984 Symp. GaAs Related Compounds, Inst. Phys. Conf. Ser.*, 1985, p. 247.

[2] G. E. Bulman, V. M. Robbins, and G. E. Stillman, "The determination of impact ionization coefficients in (100) gallium arsenide using avalanche noise and photocurrent multiplication measurements," *IEEE Trans. Electron Devices*, vol. ED-32, no. 11, pp. 2454–2466, Nov. 1985.

[3] V. M. Robbins, S. C. Smith, and G. E. Stillman, "Impact ionization in $Al_xGa_{1-x}As$ for $\boldsymbol{x} = \mathbf{0.1}$–0.4," *Appl. Phys. Lett.*, vol. 52, no. 4, pp. 296–298, Jun. 1988.

[4] S. A. Plimmer, J. P. R. David, D. C. Herbert, T. W. Lee, G. J. Rees, P. A. Houston, R. Grey, P. N. Robson, A. W. Higgs, and D. R. Wight, "Investigation of impact ionization in thin GaAs diodes," *IEEE Trans. Electron Devices*, vol. 43, pp. 1066–1072, July 1996.

[5] S. A. Plimmer, J. P. R. David, G. J. Rees, R. Grey, D. C. Herbert, D. R. Wright, and A. W. Higgs, "Impact ionization in thin $Al_xGa_{1-x}As$ ($\boldsymbol{x} = \mathbf{0.15}$–0.30) p-i-n diodes," *J. Appl. Phys.*, vol. 82, no. 3, pp. 1231–1235, Aug. 1997.

[6] S. A. Plimmer, J. P. R. David, G. J. Rees, and P. N. Robson, "Ionization coefficients in $Al_xGa_{1-x}As$ ($\boldsymbol{x} = \mathbf{0}$–0.60)," *Semicond. Sci. Technol.*, vol. 15, pp. 692–699, 2000.

[7] X. G. Zheng, P. Yuan, X. Sun, G. S. Kinsey, A. L. Holmes, B. G. Streetman, and J. C. Campbell, "Temperature dependence of the ionization coefficients of $Al_xGa_{1-x}As$," *IEEE J. Quantum Electron.*, vol. 36, pp. 1168–1173, Oct. 2000.

[8] B. K. Ng, J. P. R. David, S. A. Plimmer, M. Hopkinson, R. C. Tozer, and G. J. Rees, "Impact ionization coefficients of $Al_{0.8}Ga_{0.2}As$," *Appl. Phys. Lett.*, vol. 77, no. 26, pp. 4374–4376, Dec. 2000.

[9] M. H. Woods, W. C. Johnson, and M. A. Lampert, "Use of a Schottky barrier to measure impact ionization coefficients in semiconductors," *Solid-State Electron.*, vol. 16, pp. 381–385, 1973.

[10] K. F. Li, D. S. Ong, J. P. R. David, G. J. Rees, R. C. Tozer, P. N. Robson, and R. Grey, "Avalanche multiplication noise characteristics in thin GaAs p^+-i-n^+ diodes," *IEEE Trans. Electron Devices*, vol. 45, pp. 2102–2107, Oct. 1998.

[11] D. E. Aspnes, S. M. Kelso, R. A. Logan, and R. Bhat, "Optical properties of $Al_xGa_{1-x}As$," *J. Appl. Phys.*, vol. 60, no. 2, pp. 754–767, Jul. 1986.

[12] G. E. Stillman and C. M. Wolfe, "Avalanche photodiodes," in *Semiconductors and Semimetals*, R. K. Willardson and A. C. Beer, Eds. New York: Academic, 1977, vol. 12, pp. 291–393.

[13] C. H. Tan, J. P. R. David, S. A. Plimmer, G. J. Rees, R. C. Tozer, and R. Grey, "Low multiplication noise thin $Al_{0.6}Ga_{0.4}As$ avalanche photodiodes," *IEEE Trans. Electron Devices*, vol. 48, pp. 1310–1317, July 2001.

[14] J. Allam, "Universal dependence of avalanche breakdown on bandstructure: Choosing materials for high-power devices," *Jpn. J. Appl. Phys.*, pt. 1, vol. 36, no. 3B, pp. 1529–1542, Mar. 1997.