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Temperature Dependence of Impact Ionization in GaAs

C. Groves, R. Ghin, J. P. R. David, and G. J. Rees

Abstract—The temperature dependence of electron and hole impact ionization in gallium arsenide (GaAs) has been determined from photomultiplication measurements at temperatures between 20 K and 500 K. It is found that impact ionization is suppressed by increasing temperature because of the increase in phonon scattering. Temperature variations in avalanche multiplication are shown to decrease with decreasing avalanche region width, and the effect is interpreted in terms of the reduced phonon scattering in the correspondingly reduced ionization path length. Effective electron and hole ionization coefficients are derived and are shown to predict accurately multiplication characteristics and breakdown voltage as a function of temperature in p^+in^+ diodes with i-regions as thin as 0.5 μm .

Index Terms—Avalanche diodes, avalanche photodiodes, impact ionization, ionization coefficients, semiconductor materials measurements, temperature dependence.

I. INTRODUCTION

AVALANCHE multiplication resulting from impact ionization is an important process in several types of devices, such as transistors, where it limits the maximum operating power and in avalanche photodiodes (APDs), where it provides internal gain. The impact ionization process depends on temperature, largely via scattering from optical phonons of energy $\hbar\omega$, whose population is given by

$$n = \frac{1}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1}. \quad (1)$$

Furthermore, despite heatsinking, power devices generally operate at temperatures above ambient while other devices, such as photon counting APDs, often require cooling to suppress dark count. It is therefore of interest to characterize the temperature dependence of impact ionization to predict accurately device behavior and optimize device design.

Impact ionization is conventionally described in terms of coefficients α and β for electrons and holes respectively, which are the reciprocal of the mean distance between successive ionization events.

The recently renewed interest in measuring the temperature dependence of impact ionization in GaAs [1], [2] is due to the incomplete and conflicting data reported in earlier literature

[3]–[6]. Chang and Sze [3] performed the first investigation into the temperature dependence of ionization coefficients in GaAs, in which coefficients were shown to change in a highly nonuniform way with temperature. Mars [4] followed up this work by predicting ionization coefficients as a function of temperature; however, the agreement between measured breakdown and predicted voltages was poor. Capasso and co-workers [5], [6] found $\beta > \alpha$ at temperatures up to 470 K and $\alpha > \beta$ and above at 470 K, in disagreement with other investigations at room temperature [7], [8].

In [1] and [2] electron multiplication was measured as a function of temperature at electric fields up to 400 kV/cm. However, in modern submicron devices the fields can be significantly higher. With increasing electric field strength F the distance over which a carrier must travel before its ionization coefficient comes into equilibrium with the electric field, termed the “dead space,” becomes an increasingly significant fraction of the mean ionization path length [9], [10]. This is because α and β depend exponentially on inverse fields, while the dead space, given approximately at high fields by the ballistic ionization path length, varies as

$$d = \frac{E_{\text{th}}}{qF}. \quad (2)$$

Here E_{th} is the ionization threshold energy and q is the electronic charge.

Harrison *et al.* [11] observed that in $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ the temperature dependence of α reduces with increasing field, essentially because carriers scatter less often during their correspondingly shorter ionization path lengths. In this paper, we examine the effect in GaAs. We report measurements of photomultiplication on a series of GaAs diodes with intrinsic region thicknesses ranging from $w \sim 1 \mu\text{m}$ down to $\sim 0.025 \mu\text{m}$, over temperatures between 20 and 500 K. Both p^+in^+ and n^+ip^+ diodes were measured using both pure electron and pure hole injection in order to extract both α and β .

II. EXPERIMENTAL DETAILS

A series of GaAs p^+in^+ and n^+ip^+ diodes was grown using Be and Si as p- and n-type dopants respectively. Circular mesas with diameters of 100 to 400 μm , with annular top contacts to allow optical access, were fabricated by wet chemical etching. The nominal i-region thicknesses of the p^+in^+ diodes were $w = 1, 0.5, 0.3, 0.1, 0.05$, and $0.025 \mu\text{m}$, respectively, while the n^+ip^+ diodes were grown with $w = 1$ and $0.1 \mu\text{m}$. All diodes were grown by MBE, with the exception of the $w = 0.5 \mu\text{m}$ p^+in^+ diode which was grown by MOVPE. The i-region

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thicknesses were estimated from capacitance–voltage (C – V) and, in some cases, SIMS measurements, to be $w = 1.1, 0.48, 0.28, 0.15, 0.049,$ and $0.023 \mu\text{m}$, respectively, in the p^+in^+ diodes, and $w = 0.95$ and $0.095 \mu\text{m}$ in the n^+ip^+ diodes. These measurements also showed that the cladding doping was high ($>10^{18} \text{ cm}^{-3}$) in comparison with the unintentional doping in the i -region ($\sim 10^{16} \text{ cm}^{-3}$) in all cases.

All devices were checked for low dark current and sharp breakdown. Pure electron (hole) initiated multiplication, M_e (M_h) was achieved by illuminating the top surface of the p^+in^+ (n^+ip^+) diodes with laser light of wavelengths 633, 594, or 515 nm. The absorption coefficient of GaAs at 633 nm is approximately $4 \times 10^4 \text{ cm}^{-1}$ [12] and so we estimate that more than 98% of the incident light is absorbed in the $1 \mu\text{m}$ $p^+(n^+)$ cladding region. The light spot was focussed down to less than $10 \mu\text{m}$ in diameter to avoid significant mesa edge injection. The incident laser power was varied to provide photocurrents between 0.1 and $10 \mu\text{A}$ to check that multiplication was independent of primary photocurrent.

DC multiplication measurements were obtained by normalizing the measured dc photocurrent as a function of reverse bias after subtracting the dark current. In cases where the dark current was high, the incident light was chopped mechanically and the resultant ac photocurrent detected with a lock-in amplifier. The measured photocurrent was corrected for the bias-dependent collection efficiency of the depletion region after Woods *et al.* [13]. Photocurrent measurements were made on a number of devices across the wafers to ensure reproducibility.

Low-temperature measurements were performed on all layers by placing the devices bonded onto TO-5 headers in a closed cycle He cryostat. High-temperature ($>290 \text{ K}$) photomultiplication measurements were performed on devices bonded onto flat ceramic headers placed in a furnace. The breakdown voltage, V_{bd} , is defined here as the voltage for which the dark current increases by more than an order of magnitude over a small voltage increment ($\sim 100 \text{ mV}$). Where V_{bd} could not be determined reliably from dark current or photomultiplication measurements, an estimate was obtained by fitting the measured multiplication characteristic to the Miller expression [14], which is given below

$$M_e = \frac{1}{1 - (V/V_{bd})^s}. \quad (3)$$

Here s is dimensionless constant. V_{bd} was measured at high temperatures by dark current measurements on the $w = 1.1$ and $0.48 \mu\text{m}$ p^+in^+ diodes; “soft” breakdown behavior prevented similar measurements on the other devices. V_{bd} was determined on a number of devices to ensure reproducibility and that breakdown was not due to defects.

To check that temperature variation was not appreciably affecting the electric field profile via carrier freeze-out in the cladding layers, low-temperature C – V measurements were made on the $w = 0.023 \mu\text{m}$ p^+in^+ layer. The C – V profiles at 290 and 77 K were identical, confirming that, to within the resolution of the measurement, the electric field profile did not change.

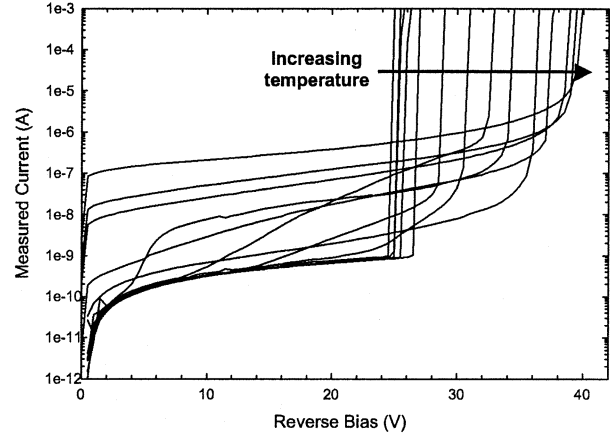


Fig. 1. Dark current as measured on a $w = 1.1 \mu\text{m}$ device at 20, 40, 60, 77, 100, 150, 200, 250, 290, 350, 400, 450, 475, and 500 K, respectively.

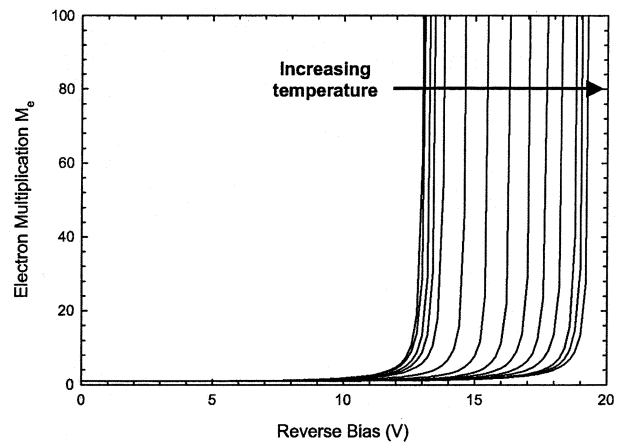


Fig. 2. Measured M_e for a $w = 0.48 \mu\text{m}$ device as a function of temperature (as in Fig. 1).

III. RESULTS AND DISCUSSION

Fig. 1 shows typical dark current characteristics for the $w = 1.1 \mu\text{m}$ p^+in^+ device at temperatures between 20 and 500 K. Breakdown appears abrupt for all curves shown, despite increasing dark current with temperature. These curves are typical of the other devices measured, with the exception of the p^+in^+ diodes having $w = 0.049$ and $0.023 \mu\text{m}$ which showed significantly increased dark current. It is clear that V_{bd} has a positive temperature coefficient, confirming that breakdown is due to avalanching rather than tunnelling.

Measurements of $M_e(M_h)$ were carried out at temperatures between 20 and 290 K on p^+in^+ (n^+ip^+) diodes of all thicknesses, and also between 290 and 500 K on the $w = 0.48 \mu\text{m}$ p^+in^+ diode. Fig. 2 shows M_e for a $w = 0.48 \mu\text{m}$ p^+in^+ diode at temperatures between 20 and 500 K. As expected, increasing the temperature causes the multiplication characteristic to shift to higher voltages, since higher electric fields are required to offset the increase in carrier cooling by phonon scattering and maintain multiplication. Fig. 2 also shows that the temperature dependence of multiplication is not uniform, since the multiplication curves crowd together at low temperatures. This is probably due to the saturation of the phonon emission ($\sim n+1$) and absorption ($\sim n$) scattering rates at low temperatures where n approaches zero [2].

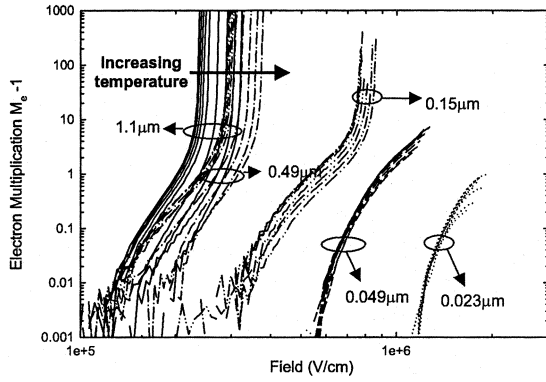


Fig. 3. Measured M_e characteristics for the $w = 1.1, 0.48, 0.15, 0.049,$ and $0.023 \mu\text{m}$ $\text{p}^+\text{i}\text{n}^+$ diodes at temperatures between 20 and 290 K (as in Fig. 1).

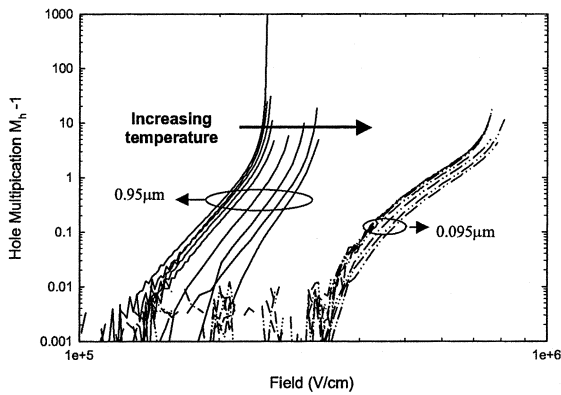


Fig. 4. Measured M_h characteristics for the $w = 0.95$ and $0.095 \mu\text{m}$ $\text{n}^+\text{i}\text{p}^+$ diodes at temperatures between 20 and 290 K (as in Fig. 1).

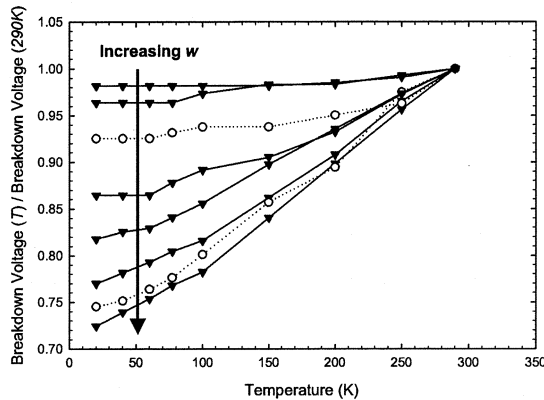


Fig. 5. V_{bd} (including a 1.2 V built-in voltage) versus temperature normalized to the 290 K value for all $\text{p}^+\text{i}\text{n}^+$ (filled symbols) and $\text{n}^+\text{i}\text{p}^+$ (hollow symbols) diodes.

Figs. 3 and 4 show similar multiplication characteristics for all $\text{p}^+\text{i}\text{n}^+$ ($\text{n}^+\text{i}\text{p}^+$) diodes, respectively, displayed on a log scale, confirming that multiplication has been determined reliably down to levels of $M_e(M_h) = 1.01$ before noise begins to dominate. The $w = 0.28 \mu\text{m}$ $\text{p}^+\text{i}\text{n}^+$ diode is omitted for the sake of clarity. It is clear from this figure that the temperature dependence of $M_e(M_h)$ decreases markedly with thickness of the multiplication region, in agreement with the findings for $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ [11]. This behavior also carries over into the breakdown voltage, V_{bd} , as shown in Fig. 5.

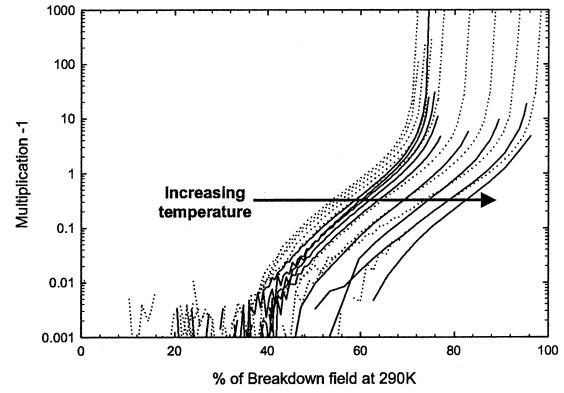


Fig. 6. M_e (dotted lines) and M_h (solid lines) for the nominally $w = 1 \mu\text{m}$ structures as a function of field, normalized to the breakdown field at 290 K, at temperatures between 20 and 290 K (as in Fig. 1).

Fig. 6 compares the field dependence of M_e and M_h at various temperatures for the nominally $w = 1 \mu\text{m}$ $\text{p}^+\text{i}\text{n}^+$ and $\text{n}^+\text{i}\text{p}^+$ diodes, normalized to the breakdown field at 290 K. It can be seen that M_e shifts in electric field with temperature at approximately the same rate as M_h (as w in the $\text{p}^+\text{i}\text{n}^+$ diode is slightly larger than in the $\text{n}^+\text{i}\text{p}^+$ diode, M_h is expected to show a greater shift with temperature if it were measured on the $\text{p}^+\text{i}\text{n}^+$ diode). This implies that the rates at which α and β change with temperature are similar, in agreement with Zheng *et al.* [1].

IV. IONIZATION COEFFICIENTS

Deriving ionization coefficients for use over a wide field range is not straightforward. At low fields, the ionization coefficient depends only upon the local electric field and so coefficients derived on one structure can be used to accurately predict multiplication for an arbitrary structure. However, in devices where the electric field is high, or changing rapidly, the analysis is more complicated, as the ionization behavior at a particular point depends upon the carrier's history; a property which is unique to the device upon which the measurement was made. In order to recover ionization coefficients that can be used on arbitrary structures, a model that implicitly accounts for a carrier's history should be used [15]–[17]. These models have proven very successful in reproducing multiplication, breakdown, and noise characteristics of APDs, however, they are complex and not easily used.

In an effort to preserve simplicity, while also maintaining some ability to predict avalanche behavior in arbitrary structures, we follow the approach of Plimmer *et al.* [18], [19] for deriving “effective” ionization coefficients, which can be used in simple analytical formulae [20] to predict multiplication and breakdown behavior. The approach involves deriving the dependence of ionization coefficients for a range of devices with different w using a local model and parameterizing the envelope to these resulting curves. Ionization coefficients derived by this method have been shown to be surprisingly effective at predicting multiplication in structures with thickness down to $w = 0.5 \mu\text{m}$ and breakdown behavior in devices as thin as $w = 0.2 \mu\text{m}$ [18], [19]. The reason why these coefficients work well, despite the exclusion of dead space effects, is discussed in more detail elsewhere [18]. While this approach is *not* as accu-

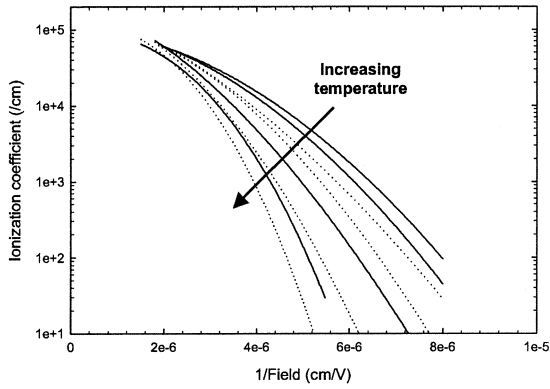


Fig. 7. Parameterized α (solid lines) and β (dotted lines) at 20, 77, 200, and 290 K.

TABLE I
PARAMETRIZATIONS OF α AND β BETWEEN 20 AND 290 K

	α (/cm)			β (/cm)		
	A (10^5)	B (10^5 /cm)	C	A (10^5)	B (10^5 /cm)	C
20K	0.98	3.46	1.90	1.64	4.95	1.57
40K	1.00	3.52	1.90	1.26	4.27	1.83
60K	1.06	3.70	1.83	1.40	4.55	1.73
77K	1.08	3.75	1.86	1.32	4.42	1.83
100K	1.31	4.18	1.82	1.52	4.86	1.73
150K	1.62	4.81	1.73	2.20	6.23	1.57
200K	2.00	5.60	1.63	1.80	5.47	1.87
250K	1.24	4.66	2.03	2.50	6.67	1.67
290K	0.96	4.47	2.33	1.24	4.99	2.33

rate as those presented in [15]–[17] it should provide a reasonable prediction of all multiplication values in thick structures and also high multiplication values in thinner structures.

Since the widths of the nominally $w = 1 \mu\text{m}$ p^+in^+ and n^+ip^+ diodes are actually different, the technique described by David *et al.* [21] for deducing local ionization coefficients is used. This approach allows accurate determination of α and β from M_e and M_h without complementary multiplication curves measured on the same width of device, at the expense of a reduction in field range over which the ionization coefficient is determined. α and β at high fields were determined by considering the breakdown voltages of the $w = 0.48 \mu\text{m}$ and $0.15 \mu\text{m}$ p^+in^+ devices. The data of Bulman *et al.* [7] were used to predict the α/β ratio at the breakdown field, which was then assumed to be independent of temperature (after Fig. 6 and [1]). This gave α and β at various fields which could be used to derive an expression for the effective ionization coefficient. The Chynoweth expression, given below, was chosen to describe the field dependence of the ionization coefficient

$$\alpha(F), \beta(F) = A \exp \left[- \left\{ \frac{B}{F} \right\}^C \right]. \quad (4)$$

A least squares fit to the calculated ionization coefficients was performed, treating A , B , and C as adjustable parameters. The coefficients obtained for all temperatures between 20 and 290 K are shown in Table I, and selected parameterizations are shown

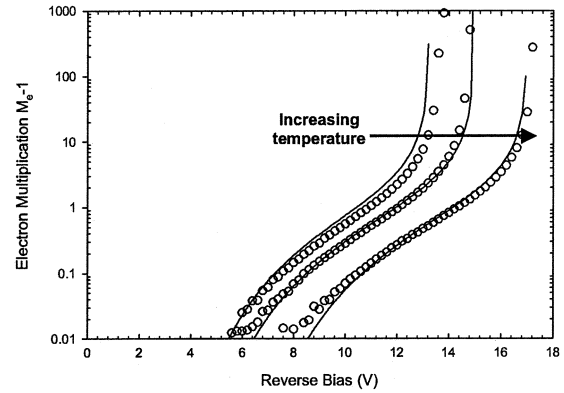


Fig. 8. Measured M_e (symbols) for a $w = 0.48 \mu\text{m}$ p^+in^+ diode compared to predicted M_e (lines) generated from the present parameterizations at 77, 150, and 290 K.

in Fig. 7. Owing to the lack of ionization coefficient data at high electric fields the parameterizations are not expected to work well for fields greater than 400 kVcm^{-1} . At electric field strengths significantly in excess of 400 kVcm^{-1} ionization behavior is not significantly temperature dependent and so ionization coefficients determined at 290 K, for example [18], could be used at other temperatures.

As a test of the parameterized coefficients, Fig. 8 shows the predicted multiplication for an ideal $w = 0.48 \mu\text{m}$ p^+in^+ diode, compared with the measured characteristic. It can be seen that the agreement is good, both at low and high multiplications. Only three temperatures are shown for the sake of clarity, all other temperatures show similar or better quality of fit. This agreement is not merely a check of self-consistency, as only the ionization coefficients at breakdown for the $w = 0.48 \mu\text{m}$ p^+in^+ diode were considered when deriving the parameterizations. The agreement is expected to deteriorate at low multiplication values in thinner structures owing to the poor treatment of dead space effects. Nevertheless, Fig. 8 shows that the present parameterizations can be used to give reliable estimates of breakdown and multiplication in arbitrary structures.

V. CONCLUSION

The electric field dependence of the electron and hole ionization coefficients in GaAs has been measured at temperatures between 20 and 290 K. The results show that as the temperature is reduced the ionization coefficient is enhanced owing to a reduction in the phonon population. It has also shown that the temperature dependence of impact ionization reduces with reducing device thickness.

Effective ionization coefficients have been derived and have been shown to predict accurately multiplication and breakdown in devices with dimensions as small as $0.5 \mu\text{m}$. The agreement is expected to deteriorate in thinner structures, however it has been shown that the temperature dependence of ionization in thin devices is small.

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