Avalanche Multiplication and Breakdown in $Ga_{0.52}In_{0.48}P$ Diodes

R. Ghin, J. P. R. David, S. A. Plimmer, M. Hopkinson, G. J. Rees, D. C. Herbert, and D. R. Wight

***Abstract*—The electron and hole photomultiplication characteristics M_e and M_h have been measured in a series of $Ga_{0.52}In_{0.48}P$ devices with high field regions ranging from 2.0 μm down to the depletion width of a heavily doped p-n junction. The hole ionization coefficient β is found to be slightly higher than the electron ionization coefficient α at low fields but at high fields they approach one another. α and β are found to be significantly lower than in GaAs across the entire range of electric fields studied, and the breakdown voltage of $Ga_{0.52}In_{0.48}P$ is approximately 1.9 times higher than for similar GaAs structures. Contrary to the behavior observed in GaAs, the multiplication characteristics in all except the thinnest structures appear to be relatively unaffected by the dead space, the minimum distance required to gain sufficient energy to initiate impact ionization. In these very thin structures, a local description of multiplication cannot account for the ionization behavior accurately, and therefore, a Monte Carlo (MC) model has been used to reproduce the measured multiplication characteristics and extract the ionization coefficients.**

I. Introduction

THE ternary compound $Ga_{0.52}In_{0.48}P$ is becoming increasingly important especially for high-power and high-temperature devices, mainly because of its large direct bandgap ($E_g = 1.91$ eV at 295K). One of the main limiting factors, e.g., in microwave devices at very high electric fields, is the onset of avalanche multiplication. Accurate knowledge of the ionization coefficients which govern this multiplication process, and ultimately breakdown, is therefore important in device design. Measurements performed on bulk $Ga_{0.52}In_{0.48}P$ p-i-n structures [1], [2] show that α and β are very similar and are much lower than in GaAs for the same electric field. However, these measurements have only been performed on thick multiplication structures, and modern semiconductor devices can have high electric fields across short distances. Recent multiplication measurements on GaAs have shown that the dead space can be very significant in thin structures [3]. In heterojunction bipolar transistors (HBT's), this dead space has been shown to reduce the multiplication occurring in heavily doped collectors [4]. Any attempt to model such devices will therefore require knowledge of the dead space and the ionization coefficients, especially at high electric fields.

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In this paper, we report detailed measurements of photomultiplication characteristics performed on $Ga_{0.52}In_{0.48}P$ p-i-n diodes with nominal i-region thicknesses from 2 μm down to 0.1 μm and on a heavily doped p-n junction. From these, we deduce the ionization coefficients over a wide electric field range and also demonstrate the influence of the dead space. Conventional analytical models are unsuitable for modeling the multiplication characteristics in the thinner structures as they are incapable of accounting accurately for the dead space. However, a simple Monte Carlo (MC) model is shown to give good agreement with the measured multiplication characteristics, thereby allowing us to determine α and β at higher fields.

II. Experiment

The $Ga_{0.52}In_{0.48}P$ devices were grown at a temperature of 500°C by conventional solid-source molecular beam epitaxy (SSMBE) in a VG V80H MBE system using Be and Si as the p- and n-type dopants. A thick undoped $Ga_{0.52}In_{0.48}P$ layer was initially grown on an n^+ GaAs substrate, and Schottky diodes fabricated to assess the background doping level. Capacitance-voltage (CV) measurements indicated that the background doping density was approximately 3×10^{14} cm^{-3}. Very little ordering occurs in SSMBE growth of $Ga_{0.52}In_{0.48}P$, and this was confirmed by 10 K photoluminescence measurements. To assess the extent of dopant diffusion in $Ga_{0.52}In_{0.48}P$, a structure was grown with 400 Å wide doping spikes of Be varying in density from 4×10^{17} to 1×10^{19} cm^{-3}. Secondary ion mass spectroscopy (SIMS) measurements indicated that appreciable dopant diffusion occurred only when the Be doping level was greater than 5×10^{18} cm^{-3}. Similar tests using Si doping showed little diffusion even for densities of 1×10^{19} cm^{-3}.

The p-i-n devices were grown on 2-in-diameter n^+ (100) orientated GaAs substrates and comprised a 0.5-μm Si-doped n^+ GaAs buffer, a Si-doped n^+ $Ga_{0.52}In_{0.48}P$ layer, an undoped $Ga_{0.52}In_{0.48}P$ i-region, and a Be-doped p^+ $Ga_{0.52}In_{0.48}P$ cap. Thick p^+ and n^+ ($\geq$1.0 μm) layers were used in devices for photomultiplication measurements to ensure total absorption of the light and so avoid mixed injection of carriers into the high field region. The $Ga_{0.52}In_{0.48}P$ n-i-p diodes were grown on p^+ substrates in a similar manner but with the dopants reversed. Circular mesa diodes of 100–400 μm diameter were fabricated by wet chemical etching with annular top contacts to allow optical access. No premature edge breakdown was observed in any of the layers investigated. Reactive ion etching was used to

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selectively etch windows in the substrate aligned to the center of the mesas allowing back illumination of the devices.

Since the deduced ionization coefficients depend strongly on the assumed electric field profile, the i-region width (w) and the doping levels in the p$^+$, i, and n$^+$ regions must therefore be determined. To obtain these parameters, SIMS and CV measurements were performed. CV profiles were measured at both 300 K and 77 K to distinguish between Debye blurring and dopant diffusion. In order to determine the doping levels and w, the measured CV profiles were simulated by solving Poisson's equation within the depletion approximation. Results from SIMS and CV agreed closely, giving background and cladding doping levels in the thick structures of approximately mid-10^{14} and 10^{18} cm^{-3}, respectively.

Reverse current-voltage measurements were performed in the dark using a Keithley 236 source measure unit. All devices measured showed low reverse dark currents ($I_{\rm dark} <$ nA) until the onset of a sharp and clearly defined breakdown voltage ($V_{\rm bd}$) at which reverse currents increased by several orders of magnitude for a 0.1-V increment in reverse voltage. However, the thinnest p-i-n device exhibited significant tunneling in the reverse characteristics, making $V_{\rm bd}$ less precise except in the smallest area devices. Measurements were performed on several devices from each layer to ensure reproducibility of $V_{\rm bd}$.

Photomultiplication measurements were performed using excitation wavelengths from 442 nm (HeCd), 542 nm (HeNe), and 633 nm (HeNe) lasers. Pure M_e and M_h were achieved by focusing the laser light to a small spot (<10 μm) onto the p$^+$ and n$^+$ cladding layer of the back-etched p-i-n devices, respectively. DC photomultiplication was obtained by measuring the photocurrent as a function of bias after subtracting $I_{\rm dark}$. AC photomultiplication was measured using a phase sensitive lock-in amplifier with illumination chopped at ~400 Hz in a manner similar to that described in [5]. This method rejects the DC leakage currents and ensures that only the photocurrent component is measured. The incident laser power was varied to provide photocurrents in the range of 10 nA–10 μA to ensure that the multiplication characteristics were independent of the primary photocurrent. In all devices the premultiplication photocurrent exhibited a slight increase with reverse bias owing to the expansion of the depletion layer into the cladding regions, resulting in an increased collection of primary photocarriers. Since these structures have heavily doped cladding layers, this increase is small and was accounted for by a correction procedure described by Woods *et al.* [6]. All devices measured were able to demonstrate multiplication factors >15 and in some cases up to 150, indicating that $I_{\rm dark}$ did not limit the measurement range. Normalized multiplication results from different regions on a device and from different devices were similar, and identical values of $V_{\rm bd}$ were obtained, confirming that the breakdown mechanism is due to bulk avalanche and not to defects or microplasmas.

III. Results

The layers investigated and their respective i-region thicknesses are described in Table I. Photomultiplication measurements have previously been reported on layers M2, M5, and M9, p-i-n structures with nominally 1.0, 0.7, and 0.2 μm thick i-regions, respectively, [2] and these are included here for completeness. M_h was obtained on these three structures by back illumination. To confirm these results, top illumination of M1, a 1.96-μm n-i-p was performed to inject primary holes. The ionization coefficients deduced from M1, assuming an ideal n-i-p structure in which the electric field is uniform, exhibit good agreement with the earlier parameterized form of β [2], as shown in Fig. 1, and provide more accurate data at low fields.

TABLE I
LAYER NUMBERS, i-REGION THICKNESSES, MEASURED TOTAL BREAKDOWN VOLTAGE (V_T ($Ga_{0.52}In_{0.48}P$)), CALCULATED TOTAL BREAKDOWN VOLTAGE OF SIMILAR GaAs STRUCTURES (V_T (GaAs)) AND THE RATIO OF BREAKDOWN IN $Ga_{0.52}In_{0.48}P$ TO GaAs (R_T). * DENOTES n-i-p DEVICES

Layer number	'i' thickness w (μm)	V_T ($Ga_{0.52}In_{0.48}P$) (V)	V_T (GaAs) (V)	R_T
M1*	1.96	105.6	57.8	1.83
M2	1.07	66.4	35.0	1.90
M3	0.89	56.8	30.2	1.88
M4	0.874	55.8	29.0	1.86
M5	0.74	49.2	26.0	1.89
M6*	0.48	34.8	18.3	1.90
M7*	0.41	31.1	16.3	1.91
M8*	0.36	27.6	14.5	1.90
M9	0.215	19.3	10.3	1.87
M10	0.102	14.6	8.0	1.83
M11	p^+=2.34x10^{18}cm^{-3} n^+=1.17x10^{18}cm^{-3}	11.92	6.34	1.88

Ionization coefficients for M9, the nominally 0.2 μm structure, showed a slight deviation from the bulk data [2] at low electric fields, as shown in Fig. 1. To investigate this further, photomultiplication measurements were carried out on two thinner structures: M10 and M11 (nominally 0.1 μm and a heavily doped p-n junction, respectively). Fig. 2 shows the normalized top injection photomultiplication obtained using 442 nm, 542 nm, and 633 nm on M10 together with $I_{\rm dark}$ measured for M10 and M11. Since the three excitation wavelengths were absorbed to a different extent in the 1.0 μm p$^+$ cap contributing varying degrees of mixed injection in the high-field region, the fact that the normalized multiplication characteristics were identical suggests that $\alpha \approx \beta$. Owing to the high tunneling currents present in M11, only AC photomultiplication measurements were performed.

Fig. 3 shows the normalized AC photomultiplication characteristics for M9, M10, and M11. Since M10 and M11 had significant i-region doping, the ionization coefficients were obtained using a method [7] which allows for arbitrary known electric field profiles and also accounts for depletion into the contacts. It was assumed, for interpretation purposes, that

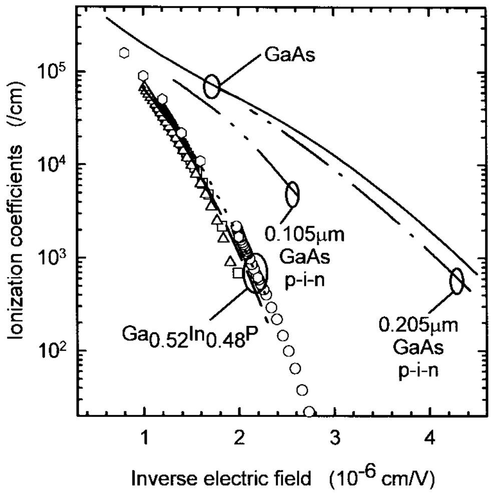

Fig. 1. $Ga_{0.52}In_{0.48}P$ impact ionization coefficients in M1 ($w = 1.96$ μm n-i-p, ◯, only β is shown), M9 ($w = 0.215$ μm p-i-n, □, $\alpha = \beta$) and M10 ($w = 0.102$ μm p-i-n, △, $\alpha = \beta$). Results at high fields (hexagon) are from a Monte Carlo model. Previously published α (— — —) and β (- - - - -) from [2] are shown for comparison. The bulk α (——) for GaAs from [17], [18] is also shown, together with the "effective" ionization coefficients of the 0.205 μm (— - — - —) and the 0.105 μm [3] (— - - - — - - - —) GaAs p-i-n structures deduced using a local model.

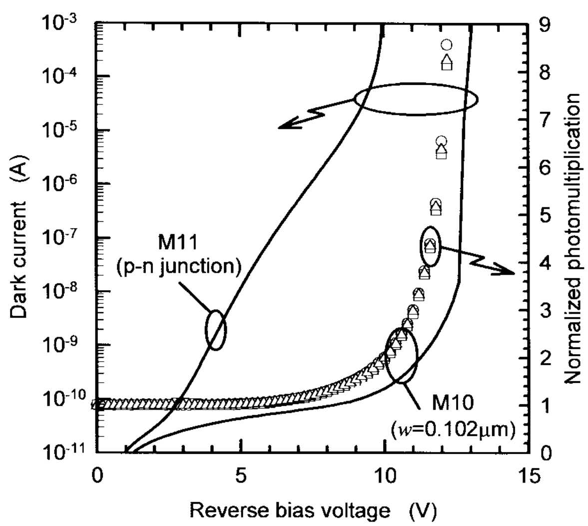

Fig. 2. Normalized photomultiplication values for M10 ($w = 0.102$ μm p-i-n) using top injection of 442 nm (◯), 542 nm (□), and 633 nm (△) excitation wavelengths. In addition, dark currents (lines) for M10 and M11 (p-n junction) are shown.

the ionization coefficients depend only on the local electric field. As shown in Fig. 1, the ionization coefficients of M10 deduced, assuming $\alpha = \beta$, deviate slightly from the bulk values at low fields owing to dead space effects but converge at higher fields in a manner similar to M9 [2]. This very short i-region structure allows us to extend the measurement of α to 1000 kV/cm. A similar analysis could not be performed on M11, owing to the very rapid variation in electric field with distance. The ionization coefficients at higher fields were, however, obtained with the aid of modeling.

Recently, both complex MC methods [8] and simpler lucky-drift arguments [9] have been used to model ionization coefficients and multiplication. While MC models suffer from

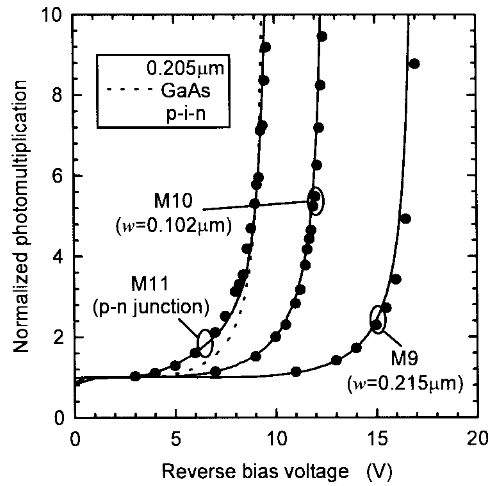

Fig. 3. M_h ($\approx M_e$) for M11 (p-n junction), M10 ($w = 0.102$ μm) , and M9 ($w = 0.215$ μm) $Ga_{0.52}In_{0.48}P$ p-i-n devices (——) from left to right. M_e for the 0.205 μm GaAs p-i-n device (- - - - -) is also shown. Symbols represent results from the Monte Carlo model (see text).

longer computer run times, the lucky drift model appears to breakdown below 0.1 μm [10]. Therefore, a simple MC technique is used here to reproduce the multiplication characteristics in the thinner structures and to obtain the high-field ionization values.

Our approach assumes single parabolic conduction and valence bands resulting in an energy independent [11] mean free path λ after which a random number uniformly distributed between 0 and 1 is used to select either self-scatter or a real scattering process. To maintain simplicity, we have assumed the common phonon model of [12] in which an average phonon energy due to absorption or emission of phonons for both electrons and holes is taken to be the mean of the LO and LA zone-edge phonon energies. This value is calculated to be 37 meV in $Ga_{0.52}In_{0.48}P$ by scaling the LO phonon energy in [13] using the scaling ratio obtained from GaAs [12], [14]. Impact ionization is modeled as an additional scattering mechanism after Keldysh [15] with a rate above the effective threshold energy $E_{\rm th}$ equal to

$$R_{\rm ii} = S\left(\frac{E - E_{\rm th}}{E_{\rm th}}\right)^{2.4} \tag{1}$$

where E is the carrier energy, $E_{\rm th}$ is taken as 2.11 eV for $Ga_{0.52}In_{0.48}P$ (termed $\langle E_{\rm ind}\rangle$ in [16]), and S is the ionization "softness" parameter. After each ionization event, the remaining energy is assumed to be divided equally between the resulting carriers. Since at the high fields of interest $\alpha \approx \beta$, the electron and hole transport were treated in a similar manner using the same parameters.

Fitted values of $\lambda = 33.5$ Å and $S = 8 \times 10^{12}$ s^{-1} were able to reproduce measured values of $\alpha = \beta$ down to fields of 455 kV/cm, as shown in Fig. 1. To simulate multiplication, the fields in the cladding and i-regions were taken as linear functions of position. We allowed minor changes to p$^+$ n$^+$, i, and w (listed in Table II) within experimental error and were able to reproduce accurately the measured multiplication characteristics, as shown in Fig. 3 for the two thinnest p-i-

TABLE II
VALUES OF THE CLADDING DOPING, i- REGION THICKNESS AND DOPING USED IN THE MONTE CARLO MODEL TO SIMULATE THE MEASURED MULTIPLICATION CHARACTERISTICS IN THE THIN p-i-n DEVICES

Layer number	'i' thickness w (μm)	cladding doping $p^+(n^+)$ (x10^{18} cm^{-3})	'i' doping i (cm^{-3})
M9	0.208	ideal p-i-n assumed	
M10	0.101	1.77(1.77)	1x10^{16}
M11	——	2.16(1.1)	——

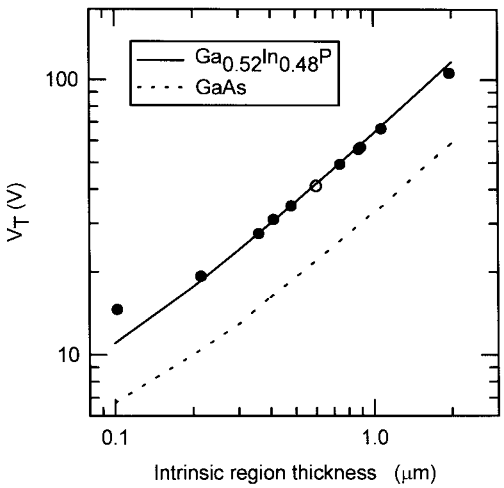

Fig. 4. Calculated breakdown voltage for $Ga_{0.52}In_{0.48}P$ (——) from present parametrised form of α and β, and for GaAs [17], [18] (- - - - -) plotted for ideal p-i-n devices as a function of the i-region thickness. Measured values for $Ga_{0.52}In_{0.48}P$ from present data (•) and from [1] (○) are also shown.

n devices and also for the heavily doped p-n junction. We therefore believe that the high-field ionization coefficients extracted from the model and shown in Fig. 1 are reliable. The parametrized forms fitted to the low-field measured data, the high-field simulated results, and our earlier ionization data [2] are

$$\alpha = 4.57 \times 10^5 \exp\left(-\left(\frac{1.413 \times 10^6}{F}\right)^{1.73}\right) \text{cm}^{-1} \quad (2a)$$

and

$$\beta = 4.73 \times 10^5 \exp\left(-\left(\frac{1.425 \times 10^6}{F}\right)^{1.65}\right) \text{cm}^{-1} \quad (2b)$$

over the electric field range 357 kV/cm to 1700 kV/cm, where F is the electric field in units of V/cm.

Our investigations show that for fields below 1 MV/cm $\beta > \alpha$ and for higher fields, the difference is negligible. To check the accuracy of the expressions (2a) and (2b), they are used to calculate the absolute breakdown voltage V_T equal to the sum of V_{bd} and the diffusion voltage (assumed equal to 1.8 eV), for a wide range of device thicknesses assuming ideal p-i-n structures. The results are plotted in Fig. 4, together with V_T measured in the dark for all layers listed in Table I. The I_{dark} measurements of breakdown on M3, M4, M6, M7, and M8 were corroborated by top illumination measurements, confirming that breakdown was due to a bulk avalanche process and not to defects or microplasmas. Pure M_e (M_h) obtained on these layers were analyzed using an ideal p-i-n (n-i-p) assumption, yielding ionization coefficients that agree well with (2).

As can be seen from Fig. 4, the agreement is very good in thicker structures where the ideal structure assumption is valid. However, because of appreciable depletion into the cladding regions, V_T measured for the nominally $w = 0.1$ μm structure is higher than predicted. Also shown in Fig. 4 are the calculated values of V_T for similar GaAs p-i-n structures using the parametrized forms of α and β from [17] and [18]. These values are listed in Table I, together with R_T, the ratio of V_T measured in $Ga_{0.52}In_{0.48}P$ to that calculated for a similar GaAs structure. Breakdown voltages are found to be 1.8–1.9 times higher in $Ga_{0.52}In_{0.48}P$ than in GaAs, even in the thinnest structures despite neglecting the effects of dead space.

IV. DISCUSSION

Fig. 1 shows the bulk electron ionization coefficients for GaAs reported by Bulman *et al.* [18] at low fields and by Millidge *et al.* [17] at high fields. In thin GaAs structures, the dead space can become a significant fraction of the total avalanching width. The ionization coefficients derived from such structures using a local analysis deviate from bulk values particularly at lower electric fields. Plimmer *et al.* [3] have shown that dead space influences the ionization behavior strongly in a GaAs p-i-n with a $w = 0.105$ μm-thick i-region but not in a $w = 0.55$ μm structure. In order to make comparisons with the present $Ga_{0.52}In_{0.48}P$ data M_e was measured using 633 nm illumination in a $w = 0.205$ μm MBE-grown GaAs p-i-n, as shown in Fig. 3. The "effective" ionization coefficients deduced using a local model from the $w = 0.205$ μm GaAs p-i-n as well as the previously reported $w = 0.105$ μm p-i-n device [3] are shown in Fig. 1. The reduction in "effective" α for GaAs occurs at low fields in structures of $w \leq 0.2$ μm and becomes increasingly pronounced as the device thickness decreases. A similar trend is seen for the thinner $Ga_{0.52}In_{0.48}P$ structures but is much less prominent.

To accentuate the low values of multiplication where dead space effects are most significant, we show in Fig. 5 $\ln(M_h - 1)$ plotted against the electric field for the $Ga_{0.52}In_{0.48}P$ p-i-n devices. This figure shows that our measurement technique is capable of determining multiplication values as low as 1.007 before experimental noise dominates. It can be seen that the onset of measurable multiplication begins at a similar field for devices with $w \geq 0.215$ μm but shifts to higher fields for thinner devices owing to effects of the dead space. Also shown in Fig. 5 is multiplication obtained using (2) with a local model for devices M9, M10, and M11. As can be seen, appreciable differences occur only for the thinnest device in which the dead space is most significant. Therefore, successful prediction of the multiplication behavior in $Ga_{0.52}In_{0.48}P$ can still be obtained using (2) with a local analysis down to avalanching distances of 0.1 μm. Moreover, both experiment and the local model converge at high multiplication values meaning that the parametrized form of α and β will be able to generate correct

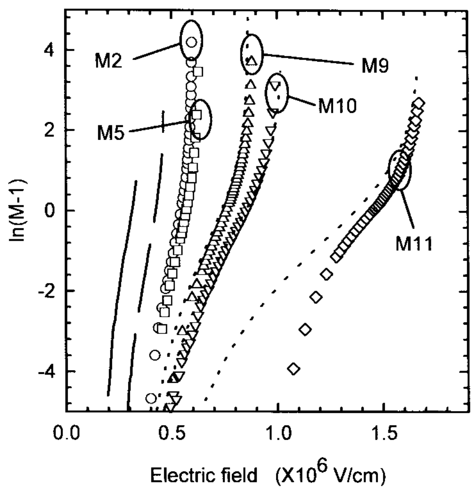

Fig. 5. Measured $\ln(M_h - 1)$ plotted against the electric field for the back etched $Ga_{0.52}In_{0.48}P$ *p-i-n* devices M2 ($w = 1.07$ μm, ◯), M5 ($w = 0.74$ μm, □), and M9 ($w = 0.215$ μm, △). Data for M10 ($w = 0.102$ μm, ▽) and M11 (*p-n* junction, ◇) are plotted against the peak electric field. The lines (- - - - -) represent data calculated using the present parametrised form of α and β with the local assumption. $\ln(M_e - 1)$ for nominally $w = 1.0$ μm GaAs [3] (——) and $Al_{0.3}Ga_{0.7}As$ [19] (— — —) structures are also shown.

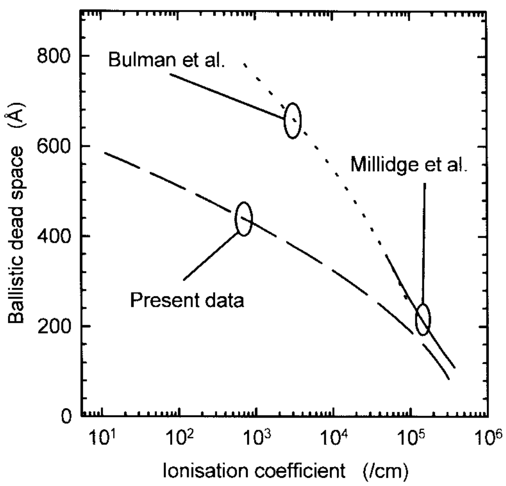

Fig. 6. Ballistic dead space plotted as a function of the ionization coefficient for GaAs from [17] (——), [18] (- - - - -), and $Ga_{0.52}In_{0.48}P$ (— — —).

$V_{\rm bd}$ values even for heavily doped p-n junctions. The reason for this has been argued previously [17] in thin GaAs structures. Thus, although dead space is significant, the measured values of $V_{\rm bd}$ agree well with those predicted by the local model because overshoot effects in ionization compensate for the dead space. Also shown in Fig. 5 are the M_e data for nominally 1.0 μm GaAs and $Al_{0.3}Ga_{0.7}As$ structures [19]. Comparison with the bulk $Ga_{0.52}In_{0.48}P$ structure M2 shows that the breakdown field increases with the average bandgap [16] in different material systems. What is perhaps surprising is that the onset of multiplication in thick devices also follows this trend.

Since the dead space increases with threshold energy, which is in turn likely to increase with bandgap, we might expect its effect to be more significant in $Ga_{0.52}In_{0.48}P$ than in GaAs, in which $E_{\rm th}$ is 1.75 eV [16]. Fig. 1 shows that the dead space affects the effective ionization coefficients in the nominally 0.2 μm GaAs structure but is hardly apparent in all but the thinnest $Ga_{0.52}In_{0.48}P$ structure. The reason for this can be understood when we compare the ballistic dead space (defined as $E_{\rm th}/qF$) to the ionization coefficient for the two materials as shown in Fig. 6. Clearly, the relative increase in $E_{\rm th}$ between materials is more than offset by the much higher field required to achieve a given ionization in $Ga_{0.52}In_{0.48}P$. This result therefore suggests that the dead space effect at the same multiplication will be relatively less significant in wide gap materials than in narrower gap materials.

V. Conclusion

We have determined the electron and hole ionization coefficients α and β in $Ga_{0.52}In_{0.48}P$ over the electric field range 357–1700 kV/cm. β is found to be slightly larger than α at low electric fields, but they become indistinguishable as the field increases. Dead space effects are observed for structures with nominal i-regions $w \leq 0.2$ μm but are relatively insignificant when compared to GaAs. The ionization coefficients in $Ga_{0.52}In_{0.48}P$ is significantly lower than in GaAs, resulting in breakdown voltages that are approximately 1.9 times higher than those in similar GaAs structures.

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