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Ng, J.S., Tan, C.H., David, J.P.R. et al. (2 more authors) (2003) Field dependence of impact ionization coefficients in In0.53Ga0.47As. IEEE Transactions on Electron Devices, 50 (4). pp. 901-905. ISSN 0018-9383

https://doi.org/10.1109/TED.2003.812492

Field Dependence of Impact Ionization Coefficients in $In_{0.53}Ga_{0.47}As$

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***Abstract*—Electron and hole ionization coefficients in $In_{0.53}Ga_{0.47}As$ are deduced from mixed carrier avalanche photomultiplication measurements on a series of p-i-n diode layers, eliminating other effects that can lead to an increase in photocurrent with reverse bias. Low field ionization is observed for electrons but not for holes, resulting in a larger ratio of ionization coefficients, even at moderately high electric fields than previously reported. The measured ionization coefficients are marginally lower than those of GaAs for fields above 250 kVcm^{-1}, supporting reports of slightly higher avalanche breakdown voltages in $In_{0.53}Ga_{0.47}As$ than in GaAs p-i-n diodes.**

***Index Terms*—Avalanche breakdown, avalanche multiplication, impact ionization, InGaAs.**

I. INTRODUCTION

BECAUSE of the effects of transistor action, the weak electron ionization coefficient measured at low fields [1], [2] may be responsible for breakdown in common-emitter configured $In_{0.53}Ga_{0.47}As$-based heterojunction bipolar transistors (HBTs) at voltages lower than that expected for the isolated collector–junction breakdown [3]. Several authors have determined that α and β, the electron and hole ionization coefficients, in $In_{0.53}Ga_{0.47}As$ using photomultiplication measurements on p-i-n diode structures [4]–[6]. While there is some disagreement among the absolute values measured for α and β, their field dependences are similiar to those of silicon (Si), GaAs, and InP, decreasing approximately exponentially with an increasing inverse field.

Using measurements on an n-p-n HBT with $In_{0.53}Ga_{0.47}As$ base and collector layers, Ritter *et al.* [1] reported anomalously high values of α, termed "low field impact ionization," at fields lower than those studied in [4]–[6]. Their results were corroborated and extended by Canali *et al.* [2] to fields as low as 20 kVcm^{-1}. Although the results in [1] and [2] agree at higher fields, the values of α are in disagreement with those in [5] and [6] for fields below 200 kVcm^{-1}. By contrast, the recent HBT measurements of β [7], [8], which agree qualitatively with those reported in [5], [6] did not show this low field impact ionization.

Although the more recent HBT measurements [1], [2], [7], [8] covered a wider electric field range than the earlier photomultiplication measurements [4]–[6], α and β could not be measured on the same HBT layer, and the interpretation relied on the simplifying assumption that $\alpha = \beta$. Furthermore, these HBT results were measured on only one layer in each investigation so that errors in determining fields and multiplication factors could not easily be detected. More critically, these HBT-based results relied on measuring the dc collector current in which leakage current was not easily distinguished from that induced by impact ionization. Most of the measurements in the previous works also required correction, either for depletion-edge movement (in the photomultiplication measurements [4]–[6]) or for Early effect (in the HBT measurements [7], [8]), introducing further uncertainties in the multiplication factors and, hence, in the ionization coefficients, especially at low fields. The uncertainties in α and β can have a significant impact on the design of HBT structures. For example, calculations using the Ebers–Moll equations [9] show that a $\pm$20% uncertainty in α and β (less than the spread between results of [4]–[8]) will result in a $\approx\mp$10% spread in the collector–emitter breakdown voltage of a common–emitter configured HBT with a 0.3-μm-thick collector and a transistor gain of 30.

Moreover, the HBT measurements used sub-micron structures with avalanche widths ranging from 0.3 μm to 0.85 μm. At a given value of multiplication, the effects of dead space exert more influence in thin than in thick structures. Neglecting such effects in sub-micron structures [1], [2], [7] is therefore less valid than in thicker structures [4]–[6]. Furthermore, at any given field thinner structures have smaller multiplication factors, which can be measured less accurately. A systematic measurement of $In_{0.53}Ga_{0.47}As$ ionization coefficients in thick structures using unambiguously determined multiplication factors is clearly desirable.

In this work, ionization coefficients in $In_{0.53}Ga_{0.47}As$ are determined from phase-sensitive photomultiplication measurements, which distinguish photocurrent from dark current, on a series of thick $In_{0.53}Ga_{0.47}As$ p-i-n structures, interpreted using a local impact ionization model that does not assume $\alpha = \beta$. The results are compared with previously published data. Breakdown voltages V_{bd} in $In_{0.53}Ga_{0.47}As$ are also calculated for a range of p$^+$-n$^-$-n$^+$ and p$^+$-n$^-$ structures using our measured ionization coefficients.

II. STRUCTURE DETAILS AND ELECTRICAL CHARACTERIZATIONS

The $In_{0.53}Ga_{0.47}As$ structures used in this work comprise three heterojunction p-i-n diodes grown by metal–organic chemical vapor deposition (MOVPE) on (100) oriented n$^+$ InP substrates. The $In_{0.53}Ga_{0.47}As$ i-region, of thickness w, is sandwiched between 0.5-μm-thick p$^+$ and n$^+$ InP cladding layers. Mesa devices with diameters of 400, 200, 100, and 50

Manuscript received October 2, 2002; revised January 28, 2003. This work was supported by the EPSRC, University of Sheffield, Sheffield, U.K. and Bookham Technology. The review of this paper was arranged by Editor M. Anwar.

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Digital Object Identifier 10.1109/TED.2003.812492

μm, respectively, were fabricated from the wafers. Annular p-type metal contacts and grid-like n-type metal contacts were deposited to allow optical access to the top and back of the devices. The i-region thickness for each layer was estimated by fitting to the capacitance-voltage measurements assuming abrupt p^+-p^--n^+ diode doping profiles. The estimated values of w are 1.8, 3.2, and 4.8 μm, respectively.

III. Photomultiplication Experiments

To deduce the multiplication factor M, phase-sensitive measurements of the avalanche multiplied photocurrent $I(V)$ were performed as a function of reverse bias V [10]. The illumination was chopped mechanically and the ac photocurrent was detected using a lock-in amplifier. Using light of different wavelength permits measurement of M corresponding to different carrier injection profiles across the avalanche region. Pure electron and pure hole initiated multiplication factors, M_e and M_h, measured on the same structure, are normally used for simple and reliable determination of ionization coefficients. However, any two sets of M, corresponding to sufficiently different, known injection profiles, can still allow reliable deduction of ionization coefficients.

In this work, M_e was measured by illuminating the top of the devices at a wavelength of $\lambda = 442$ nm, at which more than 99.9% of the injected light is absorbed in the p^+ cladding layers. Top and back illumination using $\lambda = 1064$ nm gave mixed carrier multiplication factors M_{mix1} and M_{mix2}, respectively. Optical absorption in InP at $\lambda = 1064$ nm is so weak that the light was effectively absorbed only in the i-$In_{0.53}Ga_{0.47}As$. These photomultiplication results are presented as $M(V) = I(V)/I(0)$ versus reverse bias for the three layers in Fig. 1. The advantages of measuring M_{mix1} and M_{mix2}, rather than M_e and M_h, are explained in the following section.

IV. Photocurrent Normalization

As shown in Fig. 1, an increase in $I(V)/I(0)$ is apparent at only a few volts bias and a larger increase with V is detected in M_e than in M_{mix1} and M_{mix2}. However, not all the increase in the measured photocurrent with bias is necessarily caused by avalanche multiplication. Photon recycling [11], which results from optical recombination of injected carriers in the neutral region, and depletion edge movement [12], which increases the minority carrier injection efficiency, are known to increase the photocurrent, especially at low bias. It is therefore important to ensure that these mechanisms are not misinterpreted as avalanche multiplication.

By contrast, the measurements of M_{mix1} and M_{mix2} are concerned only with carriers photogenerated in the i-$In_{0.53}Ga_{0.47}As$ region, in which carriers are immediately swept to the respective claddings by the field. These results are therefore free from contamination by photon recycling and depletion edge movement, both of which can result only from carrier injection in the cladding layers. Hence, M_{mix1} and M_{mix2} are simply given by $I(V)/I(0)$. On the other hand, M_e may be affected by these two additional mechanisms and may require correction. We therefore use the unambiguous results of M_{mix1} and M_{mix2}, which require no primary current correction, to calculate our first set of ionization coefficients. Note that M_{mix1} and M_{mix2} (shown in Fig. 1) are dissimilar, so that the equations used to calculate ionization coefficients are not ill-conditioned.

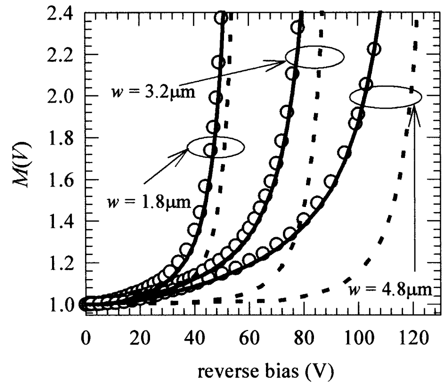

Fig. 1. Normalized photocurrents $M(V) = I(V)/I(0)$ for measurements of $M_e(\bigcirc)$, M_{mix1} and M_{mix2}.

V. Ionization Coefficients

To deduce values for the ionization coefficients, the values of M_{mix1} and M_{mix2} were calculated using a local impact ionization model and assuming ideal p-i-n diode electric field profiles. The multiplication factor for an electron-hole pair injected at position x is given by [10]

$$M(x) = \frac{(\alpha - \beta)e^{-(\alpha-\beta)x}}{\alpha e^{-(\alpha-\beta)w} - \beta}. \quad (1)$$

Pure electron injection at $x = 0$ corresponds to a multiplication $M_e = M(0)$. For the mixed carrier injection used in this work, the multiplication factor is found by integrating $M(x)$ over the multiplication region weighted by the carrier-generation rate $G(x)$ in a similar manner to that described by Li *et al.* [13]. M_{mix1} and M_{mix2} are both given by

$$M_{mix} = \frac{\int_0^w M(x)G(x)\,dx}{\int_0^w G(x)\,dx} \quad (2)$$

where $G(x) \propto \exp(\mp\gamma x)$ for M_{mix1} and M_{mix2}, respectively, and $\gamma = 2 \times 10^4$ cm^{-1} [14], [15] is the $In_{0.53}Ga_{0.47}As$ optical absorption coefficient at 1064 nm. The ionization coefficients were adjusted until the calculated values of M_{mix1} and M_{mix2} agreed with the measurements within a tolerance of 10^{-4}.

The results of α and β obtained from the three layers are in reasonable agreement, as shown in Fig. 2. For each layer, the ionization coefficients shown in Fig. 2 are reproduced from different devices. To assess the accuracy of these results further, another set of ionization coefficients (α' and β') was determined using the measurements of M_e (without correction) and M_{mix2}. α' and β' are in good agreement with α and β, as shown in Fig. 2. The agreement supports the value of γ used in our calculations and suggests that, in fact, the results of M_e need little or no primary current correction. This implies the absence of photon recycling and depletion edge movement mechanisms.

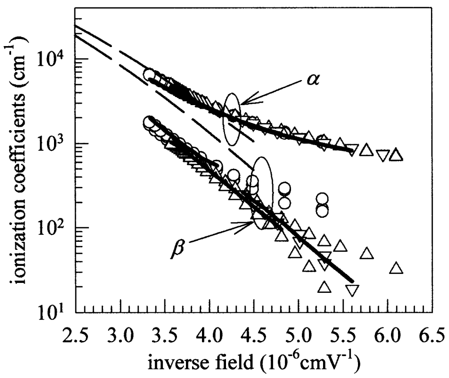

Fig. 2. (Upper set) α and (lower set) β calculated from M_{mix1} and M_{mix2} measured on layers with $w = 1.8$ μm (◯), 3.2 μm (△), and 4.8 μm (▽). The results agree well with (lines)α' and β', calculated from M_e and M_{mix2}. Dashed lines show α and β for GaAs [16].

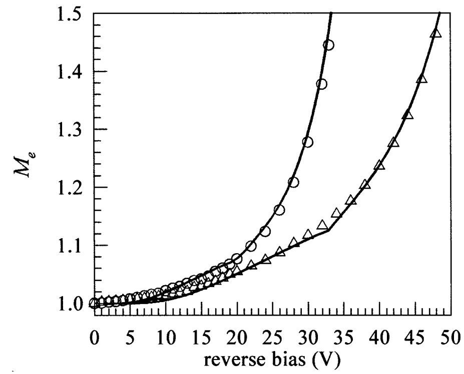

Fig. 3. Comparison of measured M_e (symbols) with values predicted using ionization coefficients from this work (lines) for additional homojunction layers with $w = 1.35$ μm (◯) and 2.2 μm (△).

In addition, since the ionization coefficient calculations ignore dead space, the agreement between results from devices with different i-region thickness suggests that dead space effects are indeed insignificant in our layers.

The spread in the results in Fig. 2 is attributed to errors in measuring multiplication factors and in determining the electric field in the $In_{0.53}Ga_{0.47}As$ avalanche regions. α can be determined accurately to low fields but the results for β show a larger spread than α among the different structures. This is probably due to the greater inaccuracy in determining M_{mix2}, which is lower than M_{mix1}, and uncertainties in the absolute values of absorption coefficients. Ionization coefficients for GaAs from [16] are also plotted in Fig. 2 to highlight the contrast between the low field impact ionization in $In_{0.53}Ga_{0.47}As$ and the conventional field dependence in GaAs.

Although there is larger variation among results for β at fields lower than 180 kVcm^{-1}, our results may be parameterized in the range of fields from 130 to 300 kVcm^{-1}, by the expressions

$$\begin{aligned}\alpha(E) &= 3.72 \times 10^6 \exp[-(4.76 \times 10^6/E)^{0.67}] \\ &\qquad 230\ \text{kVcm}^{-1} < E \leq 300\ \text{kVcm}^{-1} \\ &= 4.30 \times 10^4 \exp[-(9.30 \times 10^5/E)^{0.81}] \\ &\qquad 150\ \text{kVcm}^{-1} < E \leq 230\ \text{kVcm}^{-1} \\ &= 2.03 \times 10^3 \exp[-(1.98 \times 10^5/E)^{1.05}] \\ &\qquad 130\ \text{kVcm}^{-1} \leq E < 150\ \text{kVcm}^{-1} \end{aligned} \tag{3}$$

while β is given by

$$\beta(E) = 7.60 \times 10^4 \exp[-(7.63 \times 10^5/E)^{1.45}] \tag{4}$$

for the complete range of fields, where E is the electric field in Vcm^{-1}, and α and β are in cm^{-1}.

Photomultiplication measurements using 633-nm wavelength light to obtain M_e were performed on two additional homojunction p-i-n diodes with estimated values of $w = 1.35$ and 2.2 μm. Both structures had 1.0-μm-thick p^+ and n^+ $In_{0.53}Ga_{0.47}As$ cladding layers. The measured values of M_e are compared with those calculated using (3) and (4) in Fig. 3. The agreement provides a further check on our ionization coefficients.

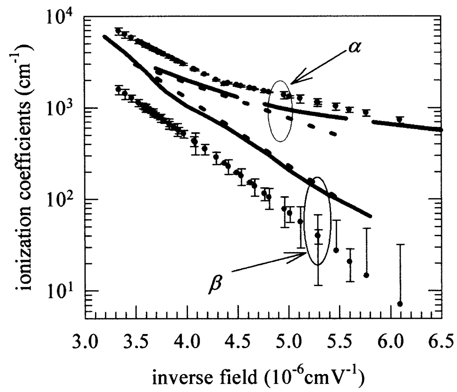

Fig. 4. Comparison of α (upper set) and β (lower set) from this work (symbols with error bars) with the published results of Urquhart *et al.* (dotted lines), Ritter *et al.* (dashed lines), and Buttari *et al.* (solid lines).

Fig. 4 shows a comparison of our measurements with those of [1], [6], [8]. Error bars are included to indicate the uncertainties in multiplication factors. The effect of different values of γ on the data has also been considered. Increasing the value of γ serves to reduce α and increase β. However, changes in ionization coefficients due to increasing γ to 2.5 × 10^4 cm^{-1} are still covered by the error bars. Calculations using $\gamma = 1.5 \times 10^4$ cm^{-1} produced different values of β from the three structures so were considered unreasonable.

VI. Discussion

In Fig. 4 ionization coefficients measured in this work are compared with the results of Urquhart *et al.* (using photomultiplication) [6], Ritter *et al.* [1] and, Buttari *et al.* (both using HBT measurements) [8]. Although slightly larger than those of Ritter *et al.* [1] at high fields, our values for α agree qualitatively and also show low field impact ionization. At lower fields, our results for α approach those of Ritter *et al.* However, our results for β are much smaller than those of Buttari *et al.* Our work therefore shows a much larger α/β ratio than the combined results of [1], [2], [7], [8]. The underestimation of α in [1] and [2] and overestimation of β in [7] and [8] are probably due to their simplifying assumption that $\alpha = \beta$. We observed no low field impact ionization for holes, which is consistent with the previous HBT measurements of [7] and [8].

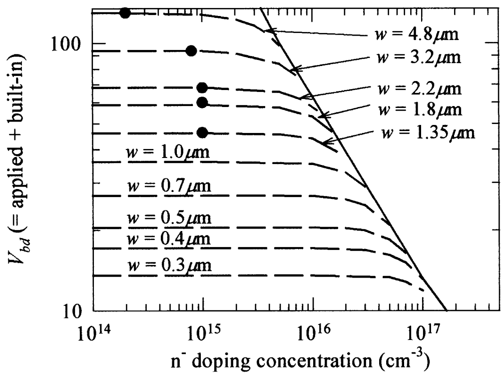

Fig. 5. Breakdown voltage of p^+-n^--n^+ diodes (dashed lines) as a function of impurity doping concentration and thickness of the n^- layer (as indicated). Breakdown voltage of abrupt p^+-n^- junctions (solid line) and the measurements from the five diodes characterized (symbols) are also shown.

Theoretical studies of the anomalous weak field dependence of α have been performed by Bude and Hess [17] and also by Isler [18]. Bude and Hess [17] argued that the effect is due to the relatively low threshold energy and high average energy of electrons, which result from the low density of states at low energies, and the large energy separation between the lowest and the subsidiary minima in the conduction band. These two considerations do not apply to the valance band so that β might be expected to follow the conventional field dependence. It is noted that indium antimony (InSb), a material with an even narrower bandgap (0.17 eV) and with a relatively large energy separation between the lowest and the subsidiary conduction band minima, has also been reported to show signs of low field electron impact ionization. In InSb, α was found to be nearly constant at fields between 5 to 10 $kVcm^{-1}$ but to increase exponentially with decreasing inverse field at higher fields [19], [20].

Fig. 5 shows breakdown voltage (applied plus built-in voltage) as a function of impurity doping concentration, n^- for p^+-n^--n^+ diodes, calculated using our extrapolated ionization coefficients. When the impurity concentration becomes too high to deplete the n^- layer fully, the p^+-n^--n^+ diodes become effectively abrupt p^+-n^- junctions so the breakdown voltages plotted in Fig. 5 become those of p^+-n^- junctions. Measured breakdown voltages of the five diodes characterized in this work, which have been reported to have values slightly higher than those of GaAs [21], are also shown in Fig. 5. As can be seen from Fig. 2, in the overlapping field range the values of ionization coefficients in $In_{0.53}Ga_{0.47}As$ and GaAs are similar. The similarity in breakdown voltages is therefore expected. The experimental data is in good agreement with the calculated breakdown voltages of p^+-n^--n^+ diodes with low impurity doping concentration, whereas calculations using the ionization coefficients of previous works [4]–[6] produced significantly different breakdown voltages, as reported in [21].

VII. Conclusions

Ionization coefficients in $In_{0.53}Ga_{0.47}As$ have been determined from photomultiplication measurements performed on three $In_{0.53}Ga_{0.47}As$ p-i-n diodes, taking careful account of factors that can give rise to erroneous results at low fields. The results confirm the low field-ionization behavior of α and the conventional field dependence of β. α and β at mid-to-high fields are found to be larger and smaller, respectively, than results published by other authors.

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