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# Temperature Dependence of Breakdown and Avalanche Multiplication in $In_{0.53}Ga_{0.47}As$ Diodes and Heterojunction Bipolar Transistors

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***Abstract*—The avalanche multiplication and impact ionization coefficients in $In_{.53}Ga_{.47}$As p-i-n and n-i-p diodes over a range of temperature from 20–400 K were measured and shown to have negative temperature dependence. This is contrary to the positive temperature dependence of the breakdown voltage measured on InP/$In_{.53}Ga_{.47}$As heterojunction bipolar transistors (HBTs) in this and previous works. It is shown that the collector–base dark current and current gain can be the overriding influence on the temperature dependence of breakdown in InP/$In_{.53}Ga_{.47}$As HBTs and could explain previous anomalous interpretations from the latter.**

## I. INTRODUCTION

AN $In_{0.53}Ga_{0.47}$As lattice matched to InP is used in heterojunction bipolar transistors (HBTs) and high electron mobility transistors for high-speed electronics. The onset of avalanche multiplication can lead to catastrophic breakdown, which can limit the upper voltage or power of devices. In most semiconductors, multiplication (and hence breakdown) is controlled by negative temperature-dependent impact ionization coefficients. However, recent measurements on n-p-n $In_{0.53}Ga_{0.47}$As HBTs [1]–[3] appear to indicate anomalous temperature breakdown behavior, leading Ritter *et al.* [1] and Neviani *et al.* [3] to suggest that $In_{0.53}Ga_{0.47}$As has a positive temperature dependence of electron impact ionization coefficient. On the other hand, Malik *et al.* [2] indicated that this behavior in HBTs can be explained by the high collector dark current. The term “dark current” is used here for thermally generated and tunneling current in the reverse biased base–collector junction in the HBT or the reverse biased p-i-n or n-i-p diode. Shamir *et al.*[4] also observed no change with temperature of the hole ionization rates in $In_{0.53}Ga_{0.47}$As from electrical characteristics of p-n-p HBTs. Our previous results on breakdown of $In_{0.53}Ga_{0.47}$As p-i-n diodes [5] indicate a more usual positive dependence of breakdown voltage with temperature. Currently, no electron ionization coefficient measurements as a function of temperature are available to corroborate or otherwise these assertions. Impact ionization can influence the maximum operating voltage of the device due to the onset of multiplication-induced breakdown. The temperature dependence of the breakdown voltage $(V_{\mathrm{BD}})$ of $In_{0.53}Ga_{0.47}$As is therefore of great importance in the case of an ionization coefficient which increases with temperature that can result in an unstable positive power dissipation feedback.

In this paper, we investigate the temperature dependence of the avalanche multiplication, and hence impact ionization coefficients, of three $In_{0.53}Ga_{0.47}$As p-i-n diodes and one $In_{0.53}Ga_{0.47}$As n-i-p diode using phase sensitive detection (PSD) photomultiplication measurements over a range of temperature from 20–400 K. This technique of modulating the injected light signal allows the avalanche multiplication to be determined unambiguously, even in the presence of high dark currents. The temperature dependence of breakdown effects in $In_{0.53}Ga_{0.47}$As HBTs was investigated and possible reasons for the anomalous temperature behavior of ionization coefficients inferred from previous HBT results are discussed.

## II. EXPERIMENTAL DETAILS

Three $In_{0.53}Ga_{0.47}$As p-i-n structures and one n-i-p structure were grown using metal organic vapor phase epitaxy on an InP substrate p-i-n structure with $i$-region thickness, $w$ obtained from modeling capacitance–voltage (*C–V*) measurements, of 1.3 $\mu$m has 1.0 $\mu$m $p^+$ and $n^+$ $In_{0.53}Ga_{0.47}$As cladding, while that with $w$ of 1.9 and 4.8 $\mu$m have 0.5 $\mu$m $p^+$ and $n^+$ InP cladding layers. The $In_{0.53}Ga_{0.47}$As n-i-p structure had an $i$-region thickness of 3.0 $\mu$m sandwiched between $n^+$ InP and $p^+$ $In_{0.53}Ga_{0.47}$As layers. Standard wet etches were used to define the circular mesa diodes of diameter 100–400 $\mu$m with annular top metal contacts to enable optical access. InP/$In_{0.53}Ga_{0.47}$As n-p-n HBT structures were grown using the same technique as the diodes on semi-insulating InP substrates, with an $n^+$ InP subcollector, a 3000-Å $In_{0.53}Ga_{0.47}$As collector ($5 \times 10^{16}$ cm$^{-3}$, n-type), an 800-Å $In_{0.53}Ga_{0.47}$As base ($1 \times 10^{19}$ cm$^{-3}$, p-type), a 50-Å $In_{0.53}Ga_{0.47}$As undoped spacer layer, and an 800-Å InP emitter.

To measure the photomultiplication characteristics in the p-i-n diodes, a 633-nm wavelength He–Ne laser was used to illuminate the top of the device. This wavelength guaranteed that nearly all the photons are absorbed in the $p^+$ cladding layer, providing pure electron injection. Due to the high dark current inherent in $In_{0.53}Ga_{0.47}$As, particularly at high voltages/temperatures, the PSD technique with a lock-in amplifier was used. This ensures the elimination of dark current from the measurement. The devices were bonded onto T05 headers, and the low-temperature dark current and photomultiplication measurements were carried out in a closed loop helium cryogenic system, while devices were placed on a heated stage for high-temperature measurements.

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## III. RESULTS

In this section, we discuss the temperature dependence of avalanche multiplication, based on photomultiplication measurements performed on various In$_{0.53}$Ga$_{0.47}$As p-i-n and n-i-p diodes and compare this with avalanche multiplication measurements in InP/In$_{0.53}$Ga$_{0.47}$As n-p-n HBTs. The temperature dependence of the electron and hole ionization coefficients is then extracted from the photomultiplication measurements.

### A. Dark Current Characteristics

It is well known that photodetectors made using the In$_{0.53}$Ga$_{0.47}$As material system exhibit large undesirable dark currents, which increase exponentially with applied voltage [6]. The typical dark-current characteristics for the diode structures used in this work are shown in Fig. 1, which shows high dark current as the temperature increases. The "soft" breakdown in In$_{0.53}$Ga$_{0.47}$As at high reverse voltages suggests that the current in this regime can be dominated by tunneling. This was verified using the band-to-band tunneling equation of Forrest *et al.* [6], which gave a good fit to the measured dark currents at high reverse bias voltage for all temperatures down to 20 K (dotted lines of Fig. 1). However, at very low temperatures, the more rapid increase in the measured dark current compared to the tunneling equation in the higher voltage region indicates that avalanche multiplication becomes the dominant current mechanism.

### B. Temperature Dependence of Avalanche Multiplication

In most fabricated devices for multiplication measurements, the measured photocurrent-voltage curves have to be corrected for the slight nonzero gradient observed experimentally at low voltages as a slop-i-ng baseline before the onset of avalanche multiplication. This effect is attributed to the increase in collection efficiency due to the depletion region extending into the contacts with increasing bias [7]. Room temperature multiplication characteristics in the p-i-n diodes in this work has been reported by Ng *et al.* [8] who have shown that the change in the collection efficiency in these diodes is negligible. Hence, the photomultiplication characteristics for the p-i-n diodes were normalized to the single value of photocurrent at a bias of $-2$ V (chosen to ensure full depletion). For the n-i-p diodes (where the hole ionization coefficient $\beta_h$ shows no low-field enhanced values [8]), a linear correction was used to obtain the normalized multiplication characteristics. To ensure that heating effects did not influence the photomultiplication values and to ensure reproducibility of the results, several devices were measured with different laser excitation intensities at each temperature. No discernable differences were observed.

Fig. 2 shows the temperature dependence of electron multiplication characteristics of the 1.3 and 1.9 $\mu$m In$_{0.53}$Ga$_{0.47}$As p-i-ns from 20–400 K and the temperature dependence of the hole multiplication for the 3.0 $\mu$m In$_{0.53}$Ga$_{0.47}$As n-i-p from 20–300 K. The results from all the layers investigated show a very limited increase in photocurrent initially and then the sudden and clear onset of the avalanche multiplication process. The avalanche multiplication of all the p-i-n and n-i-p structures clearly decreases with increasing temperature, indicating a negative temperature dependence of electron and hole ionization rates respectively. As stated previously, the modulation of the laser signal with lock-in detection rules out the adverse effects of the high dark currents. The $V_{BD}$ can be obtained by extrapolating the multiplication curve using Miller's empirical expression [9] and was previously reported [5]. The breakdown voltages of all of the In$_{0.53}$Ga$_{0.47}$As p-i-n and n-i-p structures increase with increasing temperature. These results are similar to most other semiconductors, but contrary to the positive temperature behavior of the electron ionization coefficients measured and inferred from the $V_{BD}$ data of n-p-n InP/In$_{0.53}$Ga$_{0.47}$As HBTs [1], [3].

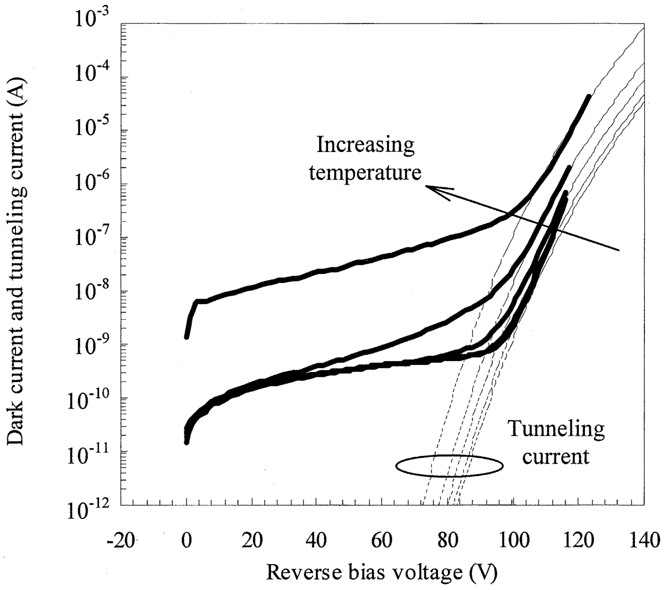

Fig. 1. Typical dark current characteristic (bold lines) of a 4.8-$\mu$m-thick In$_{0.53}$Ga$_{0.47}$As p-i-n diode from 20–300 K. Dotted lines shows the calculated tunneling current.

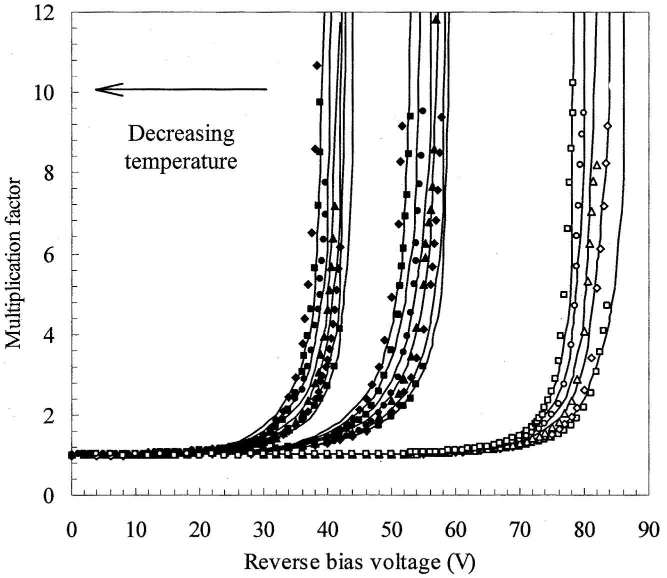

Fig. 2. Measured (symbols) and calculated (lines) multiplication characteristics of 1.3 and 1.9-$\mu$m-thick In$_{0.53}$Ga$_{0.47}$As p-i-n diode (filled symbols) from 20–400 K and 3.0 $\mu$m thick In$_{0.53}$Ga$_{0.47}$As n-i-p diode (clear symbols) from 20–300 K.

### C. Temperature Dependence of Ionization Coefficients

In this section, we deduce the temperature dependence of local ionization coefficients of $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ (i.e., ignoring dead space effects, since $w$ is thick). The simplest configuration for measurement and analysis of photomultiplication measurements is having an intrinsic region between highly doped $\mathrm{p}^+$ and $\mathrm{n}^+$ regions. For ideal p-i-n and n-i-p structures, whereby the field can be considered constant, the multiplication equations for electron and holes, respectively, can be simplified to give

$$M_e = \frac{1}{1+\frac{\alpha_e}{\alpha_e-\beta_h}\left\{\exp\left[-(\alpha_e-\beta_h)w\right]-1\right\}} \tag{1a}$$

$$M_h = \frac{1}{1+\frac{\beta_h}{\alpha_e-\beta_h}\left\{1-\exp\left[(\alpha_e-\beta_h)w\right]\right\}} \tag{1b}$$

where $\alpha_e$ is the electron ionization coefficient and $\beta_h$ is the hole ionization coefficient.

The electron and hole ionization coefficients can be extracted from the measured multiplication results if both electron initiated and hole initiated multiplication results are available for the same structure. However, due to optical access difficulties in measuring the temperature dependence of $M_h$ from the p-i-n structures by back injection, the measured $M_h$ is obtained from the n-i-p structure. Hence, to determine the parameterized expression for $\alpha_e$ and $\beta_h$ of $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$, empirical expressions for the ionization coefficients are verified by obtaining the best fit for both the measured $M_e$ of the p-i-n structures and $M_h$ of the n-i-p structure from photomultiplication measurements and using (1a) and (1b).

The parameterized ionization coefficients of $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ from 20–400 K were derived, assuming ideal p-i-n and n-i-p structures with negligible dead space. Across the range of electric field from 180–310 kV/cm for the electron ionization coefficient, $\alpha_e$, and hole ionization coefficient, $\beta_h$, the parameters can be described by

$$\alpha_e(T) = A_e(T)\exp\left[-\left(\frac{B_e(T)}{\xi}\right)^{C_e(T)}\right] \tag{2}$$

where

$$\begin{aligned} A_e(T) &= 7.2597\times10^4-(24.204\,T)+(0.3259\,T^2)\quad \mathrm{cm}^{-1}\\ B_e(T) &= 5.9988\times10^5+(3.4763\times10^2\,T)\\ &\quad +(2.4768\,T^2)\quad \mathrm{V/cm}\\ C_e(T) &= 1.1783-(7.2548\times10^{-4}\,T) \end{aligned}$$

and

$$\beta_h(T) = A_h(T)\exp\left[-\left(\frac{B_h(T)}{\xi}\right)^{C_h(T)}\right] \tag{3}$$

$$\begin{aligned} A_h(T) &= 6.1026\times10^5+(9.6637\times10^2\,T)\\ &\quad +(1.1384\,T^2)\quad \mathrm{cm}^{-1}\\ B_h(T) &= 1.3394\times10^6+(1.0699\times10^3\,T)\\ &\quad +(0.4507\,T^2)\quad \mathrm{V/cm}\\ C_h(T) &= 1.0910-(2.3505\times10^{-4}\,T). \end{aligned}$$

The equation parameters were derived as a function of temperature, where $T$ is a dimensionless quantity representing the temperature in Kelvin.

The best fit parameterized ionization coefficients are verified by calculating the multiplication factors for each layer using (2) and (3) and comparing the results with the measured photomultiplication characteristics. The temperature dependence of the calculated (using (2) and (3)) (lines) and measured (symbols) multiplication characteristics of the 1.3 $\mu$m and 1.9 $\mu$m p-i-n and 3.0 $\mu$m n-i-p diodes are given in Fig. 2, showing excellent agreement. The parameterized temperature dependence of $\alpha_e$ for $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ at room temperature were compared with those obtained from electrical measurement of n-p-n $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ HBTs [1], photomultiplication measurement of $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ diodes [8], [10]–[12] and theoretical prediction of Bude and Hess [13] are shown in Fig. 3. The results are in good agreement with all the previously published data other than those of Pearsall [10]. The best fit $\beta_h$ at room temperature is shown in Fig. 4. Room temperature $\beta_h$ from electrical measurement of p-n-p $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ HBTs [4], [14] and photomultiplication measurement of $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ diodes [8], [10]–[12] are shown in Fig. 4 for comparison. The parameterized room temperature results of the hole ionization coefficients in Fig. 4 appear to be in less agreement with other results compared to those for the electrons. However, there is an uncertainty in the $i$-region thickness peculiar to the n-i-p structure due to the smearing of the p-dop-i-ng in the lower layer during growth, causing an uncertainty in the electric field profile. This uncertainty is adequate to explain the differences between our current results and previous data from our laboratory [8]. The parameterized temperature dependence of electron and hole ionization coefficients for $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ at 20, 140, and 400 K are shown in Fig. 5.

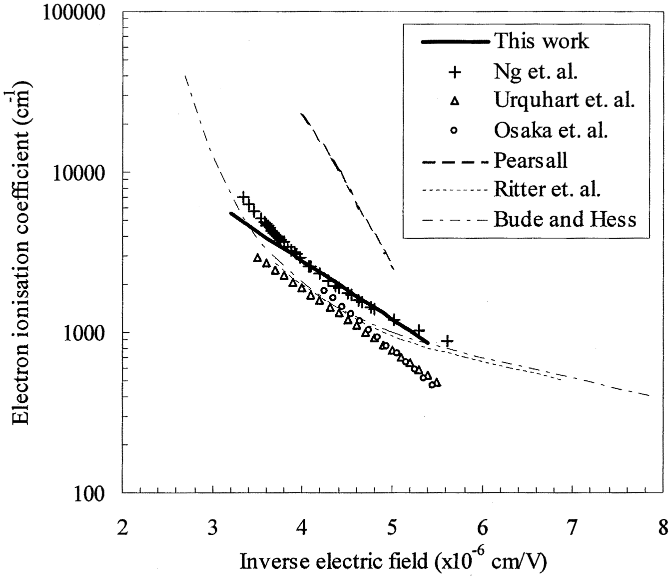

Fig. 3. Comparison of room temperature electron ionization coefficient of this work with published results based on photomultiplication experiments ([8], [10]–[12]) and results based on electrical characterization of n-p-n HBTs [1]. Theoretical predictions are also shown ([13]).

### D. Multiplication Measurements in HBTs

In order to try and reconcile the differences in the measurements made on our p-i-ns, n-i-ps and HBTs, the temperature dependence of the breakdown voltage was also measured from our n-p-n $\mathrm{In}_{0.53}\mathrm{Ga}_{0.47}\mathrm{As}$ HBTs, at temperatures of 150, 250, and 400 K as shown in Fig. 6. These results, and other recent breakdown voltage measurements in n-p-n

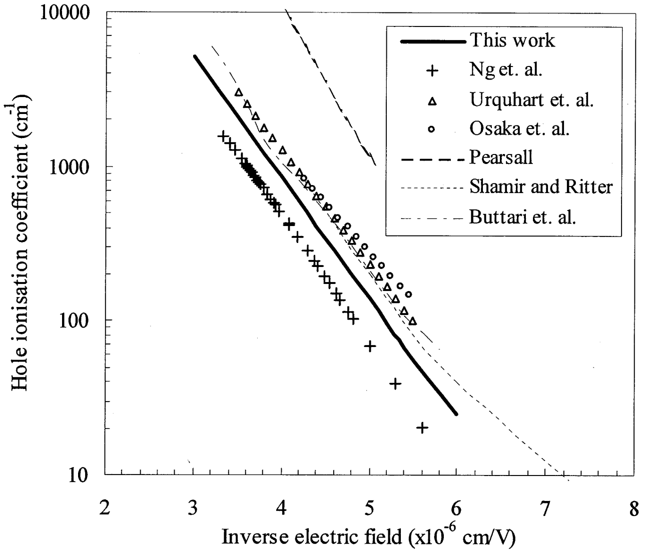

Fig. 4. Comparison of room temperature hole ionization coefficient of this work with published results based on photomultiplication experiments ([8], [10]–[12]). Results based on electrical characterization of p-n-p HBTs are also shown ([4], [14]).

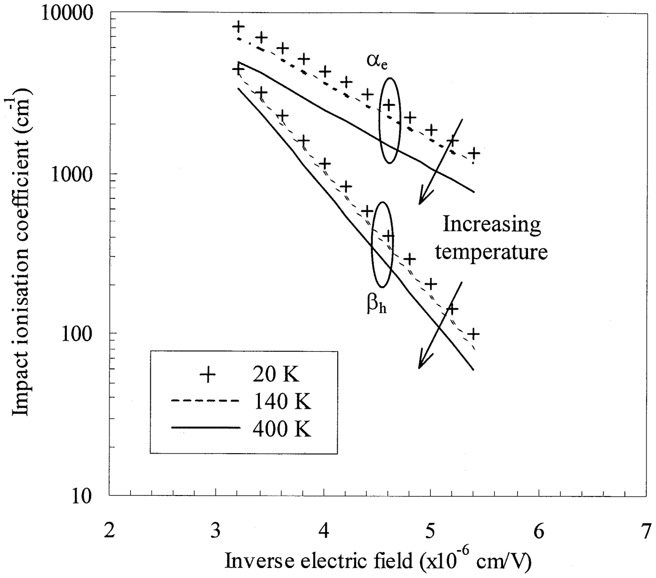

Fig. 5. "Best fit" electron and hole ionization coefficients as a function of inverse electron field for $In_{0.53}Ga_{0.47}As$ at 400, 140, and 20 K.

$In_{0.53}Ga_{0.47}As$ HBTs [1]–[3], appear to indicate anomalous temperature behavior (i.e., reducing breakdown voltage with increasing temperature). To demonstrate that the anomalous temperature-dependent voltage breakdown behavior seen in the InP/$In_{0.53}Ga_{0.47}As$ HBTs is not due to a positive temperature dependence of electron impact ionization coefficients in $In_{0.53}Ga_{0.47}As$, the emitter of our InP/$In_{0.53}Ga_{0.47}As$ HBTs was etched away to form a thin p-i-n structure from the remaining base collector junction. Fig. 7 shows the avalanche multiplication characteristics based on PSD photomultiplication measurements, which greatly reduces the detrimental effects of the dark current. The thin collector structures are not ideal for photomultiplication measurements because of the high tunneling leakage currents, which raises the noise floor, even with the use of modulated light. Despite this, a clear reduction in multiplication with increasing temperature is observed, contrary to the negative temperature dependence of breakdown with temperature in the HBTs evident in Fig. 6.

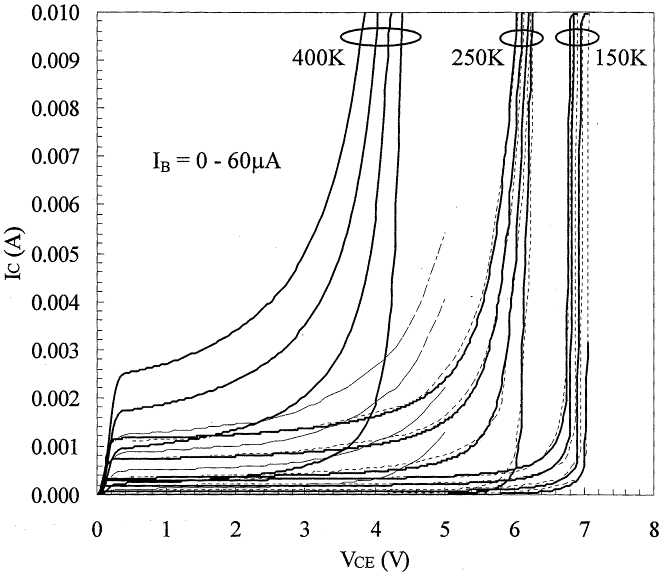

Fig. 6. Measured common-emitter current–voltage (*I–V*) characteristics at 150, 250, and 400 K for the n-p-n InP/$In_{0.53}Ga_{0.47}As$ HBT (lines). Dotted lines show calculated common-emitter *I–V* characteristic at 250 K using temperature-dependent $\beta_{\rm dc}$, $M$ and $I_{\rm CBO}$ and dash-dotted lines show calculated common-emitter *I–V* characteristics at 250 K but using dark current at 400 K.

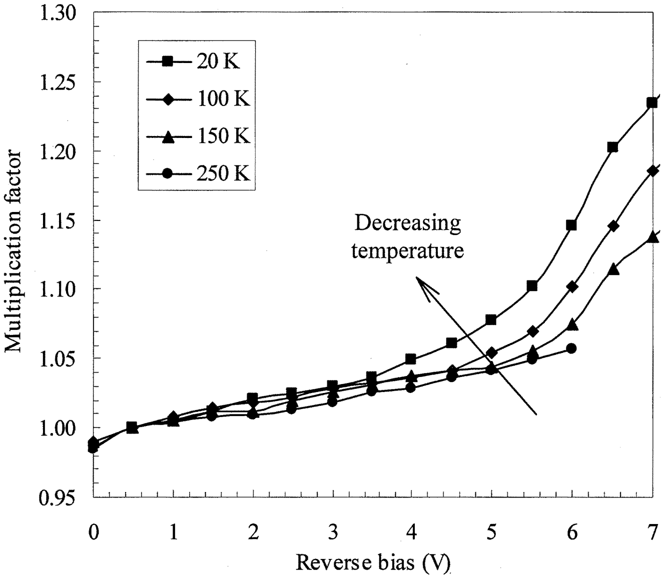

Fig. 7. Multiplication characteristics of the thin p-i-n structure ($w = 0.3$ μm) from 20–250 K. This structure was taken from a n-p-n InP/$In_{0.53}Ga_{0.47}As$ HBT with the emitter removed.

## IV. DISCUSSION

The variations of $In_{0.53}Ga_{0.47}As$ ionization coefficients as a function of temperature shown in Fig. 5 suggest that the temperature sensitivity of ionization coefficients of $In_{0.53}Ga_{0.47}As$ is small, as seen in the breakdown voltage ([5], Fig. 2). This modest change of $\alpha_e$ and $\beta_h$ with temperature may explain why

Shamir *et al.*[4] observed no change in $\beta_h$ over the range of 290–390 K from the electrical characterization of p-n-p HBTs. Our results suggest that, over a temperature variation of 100 K, we would expect only a 2.5% change in breakdown voltage.

One of the main considerations for obtaining accurate ionization coefficients from HBTs is that the open-emitter saturation current $(I_{\rm CBO})$ (i.e., collector dark current) must be negligible. This is because the dark current contributes to the negative base current (flowing from the collector to the base) in the same way as impact ionization induced base current, with the possibility of the former dominating the base current. The common-emitter collector current $I_C$ is given by [2]

$$I_C = \left(\frac{\alpha_T M}{1-\alpha_T M}\right) I_B + \left(\frac{M}{1-\alpha_T M}\right) I_{\rm CBO} \qquad (4)$$

where $\alpha_T$ is the common-base current gain, $I_B$ is the base current before the onset of multiplication and $M$ is the collector multiplication. Both the dark currents and the dc current gain, $\beta_{\rm dc}$, of our InP/In$_{0.53}$Ga$_{0.47}$As HBTs increase rapidly with temperature. Using the measured temperature dependence of $\beta_{\rm dc}$, $M$ (from Fig. 7) and $I_{\rm CBO}$ measured from our InP/In$_{0.53}$Ga$_{0.47}$As HBTs, we were able to reproduce the common emitter characteristics (shown as the dotted line in Fig. 6), using (4) for temperatures at 250 K as well as 150 K. This shows that a negative temperature dependence of multiplication is not incompatible with a negative temperature dependence of breakdown voltage in our HBTs. Good agreement was also obtained when using the independently measured (from custom p-i-n and n-i-p diodes) ionization coefficients from Fig. 5 to generate $M$ for use in (4). These observations clearly show that the temperature dependence of $\alpha_T(\beta_{\rm dc})$ and $I_{\rm CBO}$ in (4) can dominate over the opposite temperature dependence of $M$ ($\alpha_e$ and $\beta_h$).

Malik *et al.* [2] observed that the $I_{\rm CBO}$ of In$_{0.53}$Ga$_{0.47}$As is $>10^4$ times that of GaAs for low collector–base voltages. Clearly, from the dark current characteristics and at higher temperature or/and higher voltage, $I_{\rm CBO}$ [from (4)] plays an increasingly important role in determining $I_C$. The positive temperature dependence of $I_{\rm CBO}$ comes about due to the bandgap variation and its effect on the tunneling current. However, in the electrical characterization of In$_{0.53}$Ga$_{0.47}$As HBTs used to obtain the ionization coefficients, dark currents were assumed to be insignificant in the past [1], [3], [15]. Based on (4) and our results, HBTs with a positive temperature dependence of $\beta_{\rm dc}$ and $I_{\rm CBO}$, together with a negative multiplication dependence, can exhibit reduced breakdown voltage as the temperature increases. [2] To show the effects of $I_{\rm CBO}$ alone, the parameters of (4) were kept at 250 K values except for $I_{\rm CBO}$, where the measured 400 K value was used. The calculated common emitter characteristic showed a reduced breakdown voltage when a higher dark current was used (dash-dotted lines in Fig. 6). This indicates that the temperature dependence of $I_{\rm CBO}$ alone (i.e., in the case where $\beta_{\rm dc}$ is constant with temperature) is enough to dominate the temperature dependence of the breakdown voltage in InP/In$_{0.53}$Ga$_{0.47}$As HBTs. Although the ionization coefficients of In$_{0.53}$Ga$_{0.47}$As showed negative temperature dependence, the ionization coefficients are relatively temperature insensitive compared to other materials such as GaAs, making it more difficult to interpret the temperature dependence of multiplication from the common-emitter characteristics of InP/In$_{0.53}$Ga$_{0.47}$As HBTs.

The good agreement of $\alpha_e$ measured here with that of Ritter *et al.* [1] from HBT measurements indicates that, at room temperature at least, dark current is negligible and does not interfere with the measurements. To further illustrate the significance of dark current on multiplication measurements, various injected light intensities were used in our measurements on our 3.0 $\mu$m n-i-p diodes but without modulation and the use of a lock-in amplifier. This allowed us the directly observe the effects of the dark currents relative to that induced by the optical signal. These studies indicated that the dark current has to be at least three orders of magnitude less than that of the photocurrent for it to have a negligible effect on the multiplication characteristics. This is especially important at higher temperature where the dark current is more likely to dominate.

## V. CONCLUSION

The temperature-dependent avalanche multiplication of bulk In$_{0.53}$Ga$_{0.47}$As was investigated and the results between 20 and 400 K indicate a negative temperature dependence of impact ionization multiplication, unlike that previously inferred from HBTs. Empirical expressions for the ionization coefficients of In$_{0.53}$Ga$_{0.47}$As over the range 20–400 K were also deduced from the photomultiplication measurements. The discrepancy of the temperature dependence of multiplication between that measured on HBTs and that on p-i-n and n-i-p diodes most likely results from the effect of dark current and $\beta_{\rm dc}$ on the former. Using the isolated base-collector junction from the HBT, together with modulated optical injection, we demonstrated that a more usual negative temperature dependence of avalanche multiplication is not inconsistent with our, and previous, measurements of breakdown voltage as a function of temperature in InP/In$_{0.53}$Ga$_{0.47}$As HBTs.

## REFERENCES

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

[2] R. J. Malik, N. Chand, J. Nagle, R. W. Ryan, K. Alavi, and A. Y. Cho, "Temperature dependence of commom-emitter I-V and collector breakdown voltage characteristics in AlGaAs/GaAs and AlInAs/GaInAs HBT's grown by MBE," *IEEE Electron Device Lett.*, vol. 13, p. 557, Nov. 1992.

[3] A. Neviani, G. Meneghesso, E. Zanoni, M. Hafizi, and C. Canali, "Positive temperature dependence of the electron impact ionization coefficient in $\rm In_{0.53}Ga_{0.47}As/InP$ HBT's," *IEEE Electron Device Lett.*, vol. 18, p. 619, Dec. 1997.

[4] N. Sharmir and D. Ritter, "Low electric field hole impact ionization coefficients in GaInAs and GaInAsP," *IEEE Electron Device Lett.*, vol. 21, p. 509, Nov. 2000.

[5] M. Yee, W. K. Ng, J. P. R. David, P. A. Houston, and C. N. Harrison, "Negative temperature dependence of electron multiplication in $\rm In_{0.53}Ga_{0.47}As$," *Appl. Phys. Lett.*, vol. 82, p. 1224, 2003.

[6] S. R. Forrest, R. F. Leheny, R. E. Nahory, and M. A. Pollack, "$\rm In_{0.53}Ga_{0.47}As$ photodiodes with dark current limited by generation-recombination and tunneling," *Appl. Phys. Lett.*, vol. 37, p. 322, 1980.

[7] 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, p. 381, 1973.

[8] J. S. Ng, C. H. Tan, J. P. R. David, G. Hill, and G. J. Rees, "Field dependence of impact ionization coefficients in $\mathrm{In_{0.53}Ga_{0.47}As}$," *IEEE Trans. Electron Devices*, vol. 50, pp. 901–905, Apr. 2003.

[9] J. L. Moll, *Physics of Semiconductors*. New York: McGraw-Hill, 1964, pp. 211–238.

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

[11] F. Osaka, T. Mikawa, and T. Kaneda, "Impact ionization coefficients of electron and holes in (100)-oriented $\mathrm{Ga_{1-x}In_xAs_yP_{1-y}}$," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1326–1398, Sep. 1985.

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

[13] J. Bude and K. Hess, "Thresholds of impact ionization in semiconductors," *J. Appl. Phys.*, vol. 72, no. 8, p. 3554, 1992.

[14] 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, p. 197, May 2001.

[15] 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, p. 1095, 1995.

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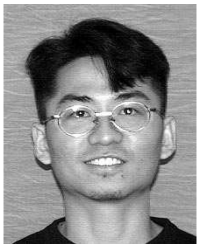

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