Measurements of the InGaAs Hole Impact Ionization Coefficient in InAlAs/InGaAs pnp HBTs

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***Abstract*—The hole multiplication factor in pnp InAlAs/InGaAs single heterojunction bipolar transistors (HBTs) has been measured as a function of the base-collector bias. The hole impact ionization coefficient $\beta_{\rm p}$ has been estimated taking into account the Early effect, $\mathbf{I_{CBO}}$, and thermal effects. Numerical corrections for dead space were made. The importance of considering second order effects is highlighted, showing that rough approximations can lead to an overestimation of the coefficient $\beta_{\rm p}$. At low electric fields, the extracted coefficient agrees with the most recent photomultiplication measurements available in the literature. At high electric fields, hole impact ionization coefficient is estimated up to values previously not reported in the literature ($\beta_{\rm p} \approx 10^4\ {\rm cm}^{-1}$).**

***Index Terms*—Early effect, HBT, impact ionization.**

I. Introduction

PHOTOMULTIPLICATION measurements on p-n junctions as a function of the bias voltage represent the most straightforward technique for quantitatively determining the electron and hole impact ionization coefficients, α_n and β_p, respectively. On $In_{0.53}Ga_{0.47}As$, these measurements were performed by Pearsall [1], Osaka *et al.* [2] and Urquhart *et al.* [3], in 1980, 1985, and 1990, respectively. Their results are compatible in the ratio of α_n over β_p, but not in the absolute values. In this paper we report on the results obtained by a different experimental technique [4], [5], based on fully electrical measurements of impact-ionization effects carried out on bipolar transistors, as recently used by Shamir *et al.* [6] on pnp $In_{0.53}Ga_{0.47}As$ HBTs.

The following results have been achieved: a) a method is presented for correcting second order phenomena in the determination of α_n, β_p, such as Early effect, base-collector reverse current I_{CBO} and self-heating, thus allowing the fully-electrical evaluation of β_p at high electric fields up to values previously not reported in the literature ($\beta_p \approx 10^4\ {\rm cm}^{-1}$); b) in the low electric field region ($E < 250$ kV/cm), results are in good agreement with most recently reported data obtained both on avalanche photodiodes [2], [3], and on HBTs [6]; c) β_p coefficient at low electric fields does not present any "tail" as in the case of α_n; as a consequence, the pnp transistors exhibit a higher breakdown voltage with respect to npn of similar collector structure and thickness.

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II. Samples Description and Theoretical Considerations

The devices analyzed were single heterojunction pnp $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HBTs designed and grown at the University of Michigan. The device technology is described in [7]. Nominal collector doping ($N_A = 3 \times 10^{16}\ {\rm cm}^{-3}$) and thickness ($W_C = 0.3\ \mu$m) result in a punch-through device, fully depleted at a base-collector voltage of about 1.1 V. The fact that carriers injected at the edge of the depletion region have to travel through a significant portion of the collector before reaching the threshold energy for ionization (0.83 eV in the case of holes in $In_{0.53}Ga_{0.47}As$ [2]) was taken into account. The corresponding "dead space," x_{th}, spans from 7 to 20% of the collector width [8], decreasing at the increase of the bias. Secondary impact ionization events were evaluated as negligible compared to primary events, due to the short active region (three to ten times shorter than that in [1]–[3]). The classical, local field impact ionization equations could be simplified and the hole multiplication factor M_h was expressed as a function of the hole impact ionization coefficient

$$M_h = 1 \bigg/ \left(1 - \int_{x_{th}}^{W_c} \beta_p(x)\, dx\right). \tag{1}$$

If the value of the ionization rate at the low-field end of the collector, $\beta_p(W_C)$, is neglected in comparison to the high-field one, $\beta_p(x_{th})$, (1) can be solved in $\beta_p(x_{th})$ and the following approximate expression can be obtained [8]:

$$\beta_p\left(E_{x_{th}}\right) \cong \left(\frac{1}{M_h^2}\frac{dM_h}{dV_{BC}}\right) \bigg/ \left(\frac{dE_{x_{th}}}{dV_{BC}}\frac{\varepsilon_s}{q\,N_a}\right) \tag{2}$$

$$\text{with } N_a = N_A - \frac{J_C}{q\,v_s} \tag{3}$$

where

- N_A constant acceptor density in the low-doped collector;
- J_C collector current density (assuming negligible current crowding);
- v_s hole drift saturation velocity (4.5×10^6 cm/s);
- V_{BC} base-collector voltage;

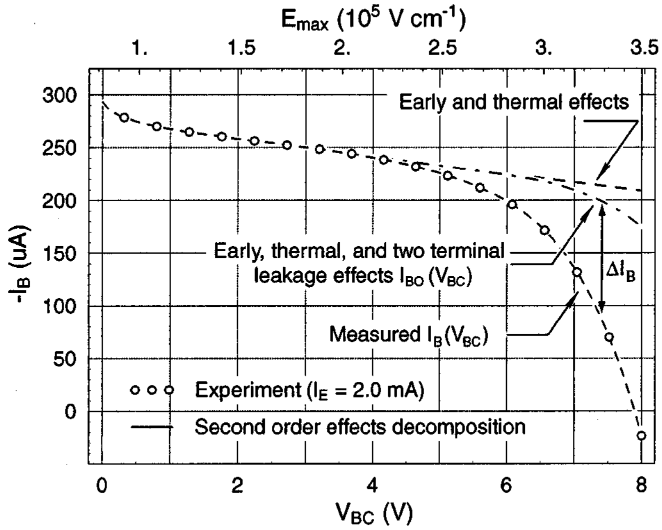

Fig. 1. Measured variations in base current at the varying of biasing conditions. The reduction due to impact ionization has been separated from the component due to other second order effects.

$E_{x_{th}}$ electric field at $x = x_{th}$.

If the low-field ionization rate $\beta_p(W_C)$ is not negligible in comparison to the high-field one $\beta_p(x_{th})$, the following equation applies:

$$\beta_p(E_{avg}) = (M_h - 1)/(W_c - x_{th}) \quad (4)$$

where E_{avg} is the average electric field in the collector region, which is the equation of choice in the case of low-doped collector devices (doping less than about 2×10^{16} cm^{-3} with the device geometries so far described). From (4) and from the fact that the "dead space," x_{th}, spans from 7 to 20% of the collector width, we can infer that the final dead space influence on the extracted β_p spans from about 7 to 25%.

III. Multiplication Measurements

Measurements were carried out on single-finger HBTs with an emitter geometry varying from 2×10 μm^2 to 5×40 μm^2. All graphs and data refer to a 5×10 μm^2 geometry device. A constant emitter current technique [4], [5] at different current levels ($I_E = 0.5 \div 2.0$ mA, $J_E = 1 \div 4$ kA/cm^2) was adopted; current crowding was found to be negligible at these current levels. This technique relies on the fact that electrons generated by impact ionization in the high field region drift toward the base and here behave as majority carriers, being collected at the base contact. Measurements of the decrease in the absolute value of base current as a function of the base-collector voltage lead to a direct evaluation of the impact ionization multiplication factor M_h

$$M_h - 1 = \frac{\Delta I_B}{I_C - \Delta I_B} \quad (5)$$

where ΔI_B is the base current decrease due to the impact ionization events and $I_C - \Delta I_B$ is the injected collector current at the edge of the base-collector depletion region which starts the impact ionization process.

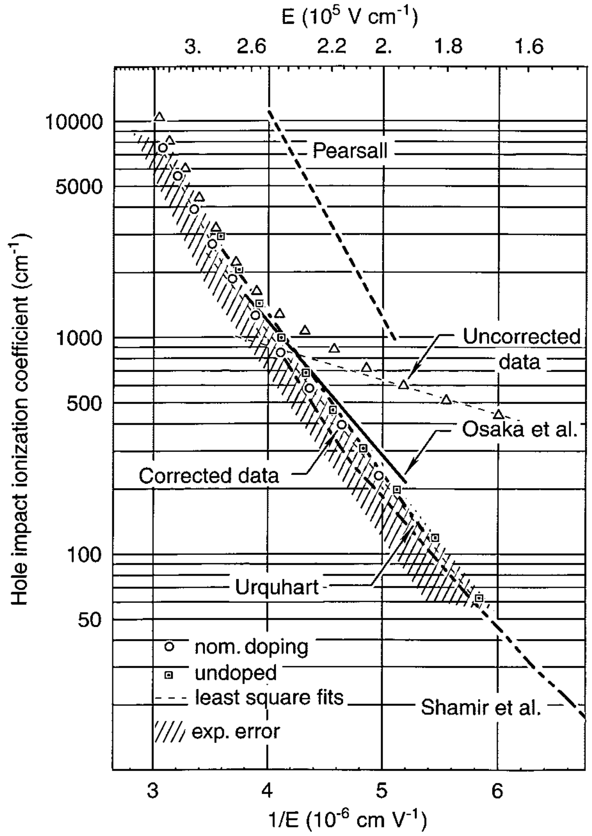

Fig. 2. Measured hole impact ionization coefficient β_p. The over-estimation of β_p induced by neglecting second order effects (open triangle) is suppressed by using (7) that takes into account second-order effects (open symbol). The square symbols represent the results obtained by using an undoped-collector approximation, and the experimental errors on collector width and doping are represented by the dashed area. The results obtained (open symbol) are in good agreement with already published work, extending the extraction of the hole impact ionization coefficient β_p up to value of $\approx 10^4$ cm^{-1}.

Assuming that all the base current decrease is due to impact ionization, the following approximation can be used

$$\Delta I_B = I_B(V_{BC}) - I_B(V_{BC} = 0) \quad (6)$$

which leads to a direct estimation of the multiplication factor (5) and of the impact ionization coefficient (2), (4). Unfortunately (6) becomes wrong when other second-order phenomena give rise to a base current variation non negligible when compared to the impact ionization one. By neglecting these effects, one comes to an over- or under-estimation of the right multiplication factor M_h. Equation (6) was quantitatively useless in the present case and a more accurate estimation of the base current variation due to impact ionization was needed, as we will discuss in the following section.

IV. Second Order Effects

On increasing V_{BC} at constant I_E, a series of effects beside impact ionization can induce a change in the base current:

1) Early effect increases the current gain, thus reducing $|I_B|$;
2) I_{CBO} increases;
3) the increase in power dissipation and junction temperature enhances the current gain, thus reducing $|I_B|$.

All these effects contribute to reduce the absolute value of the base current, leading to an overestimation of M_h and, consequently of the hole ionization coefficient. The temperature increase has been evaluated to be about 20 °C which corresponds to a 10% current gain increase (measured device thermal resistance is about 1200 °C/W**).**

As shown in Fig. 1 the decrease in I_B due to thermal and Early effects was linearly extrapolated from the behavior of I_B at low V_{BC} voltages, where impact-ionization and collector-base leakage current I_{CBO} are negligible. The decrease in I_B due to I_{CBO} was evaluated by two-terminal measurements. It was corrected by simple subtraction taking into account the fact that base-collector junction reverse current originates mostly from the extrinsic area. The correctness of this hypothesis was verified by comparing the spread in $M_h - 1$ (with an injected emitter current varying in the $1 \div 4\ \mathrm{kA/cm^2}$ range) before and after the correction. The high value in I_{CBO} prevented us from lowering the baseline for the collector current to such an extent to remove thermal effects, and high current levels proved to be detrimental for device operation, thus limiting the useful range of collector current levels. Measurements with different integration times were qualitatively compatible with the presence of thermal effects. Moreover, pulsed measurements with a pulse width less than 1 ms are necessary to completely remove parasitic thermal effects, but these measurements can not be obtained by a standard curve tracer.

Therefore, (6) has been modified as follows:

$$\Delta I_B = I_B(V_{BC}) - I_{BO}(V_{BC}) \tag{7}$$

where $I_B(V_{BC})$ is the measured base current during the V_{BC} sweep and $I_{BO}(V_{BC})$ represents the total base current associated with Early effect, thermal effect and base-collector leakage current as shown in Fig. 1.

Theoretical predictions of the Early effect based on the assumption of neutral base recombination [9] were not applicable due to the fact that in the present case the base-emitter space charge recombination, and not the neutral base one, was found to be the predominant recombination mechanism. More practical methods based on base-emitter space charge recombination [5] were qualitatively correct, but quantitatively useless due to numerical uncertainties in thermal device modeling.

V. Results and Conclusions

By taking into account these effects and using (7) (open circles in Fig. 2), the over-estimation of the impact-ionization coefficient resulting from uncorrected data was suppressed (open triangles in Fig. 2). In order to evaluate the error associated with possible uncertainties in the collector doping level, we compare in Fig. 2 the results obtained using the nominal doping (open circles) and an undoped approximation (square symbol in Fig. 2). The latter approximation is closer to the estimated effective doping measured by CV profiling on adjacent 50 μm diameter diodes ($9 \times 10^{15}\ \mathrm{cm}^{-3}$). CV profiling gave a 10% shorter collector than the nominal one. Such a reduction in the collector width has the major effect of a 10% increase in the corresponding electric fields. The experimental error on the collector width ($W = (A \cdot \varepsilon)/C$) has been estimated to be around 5% due to the following contributions:

1) area of the diode, A, determined by a SEM micrograph, introduces a maximum error of about 2%;
2) relative error associated with the C–V measurements is expected to be around 3%.

The overall experimental errors due to the evaluation of collector width and doping levels are represented in Fig. 2 as the dashed area.

In conclusion, new results on the hole impact ionization coefficients in $\mathrm{In_{0.53}Ga_{0.47}As}$ have been reported and compared with previous measurements at low electric fields. The influence of second order effects has been highlighted. Hole impact ionization coefficient has been extracted up to values previously not reported in the literature ($\beta_p \approx 10^4\ \mathrm{cm}^{-1}$) i.e., up to electric field values of 3.3×10^5 V/cm, which approach the practical values applicable to electronic devices. Reported data are comparable with results by Osaka *et al.* [2], Urquhart *et al.* [3] and Shamir *et al.* [6] (see Fig. 2) and support already published results.

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