HOLE IMPACT IONIZATION COEFFICIENT IN (100)-ORIENTED $In_{0.53}Ga_{0.47}As$ BASED ON PNP InAlAs/InGaAs HBT's

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Abstract

The hole multiplication factor in pnp $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ single heterojunction bipolar transistors (HBT's) has been measured as a function of the base-collector bias. Hole impact ionization coefficient β_p has been estimated by taking into account the Early effect, the collector-base leakage current I_{CBO}, thermal effects and the spread in the nominal device processing parameters. Numerical corrections for dead space and current-induced collector charge density variations were made. The data obtained in this way agree with the most recent photomultiplication measurements available in literature.

I. Introduction

The electron and hole impact ionization coefficients α_n and β_p in $In_{0.53}Ga_{0.47}As$ are important parameters for the modeling of the avalanche breakdown characteristics of InP-based high-speed FET's and HBT's and are key values in the design of high-field semiconductor devices such as IMPATT diodes and low-noise avalanche photodiodes (APD's) operating near the $1.55\,\mu m$ low-loss window for optical fiber telecommunication systems. Moreover, the experimental determination of the impact ionization coefficients is important for the evaluation of the physical parameters used in *ab-initio* theoretical calculations of the impact ionization coefficients [1] as well as to evaluate the validity of the theoretical approach, particularly in debated cases like that concerning the hole multiplication factor in $In_{0.53}Ga_{0.47}As$ [2]. Photomultiplication measurements on p-n junctions as a function of the bias voltage represent the most straightforward technique for quantitatively determining these coefficients. Those measurements were performed on $In_{0.53}Ga_{0.47}As$ by Pearsall [3], Osaka et al. [4] and Urquhart et al. [5], in 1980, 1985 and 1990, respectively. As shown in Fig. 1, all these results are compatible in the ratio of α_n over β_p, but there is some spread in the absolute values. In this paper we report on the results obtained by a different experimental technique [6], [7], based on fully electrical measurements of impact-ionization effects carried out on bipolar transistors. The measured hole impact ionization coefficient has been found compatible with the data of the two most recent photomultiplication measurements available in literature, that is Osaka et al. [4] and Urquhart et al. [5], deviating from what reported by Pearsall [3].

II. Samples Description and Theoretical Considerations

The devices analyzed were single heterojunction pnp $In_{0.52}Al_{0.48}As$ / $In_{0.53}Ga_{0.47}As$ HBT's designed and grown at the University of Michigan, USA. The device technology is described in [8] and the features of interest for the subsequent computations are summarized in Fig. 2. The device active layers are: a 2000 Å, p^+ $(2\times10^{19}\,cm^{-3})$ $In_{0.53}Ga_{0.47}As$ emitter cap layer; a 700 Å, p^+ $(1\times10^{19}\,cm^{-3})$ $In_{0.52}Al_{0.48}As$ cap layer; a 1500 Å, $p\,(8\times10^{17}\,cm^{-3})$ $In_{0.52}Al_{0.48}As$ emitter layer; a 100 Å, unintentionally doped $In_{0.53}Ga_{0.47}As$ spacer; a 500 Å, n^+ $(5\times10^{18}\,cm^{-3})$ $In_{0.53}Ga_{0.47}As$ base layer; a 3000 Å, p^- $(3\times10^{16}\,cm^{-3})$ $In_{0.53}Ga_{0.47}As$ collector layer; a 5000 Å, p^+ $(1\times10^{19}\,cm^{-3})$ $In_{0.53}Ga_{0.47}As$ subcollector layer; and a 1000 Å $In_{0.53}Ga_{0.47}As$ / $In_{0.52}Al_{0.48}As$ superlattice buffer. The device epilayers were grown by solid-source molecular beam epitaxy on Fe-doped semi-insulating (001) InP. Nominal collector doping ($N_A = 3\times10^{16}\,cm^{-3}$) and thickness ($W_C = 0.3\,\mu m$) result in a punch-through device, fully depleted at a base-collector voltage of about $1.1\,V$.

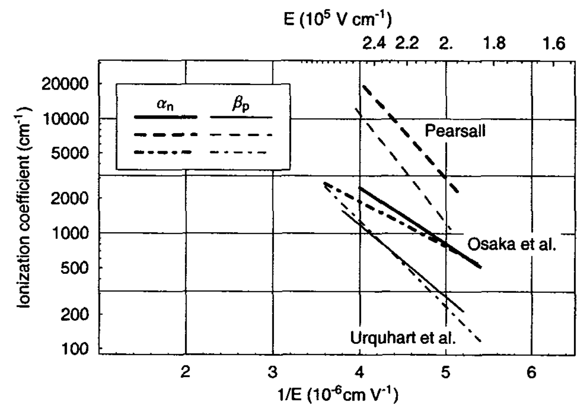

Fig. 1. Pearsall [3] (dotted lines), Osaka et al. [4] (continuous lines) and Urquhart et al. [5] (pointed-dotted lines) impact ionization coefficients.

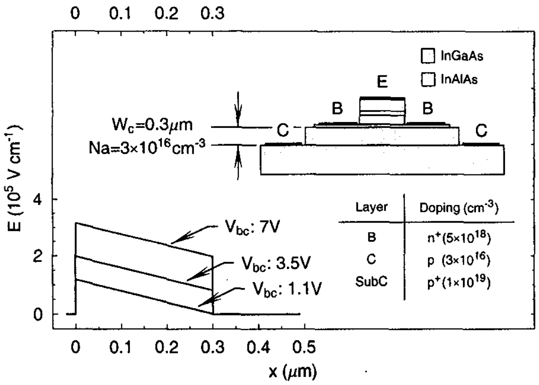

Fig. 2. PNP-HBT device structure based on InP and punch-through collector electric field at different biases.

Such a thin collector is suitable for good electrical performance of the device, but is not necessarily good for the envisaged impact ionization coefficient studies. This is due to the fact that carriers injected at the edge of the depletion region have to travel through a significant portion of the collector ($x_{th}/W_C \simeq 0.07 \div 0.2$ depending on biasing conditions) before reaching the threshold energy for ionization [9]; this results in a "dead space", x_{th}, that must be taken into account in the calculations and affects the local field multiplication model. The model used for computing the width of the non-ionizing region relies on the following equation [10]:

$$\epsilon_{th} = q \int_0^{x_{th}} E(x)\, dx \tag{1}$$

where $E(x)$ is the electric field profile with the depletion region edge at $x = 0$ and ϵ_{th} is the threshold energy for the carrier-initiated impact ionization, evaluated to be of the order of $0.83\,eV$ in $\mathrm{In_{0.53}Ga_{0.47}As}$ [4].

The use of a thin collector results also in a major advantage in terms of a negligible amount of secondary impact ionization events compared to primary ones (Fig. 3). This leads to a dramatic simplification in the classical, local field impact ionization equations and allows to express the hole multiplication factor M_h as a function of solely hole impact ionization coefficient:

$$M_h = 1 \Big/ \left(1 - \int_{x_{th}}^{W_c} \beta_p(x)\, dx\right) \tag{2}$$

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, $\beta_p(x_{th})$, (2) can be solved in $\beta_p(x_{th})$ and the following expression can be obtained:

$$\beta_p(E_{x_{th}}) = \left(\frac{1}{N_a}\frac{dN_a}{dV}\left(1 - \frac{1}{M_h}\right) + \frac{1}{M_h^2}\frac{dM_h}{dV}\right) \Big/ \left(\frac{dE_{x_{th}}}{dV}\frac{\epsilon_s}{q N_a}\right) \tag{3}$$

$$\text{with } N_a = N_A - \frac{J_C}{q\, v_s} \tag{4}$$

where N_A is the acceptor density in the low-doped collector, J_C is the collector current density (assuming negligible current crowding), v_s is the hole drift saturation velocity ($4.5 \times 10^6\ cm/s$ [11]) and V is the base-collector voltage. Equation 3 directly accounts for the non-negligible width (x_{th}) of the dead space region and for the collector charge density variations induced by current flow, as indicated in (4). The reported solution is considerably more general and accurate than classical approximations like [6]:

$$\beta_p(E_{max\,or\,avg}) = (M_h - 1)/(W_c - x_{th}) \tag{5}$$

at least with the geometries shown in Fig. 2 and for collector doping values greater than $2 \times 10^{16} cm^{-3}$. This lower bound on the collector doping is due to the neglecting of the low-field ionization rate, $\beta_p(W_C)$, in comparison to the high-field one, $\beta_p(x_{th})$. This assumption leads to an error which increases at the lowering of the collector doping and at the shortening of the depletion region. Equation 5 remains the equation of choice in the case of low-doped collector devices like that used in Canali et al. [6].

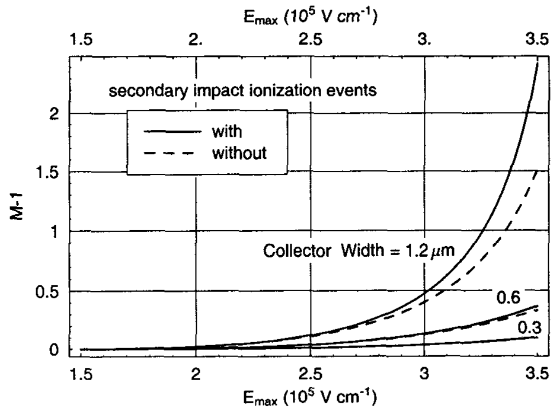

Fig. 3. Theoretical influence of secondary impact ionization events at three different collector widths, in devices having the same fully depleted collector reverse voltage.

III. Multiplication Measurements

In order to obtain accurate hole impact ionization coefficient estimations, reliable M_h measurements have to be performed. Measurements were carried out on single-finger HBT's with an emitter geometry varying from $2 \times 10\,\mu m^2$ to $5 \times 40\,\mu m^2$. All graphs and data refer to a $5 \times 10\,\mu m^2$ geometry device. A constant emitter current technique 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. The constant emitter current technique is explained in detail in [6], [7], and it basically relies on the fact that electrons generated by impact ionization in the high field region drift towards the base and behave there 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:

$$M_h - 1 = \frac{\Delta I_B}{I_C - \Delta I_B} \quad (6)$$

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. On increasing V_{BC}, at constant I_E, a series of effects beside impact ionization can induce a change in the base current: (i) Early effect increases the current gain, thus reducing $|I_B|$; (ii) I_{CBO} increases; (iii) the increase in power dissipation and junction temperature enhances the current gain, thus reducing $|I_B|$. All these effects, therefore, contribute to reduce the absolute value of the base current, thus leading to a possible overestimation of M_h and, consequently of the hole ionization coefficient. We have analyzed each source of error and have taken it into account in the final determination of ΔI_B, as discussed in the next subsections. The spread in the nominal processing values was also considered in the analysis.

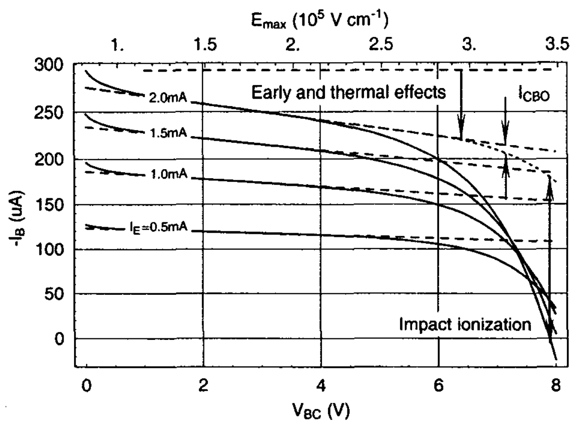

Fig. 4. Measured variations in base current at the varying of biasing conditions. The different components due to Early and thermal effects, I_{CBO}, and impact ionization are shown as distinct components. A linear approximation is used for fitting the Early component.

A. Early and Thermal Effects

Whereas from a theoretical point of view the more accurate procedure to numerically compensate the Early effect is to use a model that physically takes into account the processes involved in the changes of the base current, the non-negligible thermal effects vanished all the efforts in this direction, and implied the non-applicability of more experimental correction techniques like that in [7]. Measurements at different temperatures showed a positive temperature dependence of the current gain and a thermal resistance of about $1200\,^{o}C/W$, in good agreement with S. S. H. Hsu et al. data [12]. Because of this high thermal resistance and the chosen current levels (the lowest compatible with the non-negligible collector-base leakage current I_{CBO}), the measurements were slightly non-isothermal, with an estimated maximum temperature deviation of about $20\,^{o}C$ (at $I_E = 2\,mA$, $V_{BC} = 8\,V$).

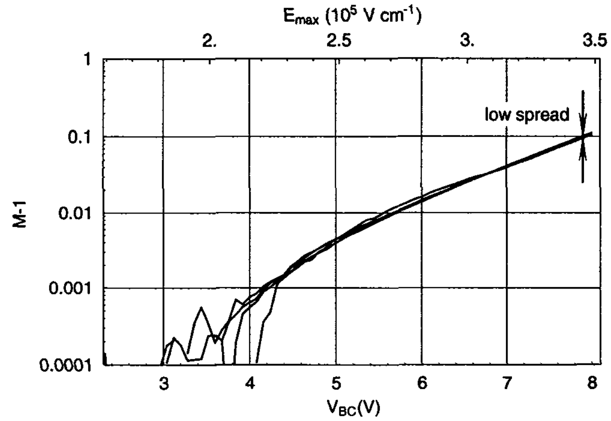

Fig. 5. Measured multiplication factor taking into account the collector-base leakage current I_{CBO}.

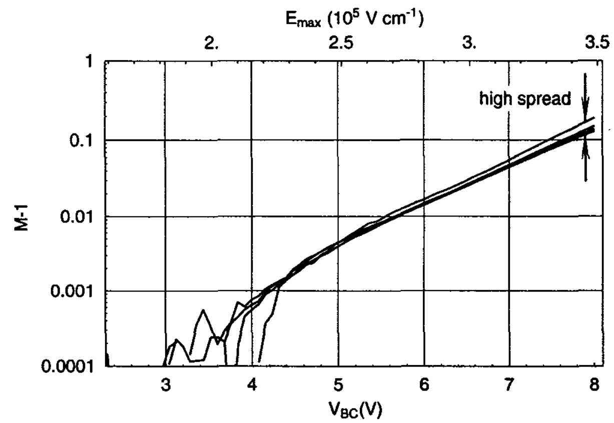

Fig. 6. Measured multiplication factor neglecting the collector-base leakage current I_{CBO}.

In first approximation, we can assume a linear decrease of I_B due to the temperature increase and the Early effect. The decrease in I_B due to these two parasitic phenomena can then be evaluated by extrapolating the behavior of I_B at low V_{BC} voltages, where impact-ionization and collector-base leakage current I_{CBO} are negligible. This allows one to calculate and subtract the Early effect and thermal contributions to ΔI_B, as shown in Fig. 4. The slight bending in the base current for low values in V_{BC} ($0V \leq V_{BC} \leq 1V$), is probably due to quasi saturation effects. In this region, due to the high resistivity of the low doped collector, the intrinsic collector-base junction is slightly forward biased (causing a sharp increase in $|I_B|$) even if the extrinsic collector-base junction remains reverse biased. Trap effects or slight thermal effects due to the increasing of the dissipated power at the increasing of the base-collector voltage cannot be completely ruled out.

B. Collector-Base Leakage Current I_{CBO}

The decrease in I_B due to the non-negligible I_{CBO} (Fig. 4), evaluated using two-terminals measurements, was corrected by simple subtraction, operating under superimposition principle hypotheses and taking into account the fact that base-collector junction reverse current originates mostly from the region outside the device active area (see Fig. 2). The correctness of this hypothesis was directly verified by the low spread in $M_h - 1$ as the emitter injected current varied in the $1 \div 4\,kA/cm^2$ range (Figs. 5 and 6).

C. Spread in Processing Parameters

In order to take into account possible deviations in the nominal processing values a 5% uncertainty in the width of the collector and a 10% error in the collector doping were introduced. These uncertainties are more than sufficient in the case of MBE-grown devices. For every value in V_{BC} the rectangle in the domain space (Collector doping $\times$ collector thickness) centered on the nominal values and sized according to the uncertainties on the parameters was mapped on the codomain space (Electric field $\times$ ionization coefficient) as stated by (1), (3) and (4). Consideration of these ranges gives rise to the grayed region in Fig. 7. The results at $I_E = 1.0, 1.5$ and $2.0mA$ were superimposed.

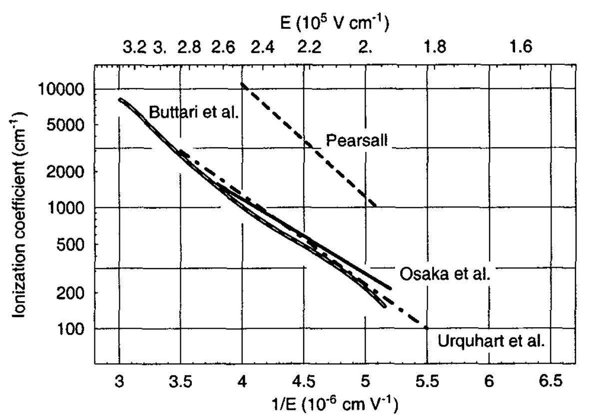

Fig. 7. Measured hole impact ionization coefficient and comparison with existing data. The hole ionization coefficient β_p has been computed taking into account a 5% spread in the collector width and a 10% spread in the collector doping.

IV. Conclusions

The results obtained for impact ionization coefficients in $In_{0.53}Ga_{0.47}As$ and a comparison with previous measurements are reported. A very low spread in the results was experienced when the emitter current is varied in the $1.0 \div 2.0mA$ range. Measurements were extended to electric fields up to $3.3\times10^5\ V/cm$, which approach the practical values applicable to electronic devices [13]. Reported data are comparable with results by Osaka et al. [4] and Urquhart et al. [5] and support already published results based on different, photo-electrical experimental techniques.

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