Experimental and Monte Carlo Analysis of Impact-Ionization in AlGaAs/GaAs HBT's

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Abstract—**We present a detailed experimental and theoretical investigation of hot electron effects occurring in AlGaAs/GaAs Heterojunction Bipolar Transistors (HBT's) operating at low current densities. Electrons heated by the strong electric field at the base-collector junction give rise to impact ionization and light emission. A new general purpose weighted Monte Carlo procedure has been developed to study such effects. The importance of dead-space effects on the multiplication factor of the device is demonstrated. Good agreement is found between theory and experiment.**

I. INTRODUCTION

HETEROJUNCTION bipolar transistors (HBT's) have recently attracted considerable attention because of their high-speed performance and high current handling capability [1], [2]. Due to their structure, they have a number of advantages over other transistors, in particular in the field of high-speed and power applications. In comparison with Si bipolar transistors, they benefit from higher cutoff frequency f_t, reduced base resistance, lower base-emitter capacitance, higher Early voltage, and higher resistivity (semi-insulating) substrates. In comparison with Field Effect Transistors (FET's) based on III-V materials, HBT's show higher transconductance, higher current and power density, lower demands for fine-line lithography, better threshold voltage matching, lower $1/f$ noise, and reduced trap-induced effects. For these reasons, they have been used for a wide variety of applications, both in the analog/microwave and in the digital domain.

Special collector doping profiles can be adopted to exploit velocity overshoot effects, thus improving HBT's high-speed performance [3]–[5]; in these designs, sharp changes in the electric field in the base-collector (B-C) space charge region are avoided, so that electrons remain in the Γ valley for a longer distance. Moreover, the collector doping profile directly influences impact-ionization effects and breakdown voltage, which are important factors for power applications of HBT's [5]–[7]. High-speed performances and breakdown voltage can not be optimized independently [5], [6]. Due to the strong electric fields present in the BC space charge region of HBT's and to the presence of remarkable nonlocal effects and hot-electron phenomena, conventional drift-diffusion device simulators can only partially afford the problem of a correct design of those devices. The physics involved in charge transport in such structures requires the use of more physically-based approaches, among which the Monte Carlo particle simulator is certainly the most attractive [5], [8]–[10].

In this paper, a theoretical and experimental characterization of impact-ionization effects in AlGaAs/GaAs HBT's is presented. A new general-purpose weighted Monte Carlo procedure which accounts for both electrons and holes has been developed, including a three-valley/three-band nonparabolic model and self-consistently coupled to a 1-D Poisson solver [12]. Impact-ionization has been included on the basis of Kane's model [13]. The experimantal and Monte Carlo analysis of impact-ionization effects is mainly limited to low current density regimes, where the occurrence of Kirk effecs and self-heating phenomena can be neglected.

The structure of the devices employed for this work is described in Section II. Section III presents experimental data concerning impact-ionization in HBT's, while Monte Carlo simulations of electrical characteristics are introduced in Section IV. Conclusions follow.

II. DEVICE STRUCTURE

In this paper we describe the results obtained on npn AlGaAs/GaAs HBT's grown by MBE at AT&T Bell Labs., whose structure is shown in Fig. 1 [15]. The semiconductor layers consisted of a 800 nm GaAs-n$^+$ layer (doped at 5×10^{18} cm^{-3}) which acts as the collector contact, followed by a 500 nm GaAs-n collector (2.5×10^{16} cm^{-3}). The GaAs-p^+ base was 120-nm thick (2×10^{19} cm^{-3}) followed by an AlGaAs-n$^+$ emitter (5×10^{17} cm^{-3}) compositionally graded immediately after the base to reduce the conduction band discontinuity at the junction [16]. An InGaAs-n$^+$ layer was used on top of the emitter to improve ohmic contact characteristics; alloyed AuGeNi was employed for both emitter and collector contacts. The epilayer was etched to form a two level circular mesa structure having an emitter diameter of 100 μm, in order to minimize the perimeter/area ratio, thus reducing surface effects [17]. For optical measurements

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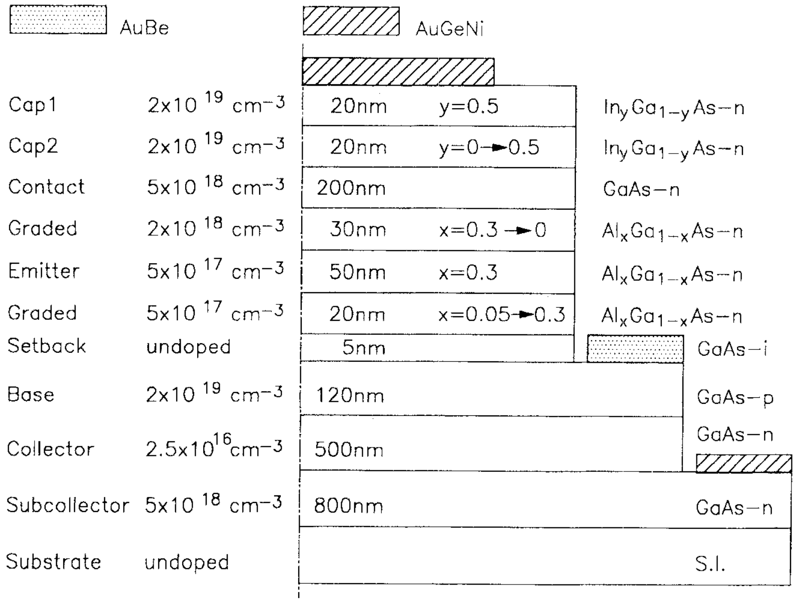


Fig. 1. Schematic cross section of the AlGaAs/GaAs n-p-n HBT. An InGaAs layer was used on the top of the emitter to improve ohmic contact characteristics. The emitter composition was graded toward the base to reduce conduction-band discontinuity at the junction.

a circular hole (30-μm diameter) was opened in the emitter metallization. The resulting active emitter area is $A_E = 7.9 \times 10^{-5}$ cm^2. The transistors exhibit nearly ideal characteristics with collector current, I_C, and base current, I_B, ideality factors of 1.01 and 1.2, respectively, reflecting the good quality of the epilayers. The current gain β is 80 at a collector current of 20 mA. β reduces to unity at $I_C \approx 1$ nA. The base-collector breakdown BV_{CBO} occurs abruptly at around 18.6 V, approaching the bulk junction breakdown voltage value [18].

III. IMPACT-IONIZATION EFFECTS: EXPERIMENTAL RESULTS

When npn HBT's are biased in the active region at high V_{CB}, electron-hole pairs are generated in the base collector space charge region by impact ionization. The generated electrons are swept into the collector, as schematically shown in Fig. 2, contributing a positive term to the collector current I_C, while the generated holes are injected into the base contributing a negative term to the base current I_B, which increases on increasing V_{CB} [15], [18].

Fig. 3 shows I_B measured as a function of V_{CB} with the HBT biased in the common base configuration and driven at different emitter currents I_E. At $V_{\text{CB}} = 0$ V impact ionization does not occur and I_B is always positive. On increasing V_{CB} the negative contribution to I_B, due to holes generated by impact ionization, becomes so high that I_B decreases until it changes its sign and becomes negative in correspondence to the "dips" in Fig. 3, [15]. The quantity $\Delta I_B = I_B(V_{\text{CB}} = 0) - I_B(V_{\text{CB}})$ is a measure of the hole current due to impact ionization, neglecting the contribution of the base-collector junction reverse current I_{CB0}, measured with open emitter. I_{CB0} remains negligible with respect to I_B and ΔI_B up to V_{CB} values close to the breakdown voltage of the BC junction. I_{CB0} remains also negligible with respect to ΔI_B even at temperatures as high as 140 °C for $V_{\text{CB}} > 7$ V.

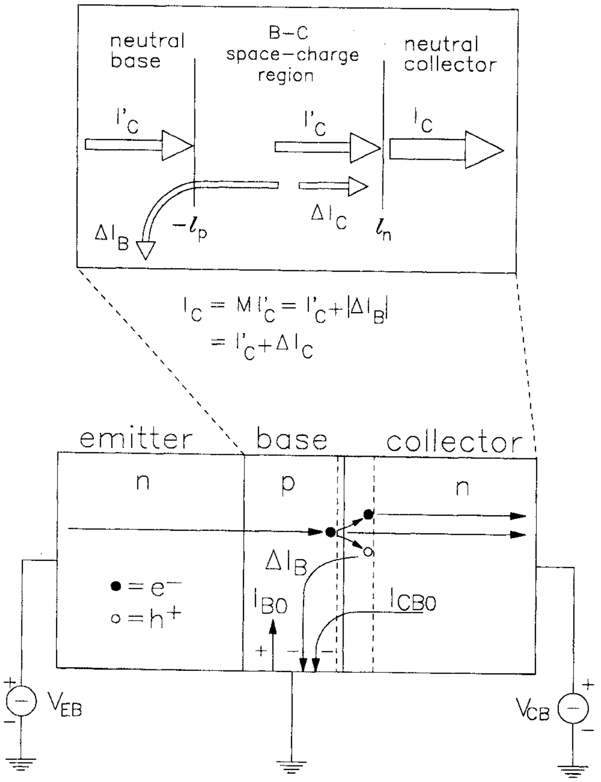


Fig. 2. (top) Schematic cross section of BC junction, identifying the various contribution to collector and base currents. I_C' is the collector current without impact-ionization, $\Delta I_C = \Delta I_B$ are the currents due to impact-ionization generated carriers. (bottom) Schematic cross section showing impact-ionization in a bipolar transistor. I_{B0} is the base current without impact-ionization, measured at $V_{\text{CB}} = 0$ V.

Impact ionization effects can be quantitatively evaluated by measuring the multiplication factor $M - 1$ defined as the

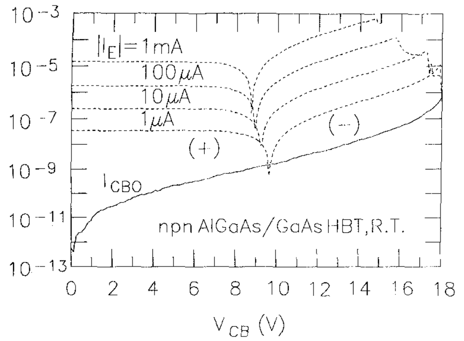


Fig. 3. Absolute value of the base current I_B (dashed lines) as a function of V_{CB} with the device driven at different and constant I_E in common base configuration. The dips are where I_B changes its sign. The reverse current of the BC junction with open emitter, I_{CB0}, is also shown (continuous line).

ratio of generated electron-hole pairs to the number of carriers injected in the collector

$$M-1=\frac{\Delta I_B}{I_C-\Delta I_B}=\frac{I_B(V_{CB})-I_{B0}}{I_C(V_{CB})-(I_B(V_{CB})-I_{B0})} \qquad (1)$$

where I_{B0} is the base current without multiplication (i.e., I_B at $V_{CB}=0$ V). This equation assumes that: 1) the Early effect on I_B is negligible; 2) the collector-base junction reverse current I_{CB0} is always negligible with respect to I_B or does not change with V_{CB}; and 3) device self-heating is negligible [15], [18].

$M-1$ depends on both V_{CB} and I_C, and, consequently, on I_E. Fig. 4 shows I_C and I_B as a function of $|I_E|$ for various values of V_{CB}. On increasing V_{CB} and I_E the number of electron-hole pairs generated by impact-ionization increases; in particular at $V_{CB}=8.6$ V, this contribution is so high that I_B reverses its sign and becomes negative. I_B is negative if $(M-1)>1$. The value of $|I_E|$ at which the reversal of I_B occurs becomes lower and lower with increasing V_{CB}. On further increasing $|I_E|$, different effects contribute to a decrease in the generation rate and I_B recovers to a positive value, as occurs for $|I_E|>10$ mA at $V_{CB}=8.6$ V (see Fig. 4). These effects are: voltage drops due to collector, R_C, and base, R_B, parasitic resistances, device self-heating, and electric field lowering in the base-collector junction due to the presence of mobile carriers. Fig. 5(a) shows $M-1$ as a function of $|I_E|$, at various V_{CB} ranging from 5 to 17 V. Measurements at high V_{CB} were interrupted at low $|I_E|$ to avoid excessive power dissipation and instabilities [19]. At low $|I_E|$ values the extracted $M-1$ values are affected by the reverse current of the base-collector junction I_{CB0}, which induces an apparent increase in the multiplication factor, and by the experimental uncertainties in the measured currents. $M-1$ remains below the experimental uncertainties up to $V_{CB}=5$ V; beyond that value $M-1$ rapidly increases as a function of V_{CB}. At high $|I_E|$ values, on the contrary, $M-1$ decreases due to series resistances, self-heating and high-injection effects.

Fig. 5(b) shows the effect of: a) reducing device self-heating by pulsing I_E with a duty cycle as low as 0.2%; and b) correcting voltage drops on parasitic resistances (the extracted values being $R_B=180\Omega, R_C=10\Omega$). We still observe a decrease in $M-1$ at high current densities. Even though the nominal current density at $I_E=-10$ mA is of the order of 10^2 A/cm^2, the electric field lowering due to the presence of mobile carriers can not be excluded because non negligible current crowding effects can take place in these large area devices.

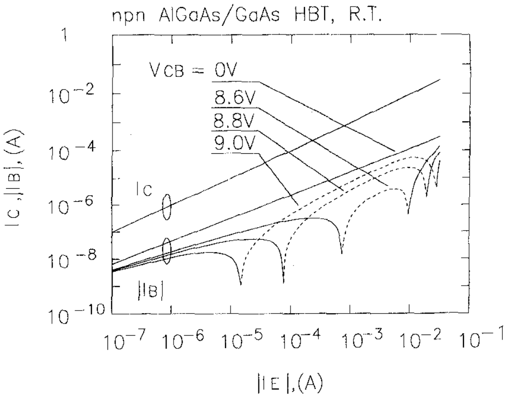
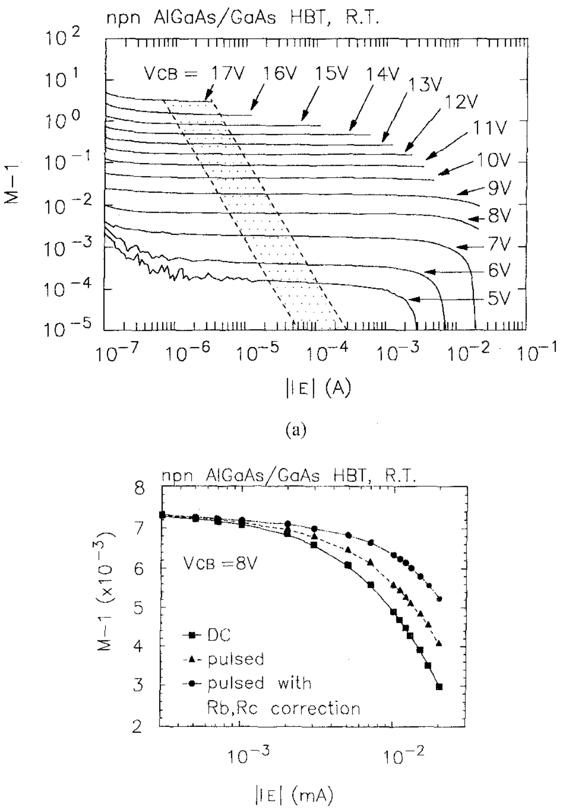


Fig. 4. Gummel plot of the AlGaAs/GaAs HBT n-p-n transistor at different V_{CB}. The negative part of I_B at $V_{CB}>8.6$ V is identified by a dashed line. The dips occur where I_B changes its sign.



(a)

(b)

Fig. 5. (a) $M-1$ as a function of $|I_E|$ at different V_{CB}. Dotted region corresponds to the I_E values chosen to obtain the dependence of $M-1$ on V_{CB}. (b) $M-1$ measured at $V_{CB}=8$ V for dc conditions, pulsed conditions (at 0.2% duty cycle), and pulsed conditions including R_C and R_B voltage-drop corrections.

In the central $|I_E|$ range $M-1$ is not affected by parasitic phenomena, and remains constant at varying I_E (Fig. 5(a)

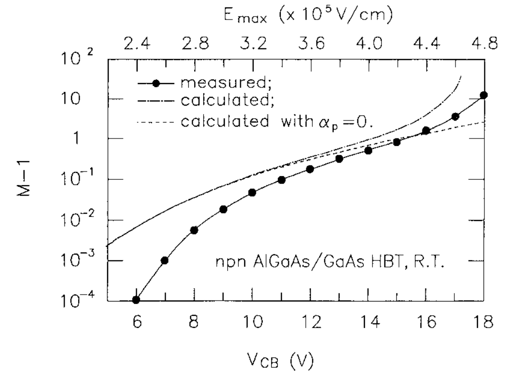


Fig. 6. $M - 1$ as a function of V_{CB} for measured data (continuous line) and data calculated from (2) including (dashed and dotted line) or excluding (dashed line) secondary ionization events due to generated holes.

dotted area); consequently, it is not necessary to introduce any correction to: Early effect, Kirk effect, and self-heating phenomena.

$M - 1$ can be obtained from the current equation in presence of generation terms as [19]

$$M - 1 = \frac{1}{1 - \int_0^{W_C} \alpha_n \exp\left[-\int_0^x (\alpha_n - \alpha_p) dx'\right] dx} - 1 \quad (2)$$

where W_C is the collector width. The field dependence of the electron and hole ionization coefficients α_n and α_p is given, according to Bulman *et al.* [20], respectively, by the expressions

$$\alpha_n(E(x)) = 1.899\ 10^5 \exp(-(5.750\ 10^5/E(x))^{1.82})(\mathrm{cm}^{-1}) \quad (3)$$

$$\alpha_p(E(x)) = 2.215\ 10^5 \exp(-(6.570\ 10^5/E(x))^{1.75})(\mathrm{cm}^{-1}). \quad (4)$$

To evaluate $E(x)$, Poisson's equation was solved neglecting the free electron contribution in the space-charge region, which is not important at the I_E values considered. Fig. 6 shows the experimental values of $M - 1$ obtained by driving the emitter with a high-impedance current source in the dashed I_E range shown in Fig. 5(a).

Experimental data were compared with the $M - 1$ values calculated according to (2) and are show in Fig. 6 with and without the contribution of the generated holes to impact ionization, i.e., assuming $\alpha_p(E(x)) = 0$ (dashed line) or given by (4) (dotted-dashed line), respectively. When the impact-ionization coefficients are calculated as a function of the local electric field, a large overestimation of the experimental data occurs for $V_{\mathrm{CB}} < 15$ V.

IV. MONTE CARLO SIMULATION OF IMPACT-IONIZATION EFFECTS

A. The Physical Models

An accurate description of hot electron phenomena in electronic devices can be obtained by means of self-consistent Monte Carlo device simulations [21]. The transport model adopted here for GaAs is based on a three-valley description of the conduction band and on three valence bands with non parabolic isotropic dispersions, where the non parabolicity factors are treated as fitting parameters and adjusted as to reproduce a variety of experimental results, including those provided by time resolved spectroscopy, [12]. The carrier interaction with polar optical, acoustic, equivalent and nonequivalent intervalley, intraband and interband phonons has been considered, within the usual golden rule scheme. In the presence of heavily doped (n^+ and p^+) regions, plasmon losses have been taken into account. Impurity scattering was treated using the Brooks–Herring approach. A list of all relevant parameters is presented in Table I.

Impact-ionization was included by adopting the model proposed by Kane [22], where the energy dependence of the ionization process is given by.

$$P(E) = P_0 \cdot \left(\frac{E - E_{\mathrm{th}}}{E_{\mathrm{th}}}\right)^a \quad (5)$$

E being the total carrier energy and E_{th} the ionization energy threshold. The free parameters a and P_0 of (5) have been determined, respectively, through the fit of the bulk ionization coefficients and from the density of states calculated from an empirical pseudopotential method. The values are given in Table I. A plot of the ionization rate obtained by our approach is presented in Fig. 7, together with a comparison with other formulations found in the literature [23]–[28]. Clearly, the use of our simplified model based on a three valley model does not differ significantly from the results obtained by most sophisticated appraoches which rely on full-band calculations. Consistently with this observation, we find that our bulk ionization coefficients for electrons and holes agree quite well with the available experimental results [12].

The simulation of impact ionization phenomena poses considerable numerical problems since it requires the knowledge of the high-energy tail of the carrier distribution function. Furthermore, in the presence-of carrier multiplication the number of simulated particles would grow above the initially set value, diverging as breakdown is approached. A special multiplication technique for both energy and real space, which is an extension of the original idea of Philips and Price [29] has been developed. Each particle is assigned a statistical weight which varies with its position in the device and its energy. With such approach, it is possible to account for regions with very different doping levels (as in bipolar transistors) and to obtain a reliable statistics of rare processes, keeping at the same time a constant number of particles. These techniques are also useful for low-injection regimes, required to avoid the occurrence of Kirk effect in the collector.

For the simulation of devices, the Monte Carlo algorithm is self-consistently coupled to a Poisson solver, as described in [21].

B. High Field Transport in the Collector

Simulations were performed using the device structure depicted in Fig. 1. Fig. 8 shows the electric field profile obtained by varying V_{CB} in the 12 V–18 V range. Very high

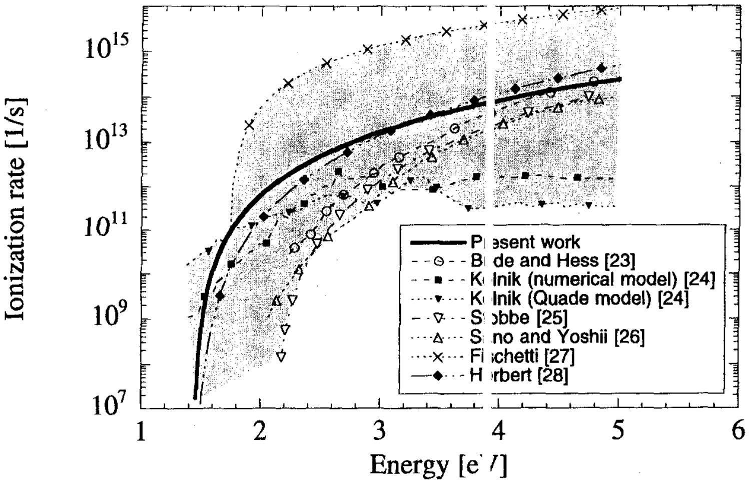


Fig. 7. Comparison between the impact ionization scattering rates as published in litterature and our Kane model (solid line). The shaded area indicates the spread of the published data.

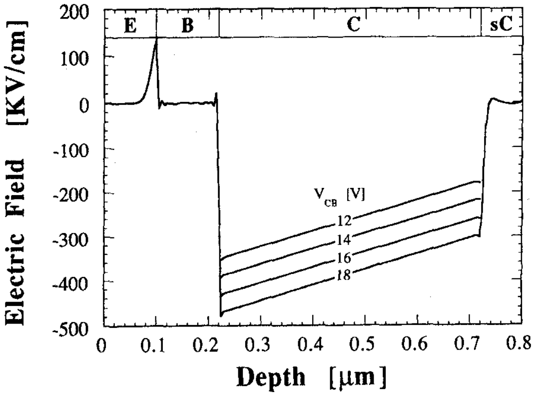


Fig. 8. Electric field profiles in the simulated HBT at various V_{BC}.

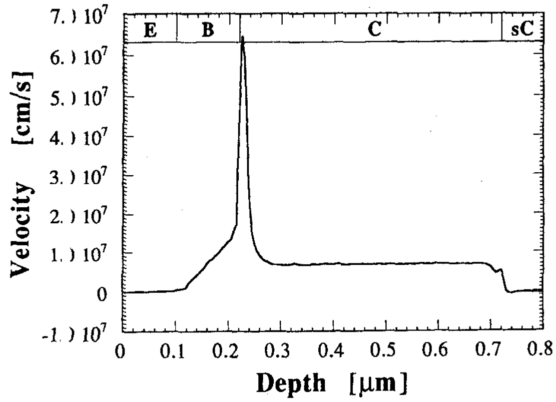


Fig. 9. Average electron velocity across the simulated HBT at $V_{CB} = 16$ V.

values of electric field are reached in the collector region, with the maximum occurring at the base-collector interface. Electrons, injected from the emitter, cross the base where they strongly interact with the dense hole plasma. As they enter the collector, they are ballistically accelerated by the junction field, reaching velocities as high as 6×10^7 cm/s. As shown in Fig. 9, which refers to $V_{CB} = 16$ V, the spatial extent of the velocity overshoot is limited to about 10 nm, as the electrons are rapidly scattered into the satellite valleys where they move at saturated velocity. Fig. 10 indeed shows that for a collector voltage of 16 V almost all electrons in the collector populate the L and X valleys in equal number. There, they are strongly heated by the collector field, obtaining the high values of average kinetic energy illustrated in Fig. 11.

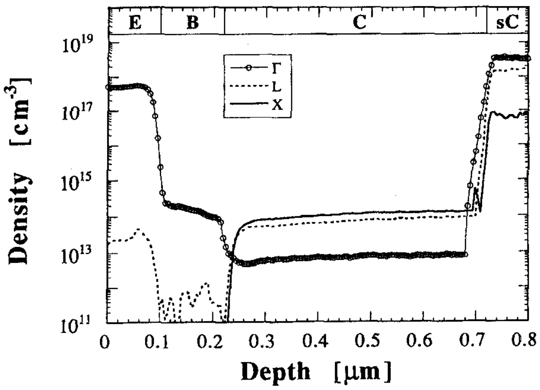


Fig. 10. Electron concentration in the different valleys at $V_{CB} = 16$ V.

C. Simulation of Impact-Ionization Phenomena: The Dead-Space Effect

Fig. 12 shows the electric field, the average electron energy and the electron ionization coefficient simulated by Monte Carlo for $V_{CB} = 18$ V that is in the near breakdown regime. Electrons are strongly heated by the high electric field at the B-C junction, reaching their maximum energy at about 80 nm inside the collector. Due to their high energy, electrons undergo impact-ionization processes. As illustrated in Fig. 12, the electrons ionization coefficient is further delayed due to the finite time and distance required for carriers to reach the ionization energy threshold. As a consequence, ionization events do not occur in correspondence to maximum electric

TABLE I

PARAMETERS USED IN THE MONTE CARLO SIMULATION FOR ELECTRONS (TOP) AND HOLES (MIDDLE). HERE H. H. STANDS FOR "HEAVY HOLES," L. H. FOR "LIGHT HOLES," AND S. O. FOR "SLIT-OFF" HOLES. OTHER PARAMETERS, INCLUDING THE IMPACT-IONIZATION ONES, ARE ALSO REPORTED (BOTTOM)

Electron parameters (300K)	**Γ** (000)	**L** (111)	**X** (100)
Acoustic deformation potential (eV)	7.0	7.0	7.0
Effective mass (m^*/m_0)	0.063	0.222	0.58
α (nonparabolicity) (eV^{-1})	0.610	0.244	0.061
Band-edge energy (eV)	1.439	1.739	1.961
Intervalley deformation potential (eV/cm)			
from Γ (000)	0.0	$7.0 \cdot 10^8$	$1.0 \cdot 10^9$
from L (111)	$7.0 \cdot 10^8$	$1.0 \cdot 10^9$	$1.0 \cdot 10^9$
from X (100)	$1.0 \cdot 10^9$	$1.0 \cdot 10^9$	$1.0 \cdot 10^9$
Intervalley phonon energy (meV)			
from Γ (000)	0.0	27.8	29.3
from L (111)	27.8	27.8	29.3
from X (100)	29.3	29.3	29.3
Number of equivalent valleys	1	4	3

Hole parameters (300K)	**H.H.**	**L.H.**	**S.O.**
Acoustic deformation potential (eV)	7.0	7.0	7.0
Effective mass (m^*/m_0)	0.45	0.085	0.154
Band-edge energy (eV)	0.0	0.0	0.35
α (nonparabolicity) (eV^{-1})	0.55	4.0	0.3
Interband deformation potential (eV/cm)			
from H.H.	$9.0 \cdot 10^8$	$7.0 \cdot 10^8$	$5.0 \cdot 10^8$
form L.H.	$7.0 \cdot 10^8$	$9.0 \cdot 10^8$	$5.0 \cdot 10^8$
from S.O.	$5.0 \cdot 10^8$	$5.0 \cdot 10^8$	$9.0 \cdot 10^8$
Interband phonon energy (meV)			
from H.H.	27.8	27.8	27.8
from L.H.	27.8	27.8	27.8
from S.O.	27.8	27.8	27.8

Parameter	**Value**
Density (g/cm^3)	5.36
Sound velocity (cm/s)	$5.22 \cdot 10^5$
ε_∞	10.92
ε_0	12.90
Optical phonon energy (meV)	35.36
Electron ionization coefficients	
P (s^{-1})	$1.29 \cdot 10^{13}$
a	3.2
E_{th} (eV)	1.439
Hole ionization coefficients	
P (s^{-1})	$6.44 \cdot 10^{11}$
a	6.35
E_{th} (eV)	1.439

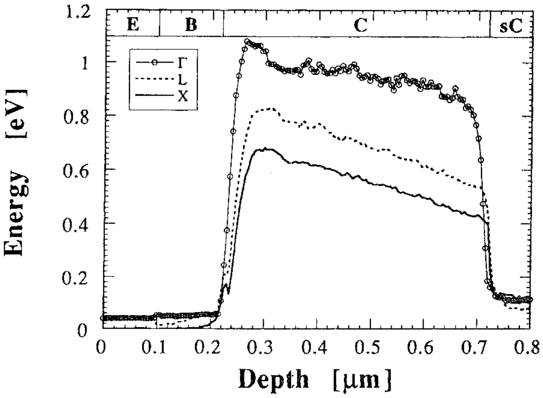


Fig. 11. Electron average energy in the different valleys for $V_{BC} = 16$ V.

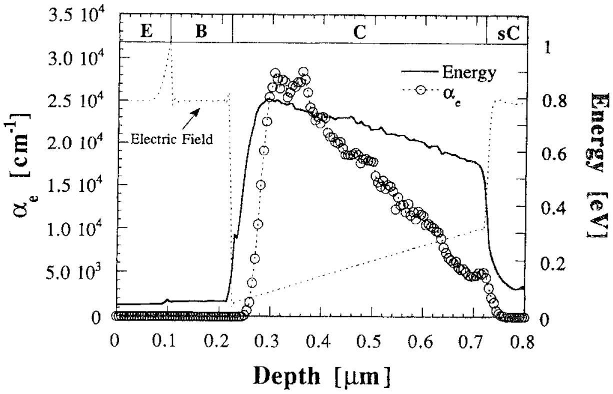


Fig. 12. Electron ionization coefficient (open circles) and kinetic energy (solid line) at $V_{CB} = 18$ V, as obtained by Monte Carlo simulations. The electric field profile is also shown. The field strength varies from 475 kV/cm at the BC junction to 300 kV/cm at the subcollector.

field, rather well into the collector. Such phenomenon is usually referred to as "dead-space" effect [30].

The behavior of the multiplication factor $M - 1$ obtained by Monte Carlo simulation is shown in Fig. 13. The Monte Carlo results (closed circle) agrees well with the measured ones (diamond). The change in the slope of the $M - 1$ curve around 18 V can be attributed to the onset of higher order processes, see Fig. 14. In fact near to the breakdown, the holes generated by primary ionizations are able to ionize before reaching the base, thus creating electrons that will in turn ionize while drifting along the collector region. Such positive feedback marks, in fact, the onset of breakdown, occurring at a collector voltage of 18.6 V.

D. Semi-Analytical Modeling of Impact-Ionization

The usual local current equation which describes the effects of impact-ionization is

$$\frac{dI_n}{dx} = \alpha_n(x)I_n(x) + \alpha_p(x)I_p(x). \qquad (6)$$

From (6) we can obtain the standard form of the $M - 1$ factor given in (2). In such local model the presence of the "dead space", that is of a high field region where impact ionization

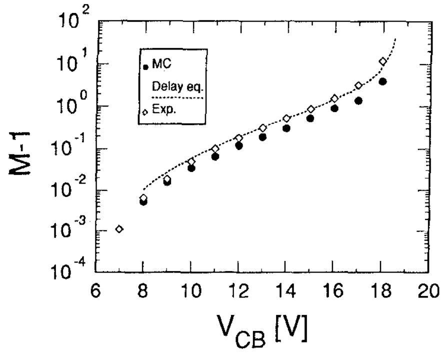


Fig. 13. Bias dependence of the multiplication factor $M - 1$: Measured at $I_E = -100$ A (diamonds), Monte Carlo simulation (closed circle) and as obtained from (7) (dotted line).

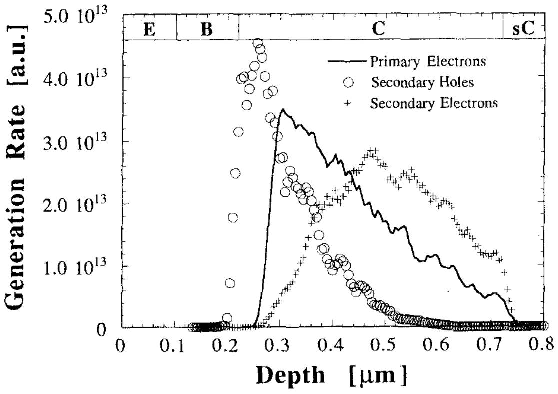


Fig. 14. Generation rate obtained by means of Monte Carlo simulation in an AlGaAs/GaAs HBT at $V_{CB} = 18$ V. The solid lines illustrates the contribution of primary electrons (those injected across the base from the E-B junction), while open circles and crosses refer to high-order contributions from holes and electrons, respectively.

does not occur, is not accounted for. As a consequence, (2) and (6) lead to an overestimation of the multiplication factor, as shown by the dashed lines in Fig. 6.

Non-local effect can be included by considering an equation with delay of the type

$$\begin{aligned}\frac{dI_n}{dx} &= \alpha_n(x)I_n(x-l_{\mathrm{DS}})\theta(x-l_{\mathrm{DS}})\\ &\quad + \alpha_p(x)I_p(x+l_{\mathrm{DS}})\theta(W-x-l_{\mathrm{DS}}) \qquad (7)\end{aligned}$$

where the Heaviside function, Θ, accounts for the fact that electrons (holes) can only ionize after a distance l_{DS} from the base-collector (collector-subcollector) junction, l_{DS} being the "dead-space" distance. The introduction of a delay accounts for the fact that the ionization rate at position x depends on the carriers which are displaced by l_{DS} from it (that is on the electron current at $x - l_{\mathrm{DS}}$ and the hole current at $x + l_{\mathrm{DS}}$). Clearly (7) leads, as limited case, to (6) and (2).

Although general prescriptions concerning the existence of solutions for such equations can be given (see [31] and references therein), analytical solutions exists only for some special cases. We have therefore solved it numerically within a finite difference scheme, using for the field profile the solution of Poisson's equation. Once the electron and hole currents are determined, the mutliplication factor is calculated as the ratio between the electrons current at the end and at the beginning of the collector. The value of l_{DS} was taken from Monte Carlo simulations. The dead-space dependence on the bias voltage is accounted for by an hyperbolic interpolation $l_{\mathrm{DS}} = A/V_{\mathrm{CB}} + B$, where the coefficients A and B are determined from the Monte Carlo values at 8 V ($l_{\mathrm{DS}} = 90$ nm) and 18 V ($l_{\mathrm{DS}} = 55$ nm), respectively. The agreement with the experimental results is excellent, and the correct value of the breakdown voltage is obtained. We notice that (7) works better than Monte Carlo because of the intrinsic limitations of the latter. In fact, avalanche current can be seen as a sum over infinite number of terms, each representing an ionization process of given order. This summation is fully taken into account in the (7), but it can not be accomplished in the Monte Carlo method because it would require a huge computational time and a huge number of simulated particles. In fact, the discrepancy between experiment and Monte Carlo becomes significant only for high bias, where the secondary particles give a contribution to the current of the same order as the primary ones (see Fig. 15).

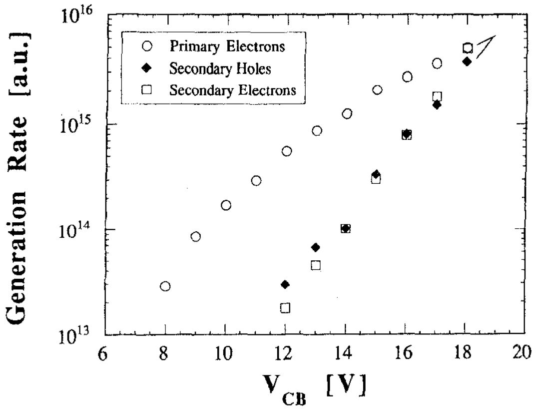


Fig. 15. Simulated generation rate for primary electrons and secondary electrons and holes as a function of V_{CB}.

V. CONCLUSION

This paper has presented a detailed experimental and theoretical investigation of hot carrier effects, impact ionization and breakdown phenomena, occurring in AlGaAs/GaAs HBT's at low current densities. Measurements of the changes in base current enable us to accurately characterize impact ionization effects while the Monte Carlo device simulation provides a detailed picture of the carrier distribution functions, of impact ionization and of dead-space effects. The simulation also predicts correctly the device breakdown, demonstrating the fundamental role of secondary holes in determining the breakdown voltage. With the aid of Monte Carlo simulations, the collector composition and doping profile can be optimized, thus solving the breakdown-speed dilemma associated with HBT's design.

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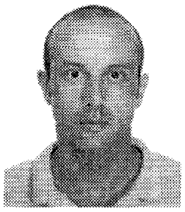

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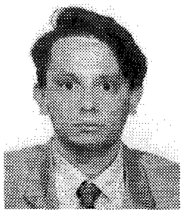

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