Avalanche multiplication and ionization coefficient in AlGaAs/InGaAs *p-n-p* heterojunction bipolar transistors

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The hole-initiated impact ionization multiplication factor M_p-1 and the ionization coefficient α_p in AlGaAs/InGaAs *p-n-p* heterojunction bipolar transistors (HBTs) are presented. A large discrepancy is observed at low electric field when the measured data from the *p-n-p* HBTs are compared with those given from avalanche photodiode. The results show that the conventional impact ionization models, based on local electric field, substantially overestimate the hole impact ionization multiplication factor M_p-1. We believe that the hole ionization coefficient in *p-n-p* HBTs where significant dead space effects occur in the collector space charge region. [S0003-6951(01)04001-3]

It is well known that the power capability of heterojunction bipolar transistors (HBTs) is limited by impact ionization occurred in the collector space charge region. At high electric fields, the impact ionization process leads to avalanche multiplication and eventually to breakdown. In order to calculate junction breakdown voltages accurately, it is necessary to obtain avalanche multiplication factors and ionization coefficients of electron and hole. The avalanche multiplication phenomena occurred in AlGaAs/GaAs, InGaP/GaAs, and InP/GaInAs *n-p-n* HBTs have been reported.[1–6] However, less effort was devoted to hole-initiated avalanche multiplication and ionization coefficient. Furthermore, *p-n-p* HBTs have recently attracted much attention because of their applications in monolithic complementary HBT technology.[7] Thus, a good knowledge of avalanche multiplication and hole ionization coefficient in *p-n-p* HBTs is necessary. In this letter, the avalanche multiplication factor and the hole ionization coefficients in AlGaAs/InGaAs *p-n-p* HBTs are presented. A strong hole dead space effect was observed at low electric fields and a simple correction for the dead space is proposed.

The devices used in this work were *p-n-p* AlGaAs/InGaAs HBTs with the GaAs collector grown by molecular beam epitaxy. The device structure is shown in Table I. Due to the low hole mobility in GaAs, an indium composition in the InGaAs base was linearly graded from 15% at the collector edge to 0% at the emitter edge to reduce the base transit time. The structures were fabricated into devices using optical lithography and selective wet etching for mesa definition. The devices exhibited a high dc current gain (β) of $\geqslant 90$ at a collector current (I_C) of $\geqslant 10$ mA with an emitter area dimension of $35\,\mu\text{m}\times 45\,\mu\text{m}$. To obtain the multiplication characteristics as a function of the electric field, the technique described by Zanoni *et al.*[1] and Canali *et al.*[3] was used. The HBT was operated in the common base mode and a constant base-emitter bias $V_{\text{BE}}=1.15\,\text{V}$ was applied to inject holes into the base, which were subsequently collected by the collector. Generated electrons due to the impact ionization are collected at the base contact, which contribute to a negative term ΔI_B in the base current[1,3]

$$\Delta I_B = I_B(V_{\text{CB}}) - I_{\text{BO}}, \tag{1}$$

where I_{BO} is the base current without multiplication and it is assumed to be equal to I_B at $V_{\text{CB}}=0$ V. Under such conditions, when the multiplication values are high, the base current may reverse its polarity and become negative. The multiplication factor M_p-1 can be evaluated from [1,3]

$$M_p - 1 = \frac{|\Delta I_B|}{I_C - |\Delta I_B|}. \tag{2}$$

The base-collector diode reverse current I_{CBO} measured at $I_E=0$ A was as low as 10 pA at $V_{\text{CB}}=13$ V, thus the parasitic contribution of I_{CBO} can be neglected. Moreover, the self-heating of the device can be also neglected in our measurement. In order to verify whether the Early effect contributes significantly to the results, the error introduced by Early effect, $\text{Err}(M_p-1)$, has been calculated according to the method proposed by Shamir *et al.*[8] The results demonstrate that $\text{Err}(M_p-1)$ is much smaller than M_p-1 for $V_{\text{CB}} \geqslant 5$ V.

Figure 1 shows the theoretical and experimental multiplication factor M_p-1 as a function of applied voltage. The

TABLE I. The *p-n-p* HBT epitaxial layer structure used in this work.

Layer	x	Doping (cm-3)	Thickness (A)
p^+-GaAs		5×10^{19}	200
p-GaAs		1×10^{18}	800
p-Al$_x$Ga$_{1-x}$As	0.3–0	5×10^{17}	200
p-Al$_x$Ga$_{1-x}$As	0.3	5×10^{17}	200
p-Al$_x$Ga$_{1-x}$As	0–0.3	5×10^{17}	300
n-In$_x$Ga$_{1-x}$As	0.15–0	5×10^{18}	500
p-In$_x$Ga$_{1-x}$As	0.15	5×10^{16}	100
p-In$_x$Ga$_{1-x}$As	0–0.15	5×10^{16}	150
p-GaAs		5×10^{16}	2500
p-GaAs		3×10^{19}	7000
SI GaAs substrate			

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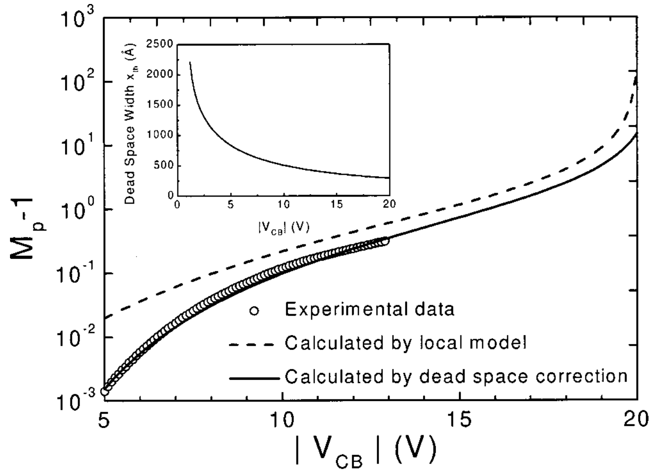

FIG. 1. Measured multiplication factor vs applied voltage in AlGaAs/InGaAs *p-n-p* HBT. Solid line shows data calculated using the dead space corrected model and dotted line shows data calculated using the local model. The inset shows the dead space width, x_{th}, vs bias V_{BC}.

dotted line shows the calculated theoretical values of $M_p - 1$ using the traditional local model.[9] The field dependence of the electron and hole ionization coefficients α_n and α_p used for the calculations is given by Bulman *et al.*[10] as

$$\alpha_n[E(x)]=1.899\times10^5\exp\{-[5.570\times10^5/E(x)]^{1.82}\}, \tag{3}$$

$$\alpha_p[e(x)]=2.215\times10^5\exp\{-[6.570\times10^5/E(x)]^{1.75}\}. \tag{4}$$

They were determined based on the extremely detailed study of photocurrent multiplication measurements using a large number of wafers and GaAs *p-i-n* diodes. The measurements covered a very large electrical field (from 2×10^5 to $6\times10^5\ \mathrm{V\,cm^{-1}}$) gave excellent reproducibility. To calculate $E(x)$, Poisson's equation was solved by neglecting the free hole contribution in the space-charge region.

It can be seen from the plot of $M_p - 1$ versus local electric field (Fig. 1) that a large overestimation of the experimental data occurs at low bias voltages. We attribute this effect to the fact that there is a strong dead space effect in *p-n-p* AlGaAs/GaInAs HBTs. For devices having low carrier concentration and wide active regions, such as photomultiplication diode and traditional Si bipolar transistors, the dead space constitutes a small fraction of the total depletion region and its effects are negligible. However, for advanced HBT devices with narrow depletion region and heavier doped collector, the dead space can be significant. The inset in Fig. 1 shows the curve of dead space width, x_{th}, versus bias V_{BC}. This further suggests the importance of dead space effect at low bias. Similarly, strong dead space effect of injected electron has also been found in *n-p-n* AlGaAs/GaAs HBTs.[2,4]

The dead space effects can be calculated by using the model proposed by Fliteroft *et al.*[5] We assume that a hole injected into the depletion region must travel a finite distance, x_{th}, before causing ionization. In this dead space, the probability of ionization by the injected carrier is assumed to be zero, and x_{th} is defined by[10]

$$\epsilon_{th}=\int_0^{x_{th}}E(x)dx, \tag{5}$$

where ϵ_{th} is the threshold energy for ionization initiated by hole and $E(x)$ is the electric field profile in the space charge region of the collector. Solving the integral in (5) yields an expression for x_{th} given by[5]

$$x_{th}=\frac{E_m-\sqrt{E_m^2-2\varepsilon_{th}\frac{dE}{dx}}}{\frac{dE}{dx}}, \tag{6}$$

where E_m is the maximum value of electric field occurring at the p^+n junction. E_m and dE/dx can be found by solving the Poission's equations.

In the dead space, α_p is zero for $0<x<x_{th}$ and only electrons entering from the collector region where $x>x_{th}$ contribute to impact ionization. We assume that electrons come from outside the dead space, which cause impact ionization within the dead space, do not cause secondary ionization. Under these conditions, the electron current that can generate electron-hole pairs by impact ionization in the dead space may be assumed to be constant throughout the dead space. We also assume that the dead space effect for electrons generated near the subcollector is negligible. The effect of dead space on M_p may then be modeled by[11]

$$1-\frac{1}{M_p}=\left[1+\int_0^{x_{th}}\alpha_n(x)dx\right]\int_{x_{th}}^{W_C}\alpha_p(x)\times\exp\left\{-\int_{x_{th}}^{x}[\alpha_p(x')-\alpha_n(x')]dx'\right\}dx, \tag{7}$$

where $\alpha_n(x)$ and $\alpha_p(x)$ are given by Eqs. (3) and (4), respectively, and W_C is the width of collector space charge region. Capacitance–voltage measurements demonstrate that depletion region width is in excellent agreement with the collector width.

The built-in voltage was calculated to be 1.365 V for our device. Equation (7) was then solved using numerical integral to find values of $M_p - 1$ for the dead space corrected local model. The solid line in Fig. 1 indicates that the dead space corrected model produces multiplication data which tally with the experimental results when a threshold energy of 2.5 eV is assumed which coincides with the predicted value.[12]

In order to further illustrate the nonlocal effects, the conventional deduction of α_p from M_p for punchthrough condition was carried out in which α_p is assumed to be dependent only on the electric field. In the case of an abrupt n^+p junction at punchthrough, the hole ionization coefficient can be obtained by[13]

$$\alpha_p=\frac{E_m-E_d}{M_nM_p}\frac{dM_p}{dV_{CB}}, \tag{8}$$

where E_m and E_d are the maximum electric field at the n^+p junction and the electric field at the edge of the *n* region, respectively. Since our measurements only yield multiplication factor for pure hole injection, in order to deduce α_p, we assume that the electron multiplication is equal to the hole multiplication. This approximation is justified at low electric fields where both electron and hole multiplication factor are very close to unity. Figure 2 shows the hole ionization coef-

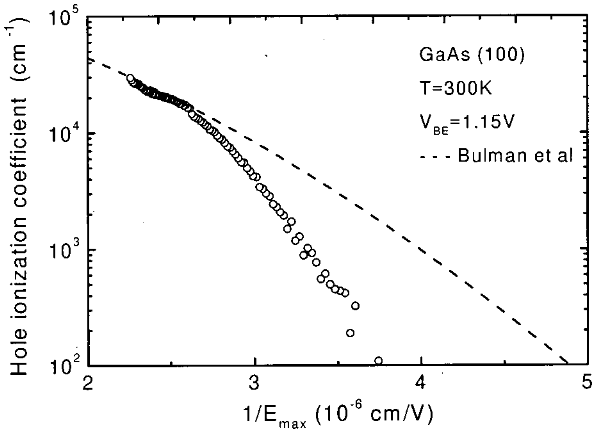

FIG. 2. Hole ionization coefficient in GaAs vs inverse electric field as obtained from collector multiplication factor measurement. Dashed line shows the results based on Ref. 10.

ficient calculated from the multiplication factor measurement. The data of Bulman *et al.* calculated from expression (4) is also shown in Fig. 2. It can be seen that the α_p values agree with the data of Bulman *et al.* at high electric field, but fall significantly below the bulk values at low electric field. The lower the bias, the larger the discrepancy. This demonstrates again that the conventional impact ionization models, based on local electric field, substantially overestimate the hole ionization coefficient in advanced *p-n-p* HBTs where significant dead space effect occurs in the base-collector space charge region.

It should be pointed out that, since the electric field varies fast in the collector, the holes may never reach their steady-state distribution. Therefore, using concept of the electric dependent ionization coefficient outside the dead space in this letter may induce certain inaccuracy in the calculation of impact ionization rate as well as the estimation of the dead space width. The only accurate method to calculate the ionization rate is by Monte Carlo simulations which take the energy distribution of holes in the collector into account.[14,15] However, this is beyond the scope of this letter. The emphasis made in this letter is to reveal the importance of the ''nonlocal'' effect for avalanche multiplication characteristics in AlGaAs/InGaAs *p-n-p* HBTs. It will provide a guideline for the investigations of avalanche multiplication in GaAs-based *p-n-p* HBTs.

In conclusion, measurements of hole avalanche multiplication characteristics and ionization coefficient on AlGaAs/InGaAs *p-n-p* HBTs were performed and the results show that there is a strong dead space effect in *p-n-p* HBTs at low bias voltages. The local electric field model is not accurate for predicting the hole ionization coefficient and hence the nonlocal electric field effect has to be taken into consideration to yield a more accurate prediction of the avalanche multiplication effect in AlGaAs/GaAs *p-n-p* HBTs.

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