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

Bei Ping Yan, Edward S Yang

Department of Electrical & Electronic Engineering
The University of Hong Kong
Pokfulam Road, Hong Kong
Email address: bpyan@eee.hku.hk

Suggested area: Compound Semiconductor Devices and Technology

Abstract--- 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 are presented. A large departure is observed at low electric field when comparison is made between the measured data and those obtained from avalanche photodiode measurements. 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 and the hole ionization coefficient in p-n-p heterojunction bipolar transistors where significant dead space effects occur in the collector space charge region.

1. Introduction

It is well known that the power capability of heterojunction bipolar transistors (HBT's) is limited by impact ionization phenomena 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 HBT's have been reported [1-6]. However, there has been no report in hole-initiated avalanche multiplication and impact ionization coefficient. The p-n-p HBT's 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 HBT's is necessary. In this paper, the avalanche multiplication factor and the hole impact ionization coefficients in AlGaAs/InGaAs p-n-p HBT's are presented. A strong hole dead space effect was observed at low electric fields and a simple correction for the dead space is proposed.

Table 1
The p-n-p HBT epitaxial layer structure

Layer	x	Doping (cm-3)	Thickness (A)
p+-GaAs		5×10^{19}	200
p-GaAs		1×10^{18}	800
p-$Al_xGa_{1-x}As$	0.3-0	5×10^{17}	200
p-$Al_xGa_{1-x}As$	0.3	5×10^{17}	200
p-$Al_xGa_{1-x}As$	0-0.3	5×10^{17}	300
n-$In_xGa_{1-x}As$	0.15-0	5×10^{18}	500
p-$In_xGa_{1-x}As$	0.15	5×10^{16}	100
p-$In_xGa_{1-x}As$	0-0.15	5×10^{16}	150
p-GaAs		5×10^{16}	2500
p-GaAs		3×10^{19}	7000
S. I. Substrate			

2. Device Fabrication and Experiments

The devices used in this work were p-n-p AlGaAs/InGaAs HBT's with the GaAs collector grown by MBE. The device structure is shown in Table 1. In view of 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 ≥90 at a collector current

(0-7803-6304-3/00/$10.00 ©2000 IEEE)

(I_C) of ≥10 mA with an emitter area dimension of 35µm ×45µm. To obtain the multiplication characteristics as a function of the electric field, the technique described by Zanoni [1] and Canali et. al. [3] was used. The HBT was operated in the common base mode and a constant base-emitter bias V_{BE}=1.15V was applied to inject hole into the base to be collected by the collector. Generated electrons are collected at the base contact, which contribute to a negative term ΔI_B in the base current[1][3]:

$$\Delta I_B = I_B(V_{CB}) - I_{BO} \qquad (1)$$

where I_{BO} is the base current without multiplication and it is assumed to be equal to I_B at V_{CB}=0 V. Under 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]:

$$M_p - 1 = \frac{|\Delta I_B|}{I_C - |\Delta I_B|} \qquad (2)$$

3. Theoretical Modeling

From standard ionization theory, the expression for hole multiplication, Mp, is given as:

$$M_p - 1 = \frac{1}{1 - \int_0^{W_C} \alpha_p(x) \exp\left\{-\int_0^{x} [\alpha_p(x') - \alpha_n(x')] dx'\right\}} - 1 \qquad (3)$$

where α_p (x) and α_n(x) are the hole and electron ionization coefficients, respectively, as a function of distance, and W_C is the width of collector space charge region. To model the effects of dead space, 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 [9]

$$\varepsilon_{th} = \int_0^{x_{th}} E(x) dx \qquad (4)$$

where E (x) is the electric field profile in the space charge region of the collector with the maximum electric field occurring at x=0. ε_{th} is the threshold energy for ionization initiated by hole. Solving the integral in (4) yields an expression for x_{th} given by [5]

$$x_{th} = \frac{E_m - \sqrt{E_m^2 - 2\varepsilon_{th}\dfrac{dE}{dx}}}{\dfrac{dE}{dx}} \qquad (5)$$

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 Poisson's equation.

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 sub-collector is negligible. The effect of dead space upon M_p may then be modeled by [10]

$$1 - \frac{1}{M_p} = \left[1 + \int_0^{x_{th}} \alpha_n(x) dx\right] \bullet \int_{x_{th}}^{W_C} \alpha_p(x) \exp\left\{-\int_{x_{th}}^{x} \left[\alpha_p(x') - \alpha_n(x')\right] dx'\right\} dx \qquad (6)$$

To obtain the multiplication factor as a function of bias voltage, Poisson's equation was solved to determine the electric field profile in the collector. The built in voltage was calculated to be 1.365V for our device. Local values for α_n and α_p were calculated using the published data of Bulman et al [9]. Equations (3) and (6) were then solved using numerical integral to find values of M_p-1 for the dead space corrected local model.

4. Results and Discussion

The base-collector diode reverse current I_{CBO} measured at I_E=0 was very low (10pA at V_{CB} =13 V) thus the parasitic contribution of I_{CBO} can be neglected. The self-heating of the device can be also neglected in our measurement. In order to verify that the Early effect does not contribute significantly to the results, M_p-1 was measured also at different emitter current levels from 0.1mA to 0.5mA. The obtained curves of M_p-1 vs V_{CB} were identical. Since in the case of significant carrier modulation of the electric field M_p-1 depends on the emitter current. Our results indicate that this effect can be neglected.

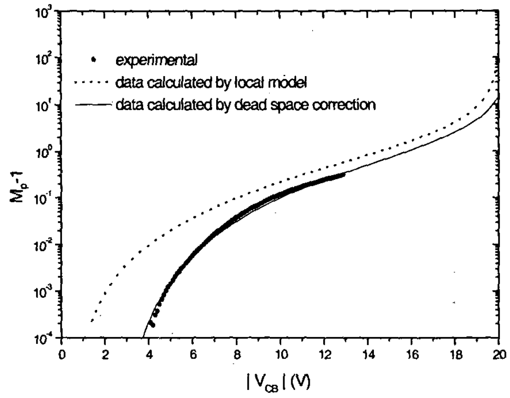

Fig. 1 Measured multiplication factor versus applied voltage in AlGaAs/InGaAs p-n-p HBT. Dotted line shows M_p-1 calculated using the local model. and solid line shows M_p-1 calculated using the dead space corrected model

Fig.1 shows the measured multiplication factor M_p-1 as a function of applied voltage. The dotted line shows the calculated theoretical values of M_p-1 using the local model [8]. The bulk data for electron and hole ionization coefficients published by Bulman et. al. [9] were used in the model. It can be seen that when the impact ionization coefficients are calculated as a function of the local electric field, a large overestimation of the experimental data occurs at low bias voltages. We attribute this to the fact that there is a strong dead space effect in the collector of the p-n-p AlGaAs/GaInAs HBT. The solid line in Fig. 1 shows M_p-1 calculated using the dead space corrected model of (6). It demonstrates that the dead space corrected model produces multiplication data in excellent agreement with the experimental results when a threshold energy of 2.5 eV is assumed which coincides with the predicted value [11].

In order to further illustrate the non-local electric field effects, the conventional deduction of α_p from M_p for punch through and non-punch through conditions was carried out in which α_p is assumed to depend only on the electric field. In the case of an abrupt n^+p junction where the collector is not fully depleted, the hole ionization coefficient can be obtained by [9]

$$\alpha_p = \frac{E_m}{M_n M_p} \bullet \frac{dM_p}{dV_{CB}} \qquad (7)$$

where E_{max} is the maximum electric field at the n^+p junction and V_{CB} is the applied voltage. Since our measurements only yield multiplication factor for pure hole injection only, we approximate the electron multiplication as equal to unity in order to deduce α_p. This approximation is justified at low electric fields where both electron and hole multiplication factor are very close to unity.

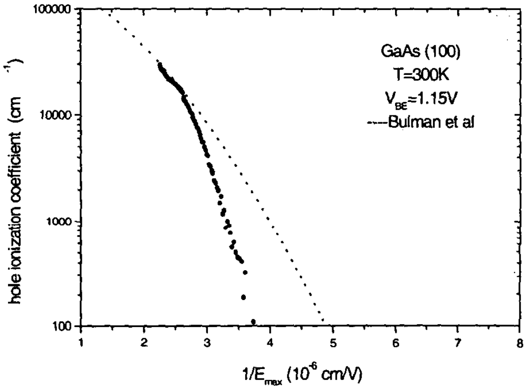

Fig. 2 Hole ionization coefficient in GaAs versus inverse electric field as obtained from collector multiplication factor measurement. Dashed line shows the results based on Reference [9].

Fig. 2 shows the hole ionization coefficient calculated from the multiplication factor measurement. 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 bulk values at low electric fields. The lower the bias, the larger the departure. It demonstrates again that the conventional impact ionization models, based on local electric field, substantially overestimate the hole ionization coefficient in advanced bipolar transistors where significant dead space effects occur in the base-collector space charge region.

4. Conclusion

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

Acknowledgement

This project is supported by the Natural Science foundation of China. The device fabrication was completed in the microelectronics center of Nanyang Technological University, Singapore. Authors would like to be grateful to Mr. Wang Hong and Dr. Ng for their valuable technical assistant and helpful discussions.

References

[1] E. Zanoni, R. Malik, P. Pavan, J. Nagle, A. Paccagnells, and C. Canali, "Negative base current and impact ionization phenomena in AlGaAs/GaAs HBT's," IEEE Electron Device Lett., vol. **13**, pp. 253-255, May 1992.

[2] A. Di Carlo and P. Lugli, "Dead-space effects under near- breakdown conditions in AlGaAs/GaAs HBT's, " IEEE Electron Device Lett., vol. **14**, pp. 103-106, Mar. 1993.

[3] C. Canali, F. Capasso, R. Malik, A.Neviani, P. Pavan, C. Tedesco, and, E. Zanoni , "measurement of the electron ionization coefficients at low electric fields in GaAs- based heterojunction bipolar transistors, " IEEE Electron Device Lett., vol. **15**, pp. 354-356, Sept. 1994.

[4] C. Canali, P. Pavan, A. Di Carlo, P. Lugli, R. Malik, M. Manfredi, L. Vendrame, and E. Zanoni "Experimental and Monte Carlo analysis of impact-ionization in AlGaAs/ GaAs HBT's" IEEE Trans. Electron Devices, vol. ED-**43**, pp. 1769-1777 , Nov. 1996.

[5] R. M. Fliteroft, J. P. R. David, P. A. Houston, C. C. Button, "Avalanche multiplication in GaInP/GaAs single heterojunction bipolar transistors," IEEE Trans. Electron Devices, vol. ED- **45**, pp. 1207-1212, July 1998.

[6] D. Ritter, R. A. Hamm, A. Feygenson, and M. B. Panish, "Anomalous electric field and temperature dependence of collector multiplication in InP/$Ga_{0.47}In_{0.53}As$ heterojunction bipolar transistors," Appl. Phys. Lett., vol. **60**, pp.3150-3152, June 1992.

[7] W. Liu, D. Hill, D. Costa, and J. S. Harris, "High-performance microwave AlGaAs-InGaAs Pnp HBT with high-DC current gain, " IEEE Microwave and Guided Wave Lett., vol. **2**, pp331-333, Aug. 1992.

[8] S. M. Sze, Physics of Semiconductor Devices. New York: Wiley, 1981

[9] G. E. Bulman, V. M. Robbins and G. E. Stillman, "The determination of impact ionization coefficients in (100) gallium arsenide using avalanche noise and photocurrent mutiplication measurements," IEEE Trans. Electron Devices, vol. ED-**32**, pp. 2454-2466, Nov. 1985.

[10] M. H. Woods, W. C. Johnson, and M. A. Lampert, "Use of a Schotty barrier to measure impact ionization coefficients in semiconductors," Solid-State Electron, vol. **16**, pp. 381-394, 1973.

[11] T. P. Pearsall, R. E. Nahory, and J. R. Chelikowsky, Phys. Rev. Lett., vol. **39**, 295, 1977.