ANALYTICAL MODEL WITH EMPIRICAL VERIFICATION FOR HETEROJUNCTION BIPOLAR TRANSISTORS UNDER ILLUMINATION

L. E. M. de Barros Jr., A. Paolella*, P. R. Herczfeld and P .Enquist+
Center for Microwave-Lightwave Engineering
Drexel University, Philadelphia, Pa. 19104
*Army Research Laboratory, Ft. Monmouth - NJ
+Research Triangle Institute, Research Triangle Park - NC

ABSTRACT

A new model for the HBT has been developed which solves for the electrical and photogenerated currents in base, emitter and collector. The model accounts for th e discontinuity in quasi-fermi level by defining an effective carrier interface velocity. Experimental and theorectical curves relating to the device behavior are presented and compared.

INTRODUCTION

The utilization of three-terminal microwave devices for photodetection received increasing attention in the past few years. Combining detection and amplification in the same device results in considerable simplification of the receiver design. The first microwave devices investigated as photodetectors were MESFETs [1,3] and HEMTs [2]. This voltage controlled devices yielded high optical gain, orders of magnitude above p-i-n diodes, but poor frequency response. The main photodetection mechanism in these devices is the photovoltaic effect, identified by Madjar *et al.* [4] , Papaionannou *et al* [5] and Paolella *et al.* [6], in which a primary photocurrent generates a photovoltage that controls the transport of the thermal carriers. The gain is high, but the process is inherently slow. The heterojunction bipolar transistor (HBT) is a current-controlled-current-source, where the photogenerated carriers contribute directly to the total photocurrent. This makes the device intrinsically faster than its unipolar counterparts. Also, recent studiesby Chandrasekhar [7] show that an active base terminal in fact enhances the performance in terms of both gain and frequency response over the floating base configuration, which is the case of the phototransistors. Furthermore HBTs provide for integrability (vertical devices); handle high current densities (10^6 A/cm^2), need low bias voltages and a single power supply, thus reduced power consumption and simpler receiver design.

In this paper we propose a comprehensive, rigorous analytical solution for the device currents, with and without illumination, based on the concept of an effective carrier transport velocity across the heterojunction. The problem is formulated in terms of the continuity equation in the three regions of the device. The suitable boundary conditions are determined and analytical expressions for dark and photocurrents are derived. Two different types of HBTs, self-aligned (SA) and non self-aligned, are analysed and their photoresponse discussed. Finally, frequency response measurement is presented.

THEORECTICAL MODEL

The theoretical problem is formulated in terms of the transport equation for the three regions (emitter, base, collector) of the device:

$$\frac{d^2\delta n_i(x)}{dx^2} - \frac{\delta n_i(x)}{\tau_i} + \rho_i\alpha_i(\lambda)\phi_0 \exp(-\alpha_i(\lambda)x) = 0 \quad (1)$$

where D_i is the diffusion coefficient, δn_i is the excess carrier concentration (electrons or holes) and τ_i is the recombination lifetime, the index *i* refers to each specific region: emitter (e),base (b) and collector (c). The last term of Eq. 1 is a result of the optical generation cariers, assumed to be zero in the large band-gap emitter region, $\alpha_i(l)$ is the absorption coefficient, ϕ_0 is the photon flux and the constant η_i is proportional to the quantum efficiency in region i. The transport equation is valid for neutral regions (zero E-field), shown in Fig. 1. The depletion region boundaries are determined by Poisson's equation.

To account for the effects introduced by the spike in the conduction band at the base-emitter junction, we use the approach of Parikh et al. [8], which defines an effective interface velocity for the carriers. It introduces a correction term to the boundary value:

$$n(x_{pe}) = n(x_{ne}) \exp[(-qV_{bi}+\Delta E_c)/kT] - \frac{F_{EN}}{S_{EN}} \tag{2}$$

where F_{EN} is the electron flux and S_{EN} is the effective velocity across the junction.

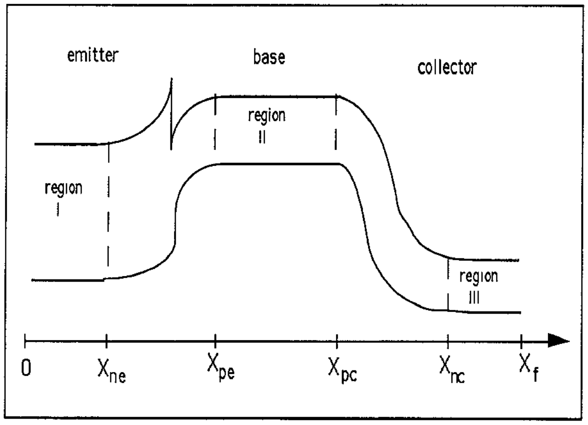

Fig. 1: Typical energy band diagram for a n-p-n single-heterojunction bipolar transistor (S-HBT)

The total current density across a junction, J_k (k=e,c), is comprised of the minority carrier currents (Jn and Jp) at the edges of the depletion region and the generation-recombination current within the space charge region, J_{G-R}:

$$J_k = J_p(x_{ne}) + J_n(x_{pe}) + J_{G-R} \tag{3}$$

Which gives a total collector current density of :

$$J_c = J_{gb} + J_{ncb} + J_{gc} + J_{pbc} + J_{G-R} \tag{4}$$

where the components are described as :

$J_{gb} = -qD_b\alpha_b K_b F_b e^{-\alpha_b x_{pc}}$ = photogenerated current in the base,

$$J_{ncb} = \frac{-qD_b}{L_b \sinh\left(\frac{W_b}{L_b}\right)}\left[T\cosh\left(\frac{W_b}{L_b}\right) + \Gamma\right]$$ = injected electron current from collector to base,

$$J_{gc} = \frac{-qD_c K_c F_3}{L_c \sinh\left(\frac{W_c}{L_c}\right)} e^{-\alpha_c x_{nc}}\left[\cosh\left(\frac{W_c}{L_c}\right) + 1\right]$$

= photocurrent in the collector,

$$J_{pbc} = \frac{qD_c p_{nc}}{L_c \tanh\left(\frac{W_c}{L_c}\right)}$$ = injected hole current from base to collector,

$$J_{G-R} = q\int_{x_{pc}}^{x_{nc}} G(x)dx = q\eta_c\phi_0[1 - \exp(\alpha_c W_{dc})]$$

= photogenerated current in the depletion region.

In the limit when the photon flux approaches zero Jgb ,Jgc and J_{G-R} vanish, and the expressions reduce to the well-known "dark" solution. The photogenerated current in the base-collector space charge region is the dominant component in the photoresponse. The different parameters appearing in these equations are defined in Appendix A.

Since the carrier densities and solution of the Poisson eq. are explicit functions of the bias voltages, by appropriate substitution, the DC characteristics of the device may be obtained. The results and comparisons with experimental data are shown next.

THEORETICAL AND EXPERIMENTAL RESULTS

The device under test, developed at the Research Triangle Institute, comprises of a 5000Å GaAs subcollector doped at 2×10^{18} cm^{-3}, 5000Å GaAs collector doped at 1.5×10^{16} cm^{-3}, 800Å GaAs base doped at 2×10^{19}, 300Å AlGaAs emitter doped at 6×10^{17} cm^{-3} with 27% of Al, 400Å AlGaAs to GaAs graded doped at $2\times10^{18}cm^{-3}$ and 2500Å GaAs cap layer doped at $2\times10^{18}cm^{-3}$. Two types of HBTs were fabricated on the same wafer: self-aligned (SA) and non self-aligned (non-SA) transistors. The non-SA device allows for light absorption in the emitter cap layer. Light from a semiconductor laser at 850nm was injected perpendicularly to the HBT. The DC input and output characteristics were obtained using a semiconductor parameter analyser. In Fig. 2, collector current as a function of base-emitter voltage is shown for both light and "dark" cases. The solid lines represent theoretical results based on the model derived above.

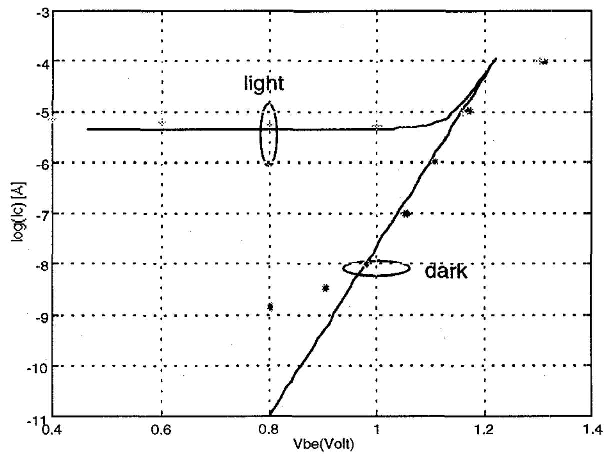

Figure 2 - Gummel plots (Ic vs. Vbe) with and without illumination. Solid lines show theoretical results and dots show experimental values.

Good agreement is noted between experimental and theoretical curves for moderate bias conditions. The discrepancy at higher bias voltages (Vbe>1.2V) is due to high injection, not included in the present model. For lower bias the curves diverge because of the non-ideal characteristics of the junctions. Figures 3 and 4 show output characteristics of the SA and non-SA devices respectively, under light and dark conditions.

In the SA device the photoresponse follows the profile of the dark curves for all bias points. The non-SA device yields negative photoresponse at low biases. The migration of photogenerated holes at the emitter cap layer back to the base region creates a reverse current which decreases the total collector current. As the collector potential is incresed this current becomes negligible with respect to the total collector current.

Although some light get absorbed in the cap layer of the non-SA device a small portion of it still contributes to the generation of carriers in the base-collector junction which results in a larger photocurrent when compared to the SA device. The output characteristics do not suggest a photovoltaic behavior, which is the dominant process in the MESFET and in HEMTs, because there is no shift in turn-on or saturation voltage with illumination [9]. Therefore the photoresponse of HBT is expected to have a larger bandwidth. Experimental results confirm this prediction, as shown in Figure 5.

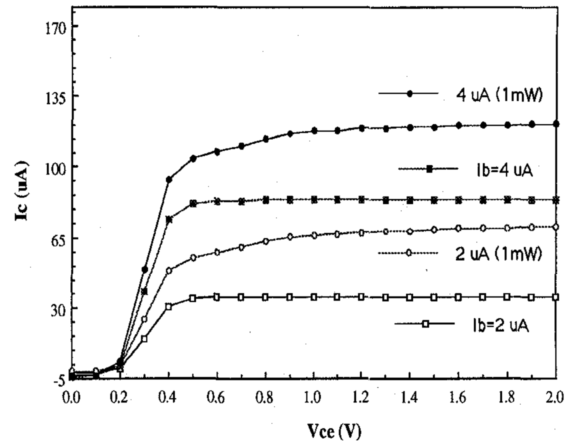

Figure 3 -DCcharacteristics for SA device. Squares show dark response and circles show photoresponse at 1mW optical power.

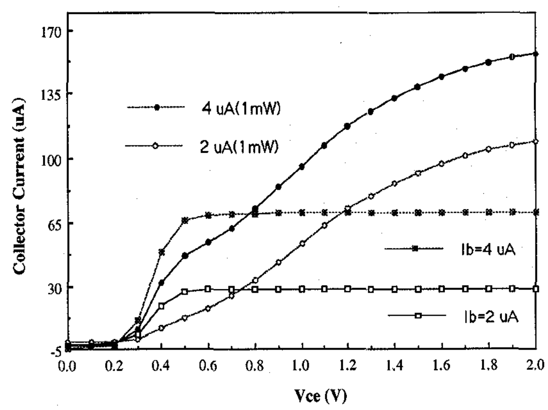

Figure 4 -DCcharacteristics for non- SA device. Squares show dark response and circles show photoresponse at 1mW optical power.

The HBT presents a bandwidth in excess of 10 GHz. The current measurements were limited by the frequency response of the laser. The low gain in the microwave link can be largely improved through better optical coupling.

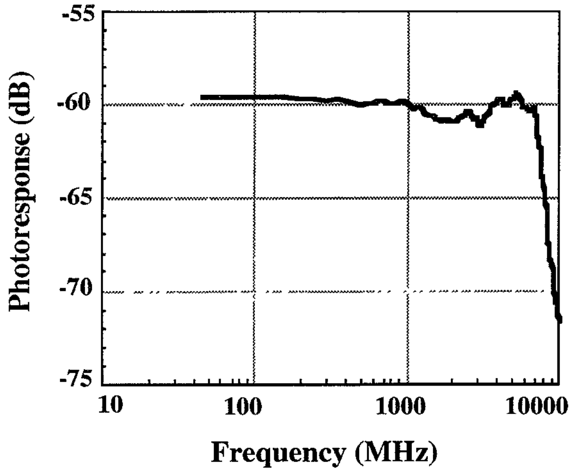

Figure 5. Photoresponse as a function of frequency.

CONCLUSIONS

A new analytical model for heterojunction bipolar transistors under illumination was presented. Good agreement between experiment and theory was observed within the ideal regions of the junctions. Self-aligned devices revealed negative photoresponse at low biases due to reverse hole current from emitter to base. The results suggest no photovoltaic behavior which implies a faster optical response at the expense of gain.

ACKNOWLEDGEMENTS

This work was partially supported by the Brazilian research council (CAPES) through a Ph.D. fellowship program, by Army contract DAALO1-92-K-0230 and NSF-INT-9002289. The development of the HBTs was supported by the Army Research Office.

REFERENCES

[1] A.A.deSalles, "Optical control of GaAs MESFETs", IEEE Trans.on MTT, Vol.MTT-31, No.10,Oct.1983, p.812

[2] R.N.Simons, "Microwave performance of an optically controlled AlGaAs/GaAs high electron mobility transistor and GaAs MESFET", IEEE Trans.on MTT, Vol.MTT-35, No.12, Dec.1987, p.1444

[3] W.D.Edwards, "Two and three terminal GaAs FET optical detectors", IEEE Trans.Elect.Dev.Lett., Vol.EDL-1,p.149, 1980

[4] A.Madjar, A.Paolella, P.Herczfeld, "Analytical model for optically generated currents in GaAs MESFETs", IEEE Trans.on MTT, Vol.40, No.8, Aug.1992, p.1681

[5] G.J.Papaionannou, J.R.Forrest, "On the photoresponse of GaAs MESFET's: back gating and deep traps effect", IEEE Trans.Elect.Dev., Vol.ED-33, No.3, Mar 1986, p.373

[6] A.Paolella, A.Madjar and P.Herczfeld, "Modeling the GaAs MESFET's photoresponse to modulated light at radio and microwave frequencies", IEEE Trans.on MTT, Vol.42, No.7, July 1994, p.1122

[7] S.Chandrasekhar, M.K.Hoppe,A.Dentai, C.H.Joyner, G.J.Qua, "Demostration of enhanced performance of an InP/InGaAs heterojunction phototransistor with a base terminal", IEEE Trans.Elect.Dev., Vol.12, No.10, Oct 1991, p.550

[8] C.D.Parikh, F.A.Lindholm, "A new charge-control model for single- and double-heterojunction bipolar transistors", IEEE Trans.Elect.Dev., Vol.39, No.6, Jun 1992, p.1303

[9] M.A.Romero, L.E.M.de Barros Jr and P.Herczfeld, "Internal photovoltaic effect in microwave devices", Proc. of 1994 IEEE MTT-S, Vol.3, p.1505, San Diego CA.

Appendix A

$L_{b,c} = (D_{b,c}\tau_{b,c})^{1/2}$; $K_{b,c} = L_{b,c}^2/1-(\alpha_{b,c}L_{b,c})^2$

$F_{b,c} = \eta_{b,c}\alpha_{b,c}\phi_0/D_{b,c}$; $\Gamma = n(x_{pe})-K_bF_b\exp(-\alpha_b x_{pe})$

$\Gamma = n(x_{pc})-K_bF_b\exp(-\alpha_b x_{pe})$