MOCVD GaInP heterojunction bipolar transistor current gain stability

V. Cabrera[i], A. Morales[ii], R. Huerta and J. Mimila[1].
Centro de Investigacîon y de Estudios Avanzados, Dpto de Ing. Eléctrica Sec; Electrônica del Estado Sólido, Ap Post. 14-740, México D. F. MEXICO.

The evolution of the GaInP/GaAs hetero-junction bipolar transistor currents during the "burn-in" process is studied. We found that during the burn-in process all the diffusion currents decrease as a function of the stressing time. The simultaneously observed current gain increase is produced by a more important reduction on the hole current injected into the emitter. Such behavior can be explained by an empirical model that considers impurity reactivation at both sides of the emitter-base junction. Thus, to suppress the burn-in process the whole structure device should be hydrogen free.

Keywords: Heterojunction; Transistor; GaInP; Burn-in

1. Introduction

GaInP/GaAs heterojunction bipolar transistors (HBT), because of their high performance, are very promising devices for applications in high frequency and high power areas [1.2]. Its better performance is due mainly to a large valence band discontinuity, that reduces the hole injection into the emitter, a small conduction band discontinuity leading to high emitter electron injection efficiency, and small GaInP surface recombination velocity. Its performances have been enhanced by the use of carbon as the acceptor dopant for the base region, as it shows high solubility, low thermal diffusion and high doping efficiency [3-5]. Although when growing carbon doped GaAs under improper conditions might lead to the formation of carbon dimers [5] which degrade carrier properties. Nevertheless, the development of this transistor has encountered some difficulties because it presents the so-called "burn-in" process [6,7]. This process consists of an increase of the current gain during the initial operation time. Although, to now it has not been satisfactorily explained nor solved. Here we present a detailed study of the behavior of the charge transport properties in the HBT and its evolution as the current gain evolves because of a current stress during the "burn-in" process.

2. Experimental details

The HBT structure used in this study is the now conventional one [1]. It comprises a sequence of five epitaxial layers whose function, thickness and dopant level are as follows; an n-GaAs, 0.1µm thick, silicon doped to 4×10^{18}cm^{-3}, sub-collector, an n-GaAs, 1.0 µm thick, silicon doped to ~10^{16}cm^{-3}, collector, a p-GaAs, 0.1 µm thick, carbon doped to ~5×10^{19}cm^{-3} base, an n-GaInP, 0.4 µm thick, silicon doped to ~2×10^{17} cm^{-3}, emitter and a n-GaAs, 0.01 µm thick, silicon doped to 4×10^{18} cm^{-3}, contacting layer. The sample was grown by low pressure metal-organic chemical vapor deposition on a three inches in diameter semi-insulating 2° off GaAs wafer, using intrinsic doping.

For stressing the transistor we proceeded in the following way. The devices were polarized at constant V_{EB} to obtain current densities where the transistor operation was undisturbed by parallel and series resistances as well as from the recombination currents. Under these operating conditions, base and collector currents were simultaneously measured (Goomel plot). Figure 1 shows the β evolution as a function of the stressing time. The current gain data of Fig. 1 are correctly fitted by the equation

$$\beta(t) = \beta_0 + \Delta\beta(1-\exp(-t/\tau_\beta)) \quad (1)$$

where β_0 is the beta value for the as grown HBT, $\Delta\beta$ is the current gain increase after having stressed the HBT and τ_β is the time constant associated to the physical process involved in the β increase.

Current data for the collector, I_C, and base, I_B, are shown in Figs. 2 and 3. Although there is the current gain increase normally seen during the "burn-in" process, Figs. 2 and 3 show that the base and collector currents decrease as the "burn-in" process goes on. All of them seem to follow an exponential-like behavior, apparently with the same time constant, as data can be correctly fitted by an equation of the type

$$I(t) = I_{0C,B} - \Delta I_{C,B}\,(1-\exp(-t/\tau_{C.B})) \quad (2)$$

where $I_{0C,B}$ are the initial values for those currents, $\Delta I_{C,B}$ are the final corresponding current increments and $\tau_{C,B}$ are the respective time constants, once again of the processes that are responsible, as it might be one independent for each current, for the current decrease.

3. Discussion

For the discussion of these results we will use the simplest Shockley model for the transistor currents

[1] e-mail: jmimila@mail.cinvestav.mx, Tel 5747 3800x6251, Fax:5747 7114
[i] V. Cabrera Arenas.- Becario CONACYT
[ii] A. Morales Hernández .- Becario Conacyt

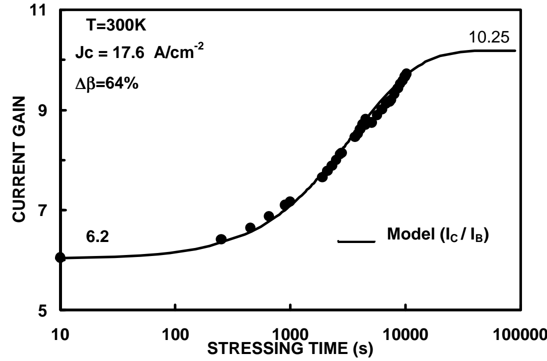

Figure 1. Transistor current gain as function of the operating time during the "burn-in" process.

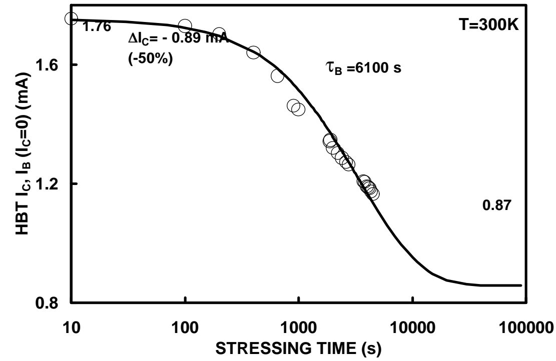

Figure 2. Collector current as a function of the stressing time.

neglecting, for the moment, the recombination at the space charge regions as well as the parallel and series resistances. Under such conditions the current density through the emitter-base junction, J_E is given by the hole current injected into the emitter from the base; J_{BE}, plus the electron current injected into the base from the emitter, J_{EB} part of which should reach the collector junction becoming the collector current; J_C.The simplest equations for J_E and J_C considering a semi-infinite emitter thickness, neglecting the contribution from the reverse polarized base-collector junction and a unitary area, are:

$$J_E = q[(D_E n^2_{iE}/(N_{DE}L_E)) + (D_B n^2_{iB}/(N_{AB}L_B))Coth(l_B/L_B)]exp(qV_{EB}/kT) \quad (3)$$

and

$$J_C = [qD_B n^2_{iB}/(N_{AB}L_B)]Sech(l_B/L_B)]exp(qV_{EB}/kT) \quad (4)$$

where q is the electron charge, D_E and L_E are the hole diffusion coefficient and diffusion length at the emitter, respectively, n_{iE} is the emitter intrinsic carrier concentration, N_{DE} is the emitter donor concentration, D_B and L_B are the electron diffusion coefficient and diffusion length at the base, respectively, n_{iB} is the base intrinsic concentration, N_{AC} is the base doping level, l_B is the neutral base thickness, k is the Boltzmann's constant, T is the operating temperature and V_{EB} is the emitter-base forward bias voltage.

The passivation of donors and acceptors (shallow and deep) by hydrogen in III-V semiconductor materials is a well known phenomenon [8]. In *p*-GaAs:C, infrared absorption analysis has shown that carbon and hydrogen bond together forming complexes that neutralize the electrical activity of the carbon atom involved in the complex [9]. This same technique has been used to demonstrate that under particular doping and growth conditions, C_{As}-H-Ga-C_{As} complexes (noted C_2-H) can be formed in addition to C_{As}-H complexes. It has been found that the electrical and chemical behavior of these C dimers; C_{As}-Ga-C_{As}, as well as C_2-H complexes is different from that of isolated substitutional carbon atoms and from C-H complexes [10]. The carbon reactivation process has recently been characterized [11].

Then, considering the presence of atomic hydrogen in the HBT growing atmosphere, it seems reasonable to assume that some hydrogen dopant passivation can be present in the emitter as well as in the base region, through Si–H and C–H complexes, respectively. Thus, the observed decreases on the injected currents might be at least partly due to an increase on the effective dopant concentration, N_E and N_A at each side of the emitter-base junction through dopant reactivation during the burn-in process.

For a single GaAs:C layer, carbon acceptor reactivation is now fully understood. In this case, assuming that H chemically bonds only to electrically active C and that during the annealing reactivation process, C-H complexes are dissociated releasing H, which in its way out can be re-trapped by active carbon atoms, a carbon reactivation law as a function of the annealing time has been obtained [11]

$$C(t) = CHexp(-t/ô_B) \quad (5)$$

where CH is the initially passivated carbon concentration, $ô_B$ is the reactivation time constant. Then $p_0(t)$ is given by

$$p_0(t) = p_{00} + CH(1-exp(t/ô_B)) \quad (6)$$

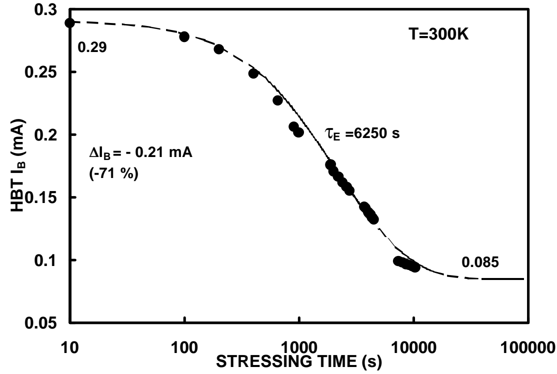

Figure 3. HBT base current as a function of the stressing time.

where p_{00} is the "as grown" hole concentration. Coming back to the HBT, considering that the burn-in process involves some dopant reactivation at each side of the emitter-base junction. We can assume that the reactivation of donors follows the same model exposed above, i.e.

$$n_{0E}(t) = n_{DE}^{+} + SH(1\text{-}\exp(\text{-}t/\hat{o}_E)) \qquad (7)$$

were n_{DE}^{+} is the "as grown" electron concentration at the emitter space charge region edge and SH is the passivated donor concentration at the same place, $\hat{o}_E$ is the corresponding reactivation time constant. Using equations 6 and 7, and the Boltzmann's approximation for the concentration of injected carriers, we obtain that, while the HBT is operating at constant V_{EB}, the hole injected current from the base into the emitter is given by

$$J_{hBE}(V_{EB},t) \;\; \alpha \;\; \frac{qD_E n_{iE}^2 L_E^{-1} \exp(qV_{EB}/kT)}{N_{E0} + SH[1-\exp(-t/\boldsymbol{t}_E)]}$$

$$= \frac{J_{h0}\exp(qV_{EB}/kT)}{1+SH * N_{E0}^{-1}[1-\exp(-t/\boldsymbol{t}_E)]} \qquad (8)$$

$$= \frac{J_h}{1+SH * N_{E0}^{-1}[1-\exp(-t/\boldsymbol{t}_E)]} \qquad (9)$$

where N_{E0} is the "as grown" electron concentration at the emitter.

In the same way the electron injected current from the emitter into the base that reaches the collector is given by

$$J_{nEB}(V_{EB},t) \;\; \alpha \;\; \frac{J_n}{1+CH * N_{A0}^{-1}[1-\exp(-t/\boldsymbol{t}_B)]} \qquad (10)$$

where N_{A0} is the "as grown" hole concentration at the base edge. Using these last equations, the HBT current gain as a function of the stressing time can finally be written as junction edge of the space charge region. Thus, to avoid the burn-in effect hydrogen, co-doping of the HBT structure, should be avoided.

$$\boldsymbol{b} = \frac{J_n[1+\frac{SH}{N_{E0}}(1-\exp(-t/\boldsymbol{t}_E))]}{J_p[1+\frac{CH}{N_{A0}}(1-\exp(-t/\boldsymbol{t}_B))]} = \qquad (11)$$

$$\boldsymbol{b}_0 \frac{1+S(1-\exp(-t/\boldsymbol{t}_E))}{1+C(1-\exp(-t/\boldsymbol{t}_B))}$$

where β_0 is the "as grown" HBT current gain, S= SH/N_{E0}, C= CH/N_{A0}.

The current experimental data on Figs. 2 and 3 have been fitted using equations 9 and 10. The data for $\beta(t)$ have been fitted using equation 11 using the fitting parameters obtained fitting I_B and I_C.

4. Conclusions

In conclusion we have shown that the "burn-in" process observed in GaInP/GaAs hetero-junction bipolar transistors is produced by a reactivation of dopant impurities at both sides of the emitter-base

References

[1] Y. F. Yang, Ch. Hsu, H.J. Ou, T. Ch. Huang and E. S. Yang, IEEE Trans. Electron. Dev. **44**, 2122 (1997)
[2] T. Oka, K. Ouchi, K. Mochizuki, and T. Nakamura, Solid-St Electron., **14**, 1611 (1997)
[3] G. E. Höfler, K. C. Hsieh, Appl. Phys. Lett. **61**, 327 (1992)
[4] N. Watanabe and H. Ito, J. Cryst. Growth **182**, 30 (1997)
[5] M. Konagai, T. Yamada, T. Akatsuka, K. Saito, E. Tokumitsu and, K. Takahashi, J. Cryst. Growth **98**, 167 (1989)
[6] O. Ueda, A. Kawano, T. Takahashi, T. Tomioka, T. Fujii and S. Sasa, Solid-St Electron. **41**, 1605 (1997)
[7] M. Borgarino, R. Plana, S. L. Delage, F. Fantini and J Graffeuil, IEEE Trans. Electron. Dev. **46**, 10 (1997)
[8] J. Chevallier, Defect and Diffusion Forum, 131-132, 9 (1996)
[9] B. Clerjaud, D. Cote, M. Krause and W. Ulrici, Phys. Rev. Lett. **65**, 1800 (1990)
[10] Y. Cheng, M. Stavola, C. R. Abernathy, S. J. Pearton and W. S. Hobson, Phys. Rev. B **49**, 2469 (1994)
[11] J. Mimila-Arroyo and S. W. Bland, Appl. Phys. Lett. **77**, 1164 (2000).