STUDY OF TEMPERATURE DEPENDENCE OF TURN-ON VOLTAGES IN III-V HBTs

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***Abstract*- We report variation of collector and base currents with temperature from 80K-400K on InGaAs/GaAs and AlGaAs/GaAs HBTs. The results obtained showed clearly that, among all the material systems studied, the InP/ $In_{0.53}Ga_{0.47}As$ HBTs have the lowest turn-on voltage (0.1V). This is in good agreement with the theoretical prediction. Although marked differences in the values of turn-on, $V_{turn-on}$ for InGaAs- and GaAs-based HBTs were observed, voltage-thermal feedback coefficients of $V_{turn-on}$ for all devices, irrespective of their material systems, do not differ considerably.**

I. INTRODUCTION

HBTs based on III-V semiconductors are of great importance in high frequency and power applications. Among all the material combinations used for HBTs, the most investigated has been the AlGaAs/GaAs system which can exhibit high current gain, f_T and f_{max}. However, the InP-based lattice matched systems, $InP/In_{0.53}Ga_{0.47}As$ in particular, came into contention not only because of its material compatibility with the optical devices, but also due to its superior transport properties.

Temperature dependence of HBTs is important for understanding the fundamental physical mechanisms governing the behaviour of such devices and for developing accurate models to facilitate their use in various circuit applications.

II. EXPERIMENTAL DETAILS

InP/InGaAs HBTs were fabricated using standard photolithography and mesa etching steps. The epitaxial layers were grown by MOCVD. The layer structures and device details were already reported [1]. Standard wet chemical etching is used to access the base and the collector using $H_2SO_4:H_2O_2:H_2O$ and $H_2SO_4:H_2O_2:H_2O$ chemical combinations respectively. For ohmic contacts Ni/AuGe/Ni/Au Au/Zn/Au were employed for n- and p-type ohmic contacts respectively. Large geometry HBTs (with emitter diameter of 70μm) were fabricated and then DC characteristics of these devices were measured using a Hewlett Packard HP4145B Semiconductor Parameter Analyzer.

III. RESULTS AND DISCUSSIONS

A. Turn-on characteristics of various III-V HBTs

In order to compare the turn-on voltages of the InP/InGaAs HBTs with typical AlGaAs/GaAs and InGaP/GaAs HBTs, we plotted the collector current densities of three devices with similar geometries but different material systems as a function of base/emitter voltage (Gummel plots) where V_{BC} = 0 as shown in Figure 1.

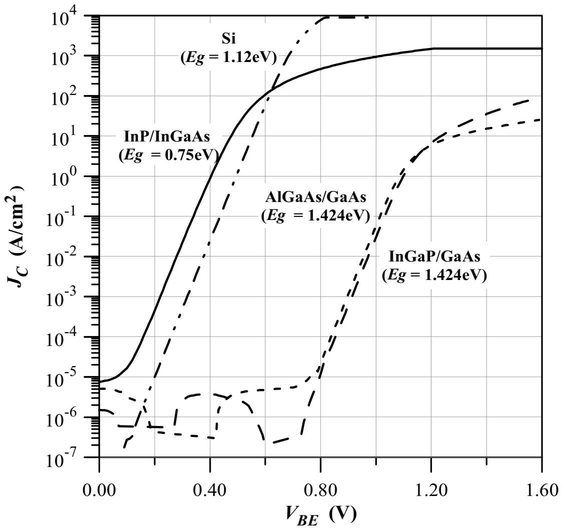

Fig.1. Comparison of collector current density as a function of Base/Emitter voltage for InP/InGaAs, AlGaAs/GaAs, InGaP/GaAs HBTs fabricated with the same processing technology and layout design and for the commercial Si bipolar device.

From Figure 1 one can determine the $\Delta V_{turn-on}$ for all four transistors which are as follows:

For GaAs-and InGaP-HBTs:$\Delta V_{turn-on}$ = 0.67V
For Si BJT and InGaAs-HBTs $\Delta V_{turn-on}$ = 0.1V

It is seen that the InP/InGaAs HBTs exhibit a lower turn-on voltage (0.1V) as compared to GaAs-based HBTs (0.67V). This clearly demonstrates the advantage of using InP/InGaAs HBTs for low power circuit applications, such as in personal and mobile telecommunications. For a given value of tun-on voltage the magnitude of current density for InP/InGaAs HBT is also much greater, added to the advantage of utilizing this type of transistor for low power high performance applications.

It is very useful to develop a simple theoretical model to verify the observed experimental data observed for the turn-on voltages measured on various transistors. One clear observation from figure 1 is that the difference in the turn-on voltages is caused primarily by the difference in the band gap energies of the InGaAs and GaAs base materials. Assuming a unity base transport factor and negligible hole current due to back injection, the collector current is proportional to the minority carrier injected, n_{pb} , at the emitter/base junction:

$$I_C \propto n_{pb} \exp\left(\frac{qV_{be}}{KT}\right) \tag{1}$$

If one measures the turn-on voltage at a fixed collector current for all devices, using Eqn.1, the turn-on voltage difference, ΔV, in InGaAs and GaAs base materials can be found by:

$$\Delta V \approx \frac{KT}{q} \ln\left[\frac{(n_i^2/N_A)_{InGaAs}}{\left(n_i^2/N_A\right)_{GaAs}}\right] \tag{2}$$

Since $(n_i)_{InGaAs}/(n_i)_{GaAs} = 10^5$, the contribution from the difference in the ratios of the base dopants (N_A) can be assumed to be minimal; therefore, ΔV was estimated (from Eqn. 2) to be 0.6V, which is in good agreement with the experimentally observed difference of 0.57V.

B. Temperature dependent of turn-on characteristics

In order to determine temperature dependence of both base and collector currents, Gummel plots at V_{BC} = 0 were measured for an InP/InGaAs HBT in the 80-400K temperature range. The measured collector currents at various temperatures are depicted in Figure 2, from which two observations can be made. First, the slope of the collector current, which determines the ideality factor n_c, changes with temperature. Second, to obtain the same level of collector current, higher voltage is required at a reduced temperature.

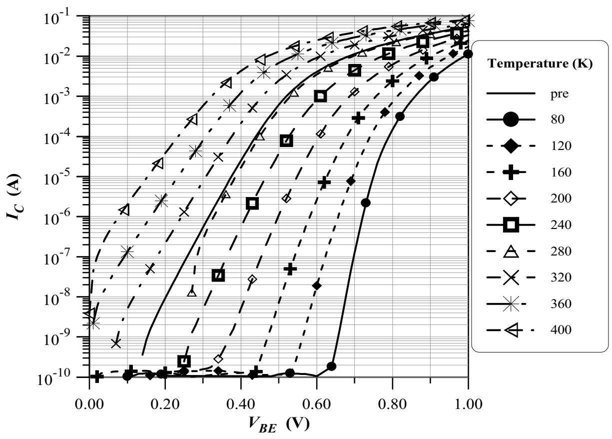

Fig. 2. Temperature dependence of collector current measured at V_{BC} = 0 for an InP/InGaAs HBTs.

The temperature dependence of the collector ideality factor, n_c extracted from the slopes of the collector currents is plotted in Figure 3. It shows that at low temperature, n_c increases with decreasing temperature, but remains almost constant at higher temperature (>200K in this case). The rise of n_c can be attributed to the enhanced tunnelling transport mechanism at low temperature.

It is very useful to derive a simple relationship for the temperature dependence of turn-on characteristics of HBTs and then define theoretically the voltage-thermal feedback coefficients of $V_{turn-on}$. Assuming diffusion based transport in the measurement temperature range, unity base transport factor and negligible hole current due to back injection, at V_{BC} = 0, the collector current density, J_C can be estimated using Boltzman approximation as:

$$J_C \approx CT^4 \exp\left(-\frac{qEg_B}{kT}\right)\exp\left(\frac{qV_{BE}}{kT}\right) \tag{3}$$

where

$$C \approx 3.219\times10^{16}\cdot\left(\frac{m_{nB}^*}{m_0}\right)^{3/2}\left(\frac{m_{pB}^*}{m_0}\right)^{3/2}\frac{\mu_{nB}(cm^2/V-s)}{N_{AB}(cm^{-3})W_B^{'}(\mathring{A})} \tag{4}$$

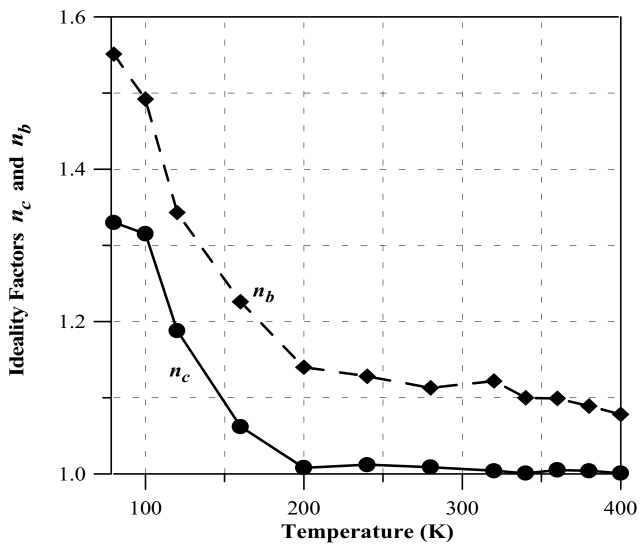

Fig.3. Temperature variation of collector and base current ideality factors, n_c and n_b, respectively, for the transistor in figure 2.

where various parameters have their usual meanings.
The sensitivity of minority carrier mobility on temperature decreases with increasing dopings. It was reported that degenerate semiconductors showed almost temperature independent metal-like mobilities [2, 3]. Thus, since all parameters considered in Eqn. [4] are associated with the highly doped base, C can be treated as a temperature independent, but material and device makeup dependent parameter.

Eqn. (3) can be re-arranged to show transistor $V_{turn\text{-}on}$ at a fixed collector current density J_C, and its temperature dependency $\phi = \partial V_{turn-on} / \partial T$ or voltage-thermal feedback coefficient, as a result, becomes:

$$\phi \approx \frac{k}{q}\left[\ln(J_C) - 4\right] - \frac{4k}{q}\ln(T) - \frac{k}{q}\ln(C) + \frac{\partial Eg_B}{\partial T} \quad (5)$$

These analyses were employed for Sample 941367PKR InP/InGaAs and the results are shown in Figure 4. As it can be seen, the simplified analysis describes well with the temperature behaviour of the transistor turn-on voltages. Its good agreement with the measurements and also with the simulated data obtained from the full simulation verifies the validity of the assumptions made, thus providing an insight to the turn-on characteristics on temperature.

Figure 4 illustrates the B/E turn-on voltages, $V_{turn\text{-}on}$, obtained at a constant collector current of 10μA as a function of substrate temperature. The turn-on voltages were found to reduce monotonically from 0.72V to 0.17V as the temperature was increased from 100K to 400K. The slope of the turn-on voltage decrement with T is defined as the voltage-thermal feedback coefficient, ϕ. For the 941367PKR InP/InGaAs HBT, ϕ was measured approximately -1.88mV/K over 200-400K. Since the turn-on measurements were made at $V_{BC} = 0$ (from Gummel plot) and low I_C of 10μA (corresponding to collector current density of 0.13A/cm^2), power dissipation due to transistor itself was negligible.

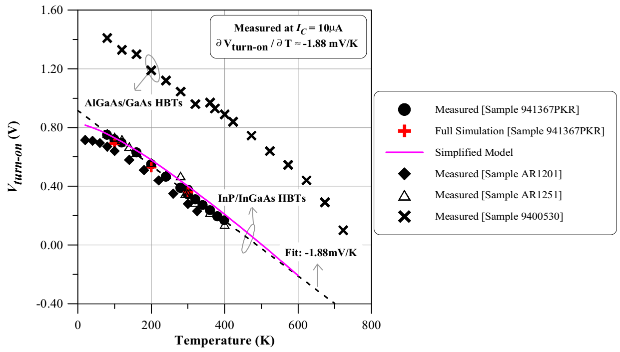

Fig. 4. Measured and calculated temperature dependence of turn-on voltages for two InP/InGaAs HBTs and an AlGaAs/GaAs HBT.

Accordingly, the actual B/E junction temperature was approximated as the external substrate temperature and therefore the voltage-thermal feedback coefficient indicated the amount of the current change with junction temperature in such transistors.

It is also shown in Figure 4, that excellent agreement was found between the measurements and those obtained from the simulation at 100K, 200K and 300K using a modified drift-diffusion model developed in this work [1].

Similar measurements were also made to Sample AR1201, AR1251 InP/InGaAs HBTs and Sample 9400530 AlGaAs/GaAs HBTs and their turn-on voltages were also depicted in Figure 4 for comparison. Although marked differences in the values of $V_{turn\text{-}on}$ for InGaAs- and GaAs-based HBTs were observed due to energy band gap differences, voltage-thermal feedback coefficients of $V_{turn\text{-}on}$ for all devices, irrespective of their material system, do not differ considerably.

The knowledge of the turn-on variation on temperature is very important in the analysis of the transistor thermal behaviour or thermal instability in relation, for example, to device self-heating.

IV. CONCLUSIONS

We have demonstrated that InP/InGaAs HBTs have a lower turn-on voltages than the conventional GaAs-based HBTs. Hence less supply voltage is needed to achieve the same collector current in InP/InGaAs system due to the intrinsic property of the base material.

E/B turn-on voltages of various III-V HBTs were found to increase as the temperature reduced from 400K to 100K. Although marked differences in the values of $V_{turn-on}$ for InGaAs- and GaAs-based HBTs were observed due to energy band gap differences, voltage-thermal feedback coefficients of $V_{turn-on}$ for all devices, irrespective of their material system, do not differ considerably.

Excellent agreement was found between the measurements and those obtained from the simulation.

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