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Characterization and modeling the effect of temperature on power HBTs InGaP/GaAs

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ABSTRACT

The variation and stability of HBT's parameters at different temperatures are important for utilizing these devices in high-power integrated circuits. The temperature dependence of the DC current gain of bipolar transistors, as a key device parameter, has been extensively investigated. A major issue of the power HBT's is that the current gain is decreased with junction temperature due to self-heating effect.Hence, how to stabilize the DC current gain and RF performances is important issue to develop the power HBTs. This work describes the DC and high-frequency temperature dependence of InGaP/GaAs HBT's. The substrate temperature (T) was varied from 25 to 150°C. The static and dynamic performances of the HBT are degraded at high temperature, due to the reduced of carrier mobility with increasing temperature. The current gain (β) decreases at high temperatures; from 140 to 127 at 25 to 150°C, while the decreases in the peak F_t and F_{max} are observed from about 110 GHz to 68 GHz and from 165 GHz to 53 GHz respectively in the temperature range of 25 to 150°C.

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1. INTRODUCTION

Because of their higher electron mobility and less parasitic, compared with Si, Gallium Arsenide (GaAs) [1] devices have been chosen for use in wireless applications for military and space service. In today's growing demand for wireless communications and the explosive growth of high-speed commercial applications, GaAs technology is widely accepted as a main technology for producing high-power, high-frequency, and low-noise products for these applications [2]. The GaAs substrate is a relatively poor thermal conductor, and the internal III–V ternary compound materials of the HBT structure possess thermal conductivities an order of magnitude lower than that for GaAs [3]. These factors lead to aggravated thermal issues that may not only degrade the device performance but also impact the device reliability. Hetero-junction bipolar transistors (HBTs) have a high potential for high-power, high efficiency microwave amplifier applications [4]. Current trends in GaAs HBT for power amplifier application are fabrication of devices with a smaller size, higher power density, and behavior less affected by thermal limitation. GaAs HBTs have higher speed and power than those of Si bipolar junction transistors (BJTs). In particular, the advantages of III–V materials enable GaAs HBTs to have a higher product of frequency and breakdown voltage even when compared to the SiGe HBTs [5]. Although the GaAs HBT technology is becoming mature, the model development lags behind. However, these devices are prone to suffer from self-heating effects, such as a decrease in dc current gain ($\beta = I_C/I_B$) with increase in V_{CE} for individual devices.

The use of InGaP as the wide bandgap emitter plus the technological and electrical advantages of the InGaP/GaAs heterostructure have pushed InGaP/GaAs heterojunction bipolar transistors (HBT) to reach considerable interest for a large range of applications from ultra-high speed logic to microwave power devices [6]. The power amplifiers using GaInP/GaAs HBT's have showed excellent performance. Working at high power densities results in heat generation that limits transistor performance so studying the variation and stability of HBT parameters at different temperatures is important for using these devices in high-level integrated circuits power. For these high-power applications, the temperature rise at any point within the junction of the power HBT can be attributed to two effects: 1) the self-heating effect caused by heat being dissipated at the point of measurement, and 2) the mutual heating effect caused by heat being dissipated by adjacent junctions. Self-heating within HBTs can bring about unusual high-power behaviors, such as thermal runaway and current-gain collapse [7]. These phenomena can seriously worsen the thermal stability of the devices, and eventually lead to catastrophic damage.

In power GaAs HBT, The temperature dependence of the DC current gain of bipolar transistors as a key device parameter has been extensively investigated [8]. A major issue of the power HBT's is that the current gain is decreased with junction temperature due to self-heating effect giving rise to a negative differential resistance. Several researches have proposed specific configurations to enhance the thermal stability of GaAs-based HBTs [9, 10]. This work describes three issues about temperature dependence: Gummel plot, current gain and RF performances of InGaP/GaAs HBT's. New data are presented that describe in detail the variation of the static characteristics (Gummel diagrams, I_C (V_{CE}), current gain (β)) and dynamics characteristics (F_t, F_{max}) at high temperature.

2. RESEARCH METHOD

In our studies we are interested in the simulation of HBT in InGaP / GaAs technology of UMS HB20M industry in order to have the effect of temperature on the electrical and frequency characteristics of these transistors. The properties of the InGaP/GaAs semiconductor layers with their thicknesses and their doping concentrations are presented in Table 1. Power components of this type consist of this same structure repeated several times and whose electrodes are connected. The simplified band alignments of an InGaP/GaAs heterostructures in Figure 1 suggest that the larger valence band discontinuity in InGaP/GaAs reduces the reverse injection of holes into emitter more efficiently, thereby further increasing the current gain and leaving a larger design space to optimize doping levels.

Table 1. The properties of the InGaP/GaAs Semiconductor Layer

Layers	Thickness (nm)	Doping level (cm-3)
Cap GaAs (n^+)	100	$N_D = 1.10^{19}$
Cap GaAs (n)	120	$N_D = 7.10^{17}$
Emitter InGaP (n)	50	$N_D = 3.10^{17}$
Base GaAs (p^+)	90	$N_A = 4.5.10^{19}$
Collector GaAs (n^-)	400	$N_D = 7.5.10^{16}$
Sub-Collector GaAs (n^+)	1000	$N_D = 5.10^{18}$
Substrat GaAs	740	$N_D = 1.10^{12}$

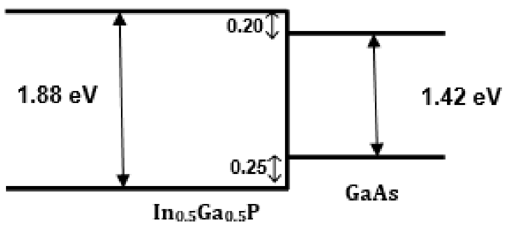


Figure 1. Block band diagram InGaP/GaAs [6]

The HBT InGaP/GaAs is a dominated material system for high speed semiconductor devices due to the high etching selectively between InGaP and GaAs material layers at x = 0.51 [11]. This mole fraction is considered in the present analysis with a high ratio of valence band discontinuity ($\Delta E_V \approx 0.40$ eV) at the heterojunction. The discontinuity of the conduction band at the emitter/base hetero-interface is very low, of the order of 0.03 eV, which can allow the effect of thermo-ionic emission to be neglected and resolved using the drift-diffusion model, if simulations are to be simplified [12].

A two-dimensional (2D) semiconductor simulation package SILVACO was used to analyze the energy band, distributions of electrons and holes and DC performances of the devices. The two-dimensional analysis takes into account the Poisson equation, Continuity equation of electrons and holes, Shockley-Read-Hall (SRH) recombination, Auger recombination, and Boltzmann statistics, simultaneously.

The first part of the simulation consists in defining the materials and the dimensions of the different layers of the structure. Then, these layers will be divided into several regions before moving on to the definition of the mesh. The model equations account for valence band discontinuity, heavy doping effects and high collector current effects. More details of the physical models can be found in [13].The variation in base current (I_B) and collector current (I_C) with base-emitter voltage (V_{BE}) is given by:

$$I_B = \frac{qA_E D_{pE}}{W_E} \frac{n_{iE}^2}{N_{DE}} \exp\left(\frac{qV_{BE}}{kT}\right) \quad (1)$$

$$I_C = \frac{qA_E D_{nB}}{W_B} \frac{n_{iB}^2}{N_{AB}} \exp\left(\frac{qV_{BE}}{kT}\right) \quad (2)$$

where q is the electronic charge, A_E is the emitter area, n_{iE} (n_{iB}) is the intrinsic carrier concentration of the emitter (base), k is the Boltzmann constant and T is the temperature, in Kelvin.

It is necessary to mesh the different areas where a compromise must be found between a mesh fines enough not to lose precision calculations. A non-uniform mesh according to the desired precision is then chosen. Figure 2 shows the mesh of different areas. For the InGaP/GaAs structure, the difference in electronic affinities between these two materials introduces discontinuities of bands. Thus, the discontinuity observed in valence bands constitutes a barrier to the passage of holes from the base to the emitter, which increases the injection efficiency.In thermodynamic equilibrium, the free carriers do not move between the junctions, and therefore there is no zone of accumulation of holes in the base near the junction as shown in Figure 3.

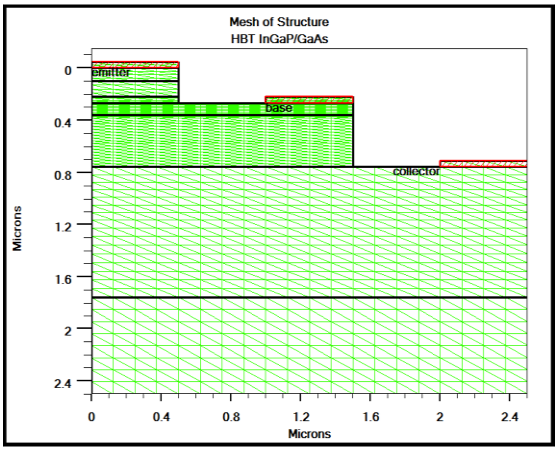


Figure 2. Mesh structure for an InGaP/GaAs HBT

The advantage of the HBT results directly from the valence-band discontinuity ΔE_V at the heterointerface, wich comes from the proper choice of the heterojunction system with emitter bandgap E_{gE}greater than base bandgapE_{gB}. ΔE_V increases the valence-band barrier height in the emitter-base heterojunction and thus reduces the back injection of the holes from the base to emitter. The heavily base doping is allowed while maintaining a large current gain, and maintains the lower base series resistance. The very thin base reduces the base transit time and improves the high frequency response of the HBT [14].

The GaInP/GaAs heterojunction favors the passage of electrons from the emitter to the base and tends to block the passage of holes to the base. Indeed, the potential barrier seen by electrons is weak compared to that seen by holes (see Figure 4). We can see that the holes density in the emitter is much lower than that of the electrons in the base, even if the holes density in the base is much higher than that of the emitter. This is due to the higher potential barrier of the valence band seen through the holes at the emitter-base heterojunction.

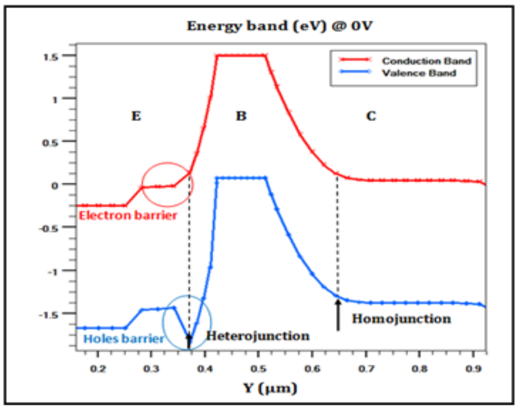


Figure 3. Energy bands of the InGaP/GaAs HBT at thermodynamic equilibrium (Along the center line going from the emitter to the collector contact)

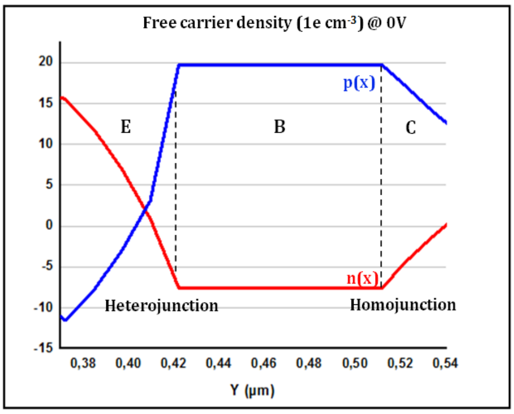
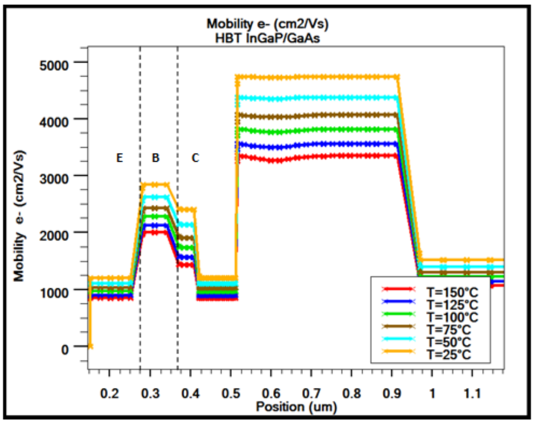


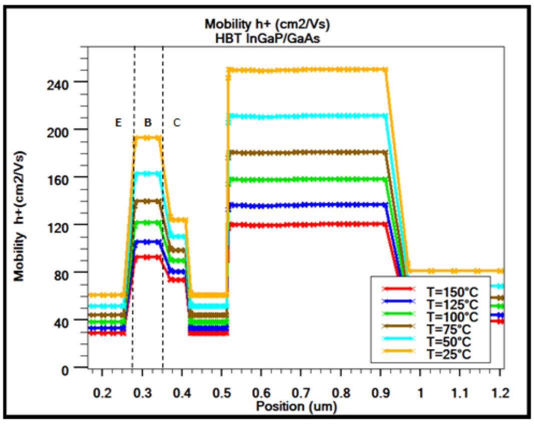
Figure 4. Results of free carrier densities n(x) and p(x) of the InGaP/GaAs HBT at thermodynamic equilibrium

With significant mobility, these are interesting elements for power and microelectronic applications [15]. The carrier mobility in the semiconductor determines the operating frequencies and the gain of the device. In fact, mobility is related to temperature according to the empirical relationships demonstrated in the literature in several forms according to the material systems concerned [16]. The increase in temperature reduces the carrier mobility and change the bandgap of making semiconductors. With the change in temperature, the mobility changes significantly, considering the degradation of electron mobility in GaAs with temperature as $T^{-2/3}$ [17].

Figure 5(a) and 5(b) shows, respectively, the distribution of mobility of electrons and holes for different temperatures in HBT InGaP. As expected, these figures show the sharp decrease in the mobility of holes and electrons with the temperature in the neutral emitter, neutral base, and neutral collector and in the region of base-collector space charge. Our studies have shown a reduction of the electron mobility of about 45% when the temperature increases from 25 °C to 150 °C.



(a)



(b)

Figure 5. Evolution of carrier mobility in HBT InGaP for T= 25-150°C.
(a) Electron mobility, (b) Holes mobility

However, to study the static behavior of the transistor as a function of temperature, it is necessary to reason at constant current by looking at the evolution of the gain in static current. Indeed, due to the temperature dependence of the base and collector currents that we have just observed, the static current gain (β) also costs temperature.

The performance advantage of HBTs is primarily derived from the use of wide bandgap emitters. If the emitter bandgap is larger than that in the base for an n-p-n HBT, the bandgap discontinuity sets up a barrier to the forward injection of electrons [18], resulting in a higher turn-on voltage for the emitter-base diode. More importantly, however, this discontinuity provides a barrier to the reverse injection of holes from the base into the emitter, increasing injection efficiency γ significantly, as modeled by Equation (3):

$$\beta \propto \gamma \propto \frac{N_E}{N_B} exp\left(\frac{\Delta E_g}{kT}\right) \quad (3)$$

The exponential term releases the N_E>N_B design contraint that limits homojunction device performance [19], and provides solutions to deal with the trade-off between current gain and power performance. While a reasonable current gain is still achievable, higher base doping level N_B and shorter base width W_B are allowable, which will improve F_t and F_{max} through reducing the base charging time τ_B and base resistance R_B, as suggested in equation (4). In addition, lower emitter doping level N_E will also lower emitter-base capacitance and related emitter junction charging time τ_E, further improving the power performance.

$$F_t \approx \frac{1}{2\pi(\tau_E+\tau_C+\tau_B)}, \ \tau_B = \frac{W_B^2}{2D_n}, \ F_{max} = \sqrt{\frac{F_t}{8\pi C_{BC} R_B}} \quad (4)$$

3. RESULTS AND DISCUSSION

3.1. DC characteristics of InGaP/GaAs HBTs

In the field of power electronics, temperature variation has a very important impact and can considerably affect the electrical characteristics of components and electronic circuits, which means that temperature is an essential parameter in semiconductor equations. As part of our measurements, the operating temperature range is 25 °C to 150 °C, this range is however sufficient to observe the influence of temperature on the operation of our HBTs. In the first step, we have simulated the Gummel characteristics of the InGaP transistor, which show the evolution of the logarithm of the base and collector currents as a function of the emitter-base voltage V_{BE} at V_{BC} = 0 V.

Figure 6 and Figure 7 plot the evolution of collector and base currents as a function of V_{BE} for different temperatures. Thus, we observe for these two currents an increase in their value when the temperature increases, which is consistent with the previous expressions (equations 1.2). This can be attributed to increased carrier mobility at low temperatures and increased low temperature bandgap.

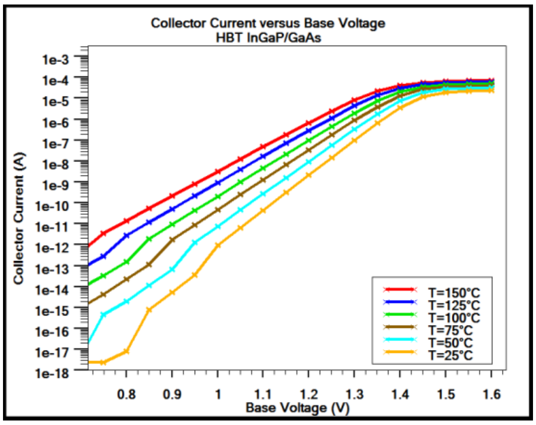


Figure 6. Collector current as a function of base-emitter voltage at various temperatures (25-150°C) for InGaP/GaAs HBT

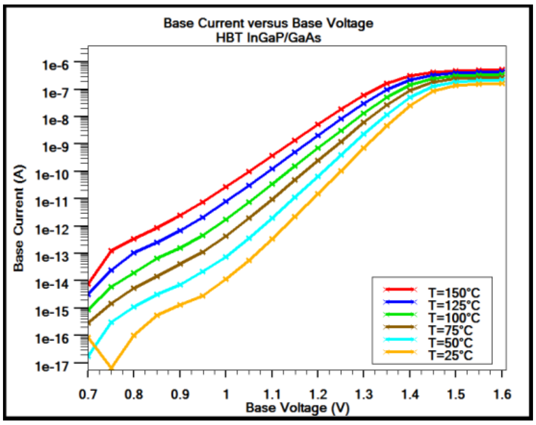


Figure 7. Base current as a function of base-emitter voltage at various temperatures (25-150°C) for InGaP/GaAs HBT

The DC base-emitter voltage (V_{BE}) is a good indicator of the junction temperature (T_j) of the HBTs. The turn-on voltage (V_{BE}) decrease with increase in temperature, this decrease is most likely due to the rise in intrinsic carrier concentration with temperature [20]. The temperature dependence of saturation currents in HBT is usually complicated due to the fact that both base transport and B-E barrier transport limitations may be important; it can be seen from the results that the saturation currents have changed with temperature.

The I_C-V_{CE} output characteristics for different constant values of I_B and for three temperatures varying between T = 25, 75, 150 °C is shown in Figure 8. We notice that the output characteristics (I_C, V_{CE}) change when the temperature increases. The differences are accentuated for the strong base currents. Our results are very similar with that demonstrated in [10] with the same type of HBT (InGaP/GaAs) but with different dimensions.

In this study, the current gain of GaInP/GaAs HBT's operated at substrate temperatures between 25 and 150°C was measured. The base-collector bias was maintained at 0V such that the junction temperature can be approximated as the substrate temperature. As shown in Figure 9, current gain decreased with increasing temperature. A 42% drop in β is observed between 25 °C and 150°C. The drop in β in this temperature range has been well studied in [9].The current gain of the HBT decreases with increasing temperature in the entire current range it can be observed in Figure 9, that the maximum gain varies from 127 at 150 °C to more than 140 at 25°C. In particular, most studies have been focused on the current gain of InGaP/GaAs HBT that prove that the lower β value in HBTs operating at high temperatures [20, 21]. This is exactly the result that we found on the gain.

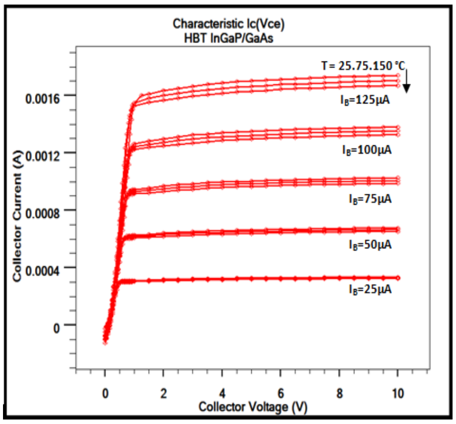


Figure 8. The output characteristics (I_C, V_{CE}) for three temperatures T= 25.75.150 °C

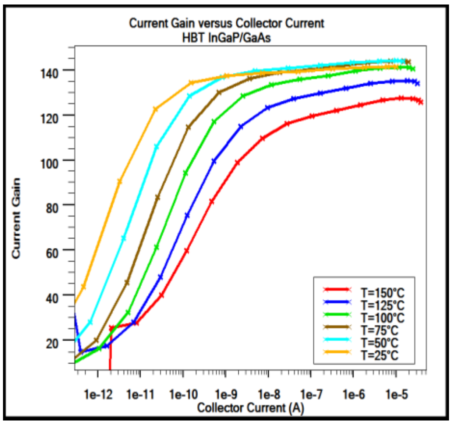


Figure 9. Evolution of current Gain (β) versus collector current (Ic) for InGaP HBT forT= 25-150°C

The main reason for the current gain degradation in HBT is the high offset of the valence band (ΔE_V) at the emitter-base heterojunction (InGaP/GaAs). It is based on the assumption that the diffusion dominates the current of the holes injected from the base to the emitter. If, however, the mechanism of the hole current is controlled by thermionic emission rather than by diffusion, the temperature dependence of the current gain will be significantly changed**.** Current gain for $Ga_{0.51}In_{0.49}P$/GaAs HBTs at 300K (≈ 25°C) comes out to be 140, which shows a close proximity with the experimental current gain value of 132[22]. If we continue to raise the temperature up to 150°C, we obtain the same results for the current gain (β) in the range 25°C-150°C. The peak of β as a function of temperature is shown in Figure 10, we observe that the peak increases from about 38 at 425°C (≈ 700 K) to 140 at 25°C (≈ 300 K).

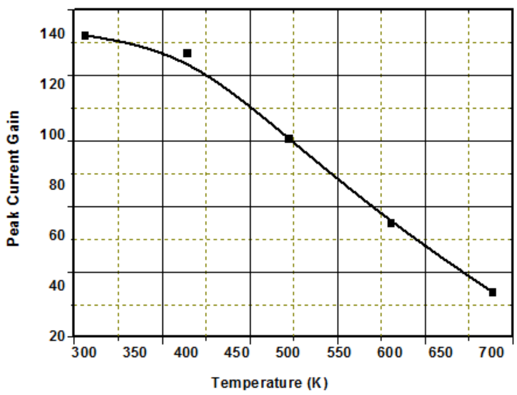


Figure 10. Peak β as a function of temperature for InGaP HBT for T= 300-700K

3.2. RF characteristics of InGaP/GaAs HBTs

The preceding paragraphs have focused on the study of the influence of temperature on the static characteristics of the HBT; we note a degradation of its various figures of merit when the temperature increases. This degradation has the effect of limiting the dynamic performance of transistors through transit times [23]. The cut-off frequencies will be studied under the effect of temperature. Thus, the possible degradation of the transition frequency F_t under the effect of the temperature can be explained on the one hand by the increase of the various transit times because of the decrease of the mobility of the carriers thus of their speeds through the transistor [24]. On the other hand, the possible increase of the parasitic elements $R_B \times C_{BC}$ leads to a fall of F_t.

Figure 11 and Figure 12 shows respectively the cut-off frequencies F_t and F_{max} as a function of the measurement temperature. We observe both degradation for these two frequencies under the effect of temperature because the low field mobility and diffusion constant are functions of temperature. Thus, the respective F_t and F_{max} falls are strictly explained by the quadratic dependence between these frequencies (equation 4) if we assume that the temperature evolution of $R_B \times C_{BC}$is negligible [25]. The decrease in F_{max} is smaller compared to that observed for F_t. Indeed, the maximum frequency decreases by 112GHz when one goes from 25°C to 150°C, i.e. a relative decrease of 32%.However, F_t decreases with temperature, and these function versus temperature are not linear. Besides, the minimum/maximum values of them are not located at the same temperature.

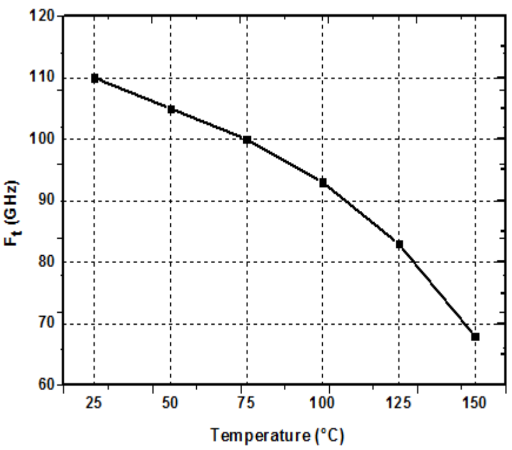


Figure 11. Evolution of F_t as a function of temperature for InGaP HBT T= 25-150°C

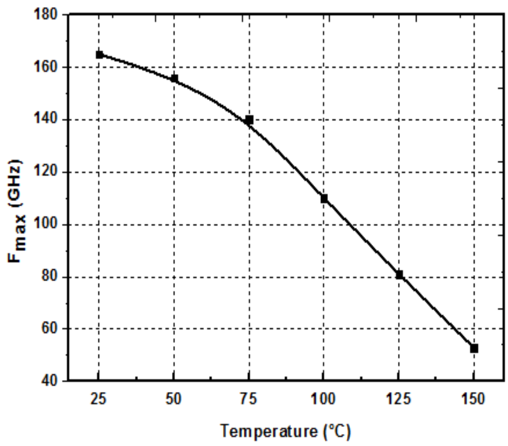


Figure 12. Evolution of F_{max} as a function of temperature for InGaP HBT T= 25-150°C

4. CONCLUSION

The static and frequency characterizations performed on our HBTs have shown satisfactory merit factors, i.e. a static current gain of nearly 140 and transition (F_t) and oscillation (F_{max}) frequencies of 110 and 165 respectively. The DC and RF performance of InGaP/GaAs are presented three issues about temperature dependence are studied: Gummel plot, current gain and RF performances. The increase of the mobility of the free carriers with temperature leads to the increase of the different currents of HBTs. The pronounced degradation of the base current also causes a decrease in the static current gain with temperature. However, this drop is very moderate and does not prevent satisfactory gain values at high temperatures. We also observed a decrease on the different transition frequencies of HBTs.

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