Comparative evolutions of short gate InGaAs channel HEMTs on InP and GaAs at cryogenic temperatures

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Abstract

The properties and performances from 300K down to 50K of short gate InGaAs channel HEMTs on GaAs and InP substrates are compared. Original data are presented particularly how depend on temperature the capacitances, the transconductance and the cut-off frequencies. The results are interpreted in term of enhanced short channel and trapping effects due to high electric fields. The temperature evolutions of the device intrinsic parameters are compared versus technology, gatelength and biases.

Introduction

We give emphasis here on the properties and performances evolutions versus temperature from 300 K down to 50K of short gatelengths pseudomorphic(PM) $In_{0.2}Ga_{0.8}As$ channel HEMTs on GaAs and lattice-matched(LM) $In_{0.53}Ga_{0.47}As$ channel HEMTs on InP. We point out the new insight of low temperature investigations, particularly at high frequencies in the physics of small devices under high electric fields. They give a useful approach of the evolution of physical processes in the investigation of small devices, which complement studies versus gatelength. We discuss how the short channel effects and carrier trapping effects in particular may contribute to these variations depending on technology, gatelength, temperature and biases. It must be underlined that the studied devices are well representative of the state of the art as shown by their 300K performances. Therefore the results give a good account of the extrinsic and intrinsic electric parameter evolutions of the respective performance improvements brought respectively by gatelength and temperature reduction for both technologies.

Experimental conditions

The GaAs PM-HEMT is presented in Fig. 1a and consists of a 12 nm $In_{0.2}Ga_{0.8}As$ channel grown on a 300 nm GaAs buffer. The channel is followed by a 3 nm $Al_{0.22}Ga_{0.78}As$ spacer, a $4*10^{12}$ cm^{-2} δ-doping, a 12 nm $1.5*10^{18}$ cm^{-3} doped $Al_{0.22}Ga_{0.78}As$ layer for the Schottky contact and a 80 nm Si-doped ($3.5*10^{18}$ cm^{-3}) cap layer.
The InP-HEMT in Fig. 1b consists of a 60 nm $In_{0.53}Ga_{0.47}As$ channel grown on a 150 nm $In_{0.52}Al_{0.48}As$ buffer on InP. The channel is followed by a 3.5 nm $In_{0.52}Al_{0.48}As$ spacer, a 11 nm Si doped layer ($6*10^{18}$ cm^{-3}), a 22 nm undoped $In_{0.52}Al_{0.48}As$ for the Schottky contact and a 10 nm undoped cap layer.

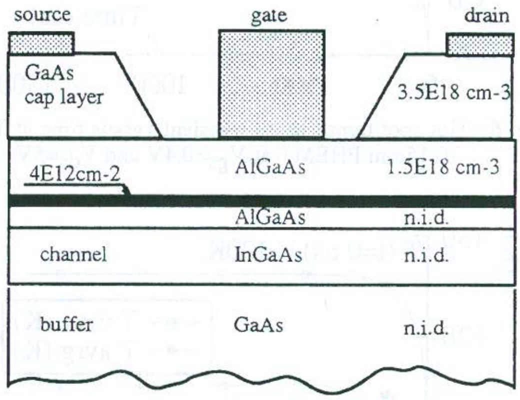

Fig. 1a : GaAs PM-HEMT

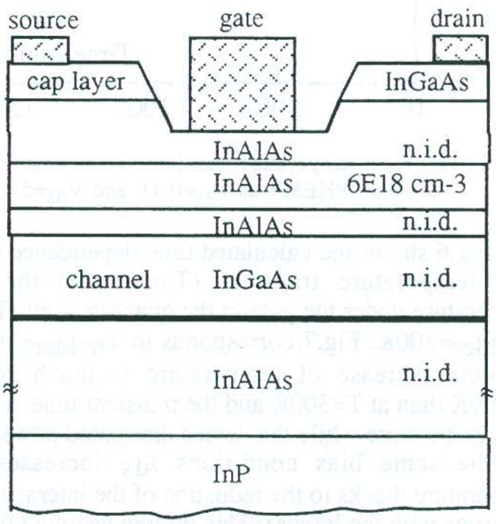

Fig. 1b : InP LM-HEMT

A chip with many transistors is placed in a cryogenic station [2] with microwave coplanar probes and optical access. In situ HF calibration and temperature control of microwave parts allow accurate S parameter measurements up to 40 GHz. They give smooth S parameter variations with no loops at all frequencies and temperatures. These features allow a direct determination of the device current and power gains and an extraction of equivalent circuit parameters versus temperature.

Results

DC characteristics.

The Fig. 2a and Fig. 2b present the Ids versus Vds characteristics at 300 K and 50 K respectively for a

0.1μm gatelength GaAs PM-HEMT and a 0.2μm InP LM-HEMT respectively, under light illumination which gives minimum observable trapping effects.

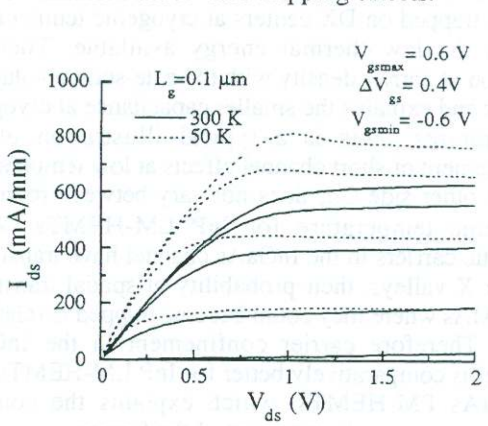

Fig. 2a : I-V characteristics at 300 K and 50 K of a 0.1 μm ultrashort gatelength GaAsPM-HEMT

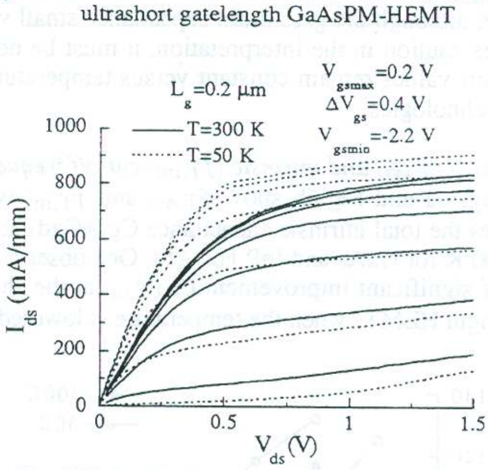

Fig. 2b : I-V characteristics at 300 K and 50 K for a 0.2 μm ultrashort gatelength InP LM-HEMT

The reduction of temperature from 300 K to 50 K induces :

- a smaller drain-source current I_{ds} when the gate-source voltage V_{gs} is near the threshold Vth,
- a larger I_{ds} for an open channel at higher V_{gs}
- an increase of the slope in the ohmic state.

The level of drain current in the InP LM-HEMT is in the same range as reported in other works for single heterojunction devices. However it must be pointed out that this current level is relatively low compared to what is predicted from a simulation of the carrier distribution in the different layers of the structure, owing to the material physical parameters the high doping level, the InGaAs transport properties. This observation is confirmed by capacitance and intrinsic cut-off frequencies as mentioned later. Therefore it is probable that an important part of the carriers are trapped permanently in InP HEMT structures at 300K. No strong detrapping is observed within the time scale of measurements (up to a few minutes for HF measurments) whatever are the conditions of temperature, electric biases or optical excitation. Besides slow capture/excitation characteristic times appear to be associated to these centers, an indication of their possible occurence at surface/interfaces.

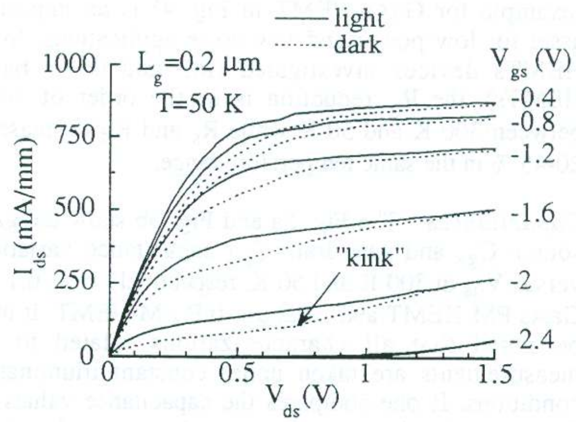

Fig. 3 : I-V characteristics of a 0.2 μm gatelength InP LM-HEMT under ligth and in the dark at 50K

The Fig. 3 illustrates the IV curves of the same 0.2 μm InP HEMT at cryogenic temperature (50 K) in two light conditions (device illuminated and in the dark). One observes a slightly smaller current in the dark while there is practically no difference at room temperature. At cryogenic temperatures and in the dark, trapped electrons do not have the thermal energy to be released and to contribute to the total current. As a comparison in GaAs PM-HEMTs, the important DX center densities present in the AlGaAs layer (confirmed by DLTS measurements) explain the collapse in the IV curve usually present at low temperature in the dark [3]. No such DX-like centers have been observed in InAlAs layers. A small kink effect is also usually observed in InP-HEMTs even in the illuminated devices (see Fig. 2b and Fig. 3); it gives rise to an increase of the output conductance above V_{ds}≈0.7V. A study of the device dc characteristics using different sweep procedures (at constant V_{gs} and constant V_{ds}), and pulse characteristics [4] shows that trapping centers responsible from the kink effect have fast responses and are located in the InAlAs layers. This conductance is usually higher in InP-HEMTs compared to GaAs-HEMTs and limit the gain voltage.

Microwave performances.

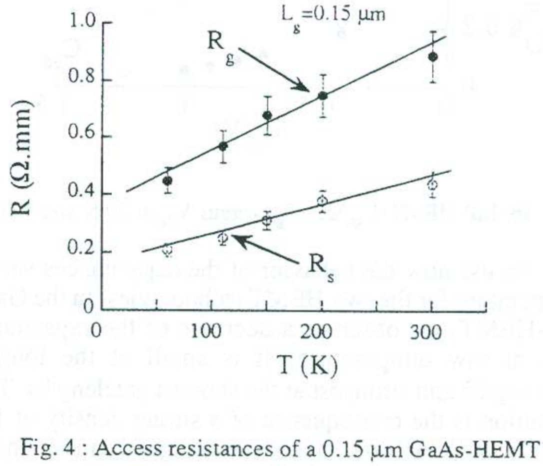

Fig. 4 : Access resistances of a 0.15 μm GaAs-HEMT

Access resistances : The reduction of the parasitic access resistances R_g (gate resistance), R_s (source resistance) and R_d (drain resistance) when the transistors are cooled (example for GaAs-HEMT in Fig. 4) is an important asset for low power and low noise applications. In all HEMTs devices investigated (InP and GaAs based HEMTs), the R_g reduction is of the order of 50 % between 300 K and 50 K while R_s and R_d decrease by 20-45 % in the same temperature range.

Capacitances : The Fig. 5a and Fig. 5b show the gate-source C_{gs} and gate-drain C_{gd} capacitance variations versus V_{ds} at 300 K and 50 K, respectively for a 0.1 µm GaAs PM-HEMT and a 0.2 µm InP LM-HEMT. It must be noted that all characterizations related to HF measurements are taken under constant illumination conditions. If one compares the capacitance values for the two technologies at constant device gatelength, it appears that the InP LM-HEMTs have significantly lower capacitances. As for the IV curves, this result is explained by a relatively low carrier density in the InGaAs channel despite the high doping level in the InAlAs layer.

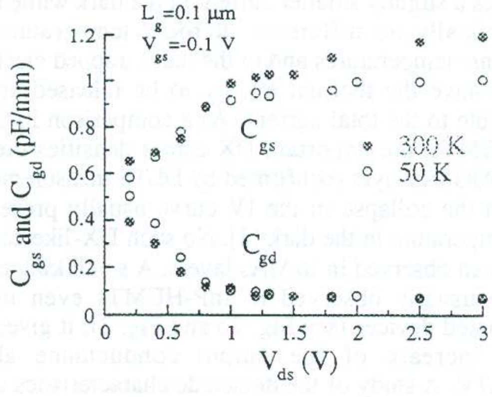

Fig. 5a: GaAsHEMT: C_{gs} and C_{gd} versus V_{ds} at 50 K and 300 K

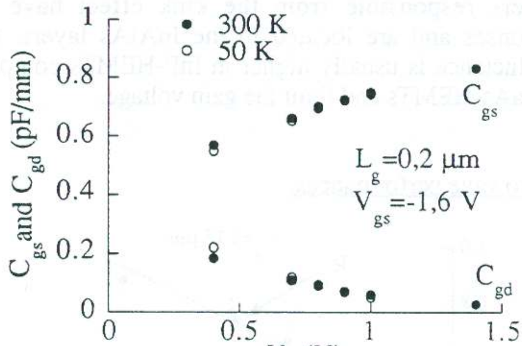

Fig. 5b: InP-HEMT:C_{gs} and C_{gd} versus V_{ds} at 50 K and 300 K.

We discuss now the behavior of the capacitances versus temperature for the two HEMT technologies. In the GaAs PM-HEMT one observes a decrease of the capacitance C_{gs} at low temperature. It is small at the longest gatelengths and strongest at the shortest gatelengths. This evolution is the consequence of a strong density of DX centers in the AlGaAs layer. The energetic carriers in the InGaAs channel, after they have transferred in L or X valleys, can easily transfer spatially in the L or X valleys of AlGaAs where they become trapped. More electrons remain trapped on DX centers at cryogenic temperatures due to the low thermal energy available. Then the variation of carrier density with the gate-source voltage is smaller and explains the smaller capacitance at cryogenic temperatures. This is a typical illustration of the enhancement of short channel effects at low temperature. On the other side C_{gs} does not vary between room and cryogenic temperature for InP LM-HEMTs. When energetic carriers in the InGaAs channel have transferred in L or X valleys, their probability of spatial transfer in the InAlAs where they could become trapped is relatively small. Therefore carrier confinement in the InGaAs channel is comparatively better for InP LM-HEMTs than for GaAs PM-HEMTs, which explains the constant capacitance versus temperature of the former.

Finally, although the gate-drain capacitance small values requires caution in the interpretation, it must be noticed that their values remain constant versus temperature for both technologies.

Extrinsic ($f_{T,ext}$) and intrinsic ($f_{T,int}$) cut-off frequency : The Fig. 6a and Fig.6b show $f_{T,ext}$ and $f_{T,int}$ (which includes the total intrinsic capacitance Cgs+Cgd) at 50 K and 300 K for GaAs and InP HEMTs. One observess the lack of significant improvement of $f_{T,int}$ at the shortest gatelength HEMTs when the temperature is lowered.

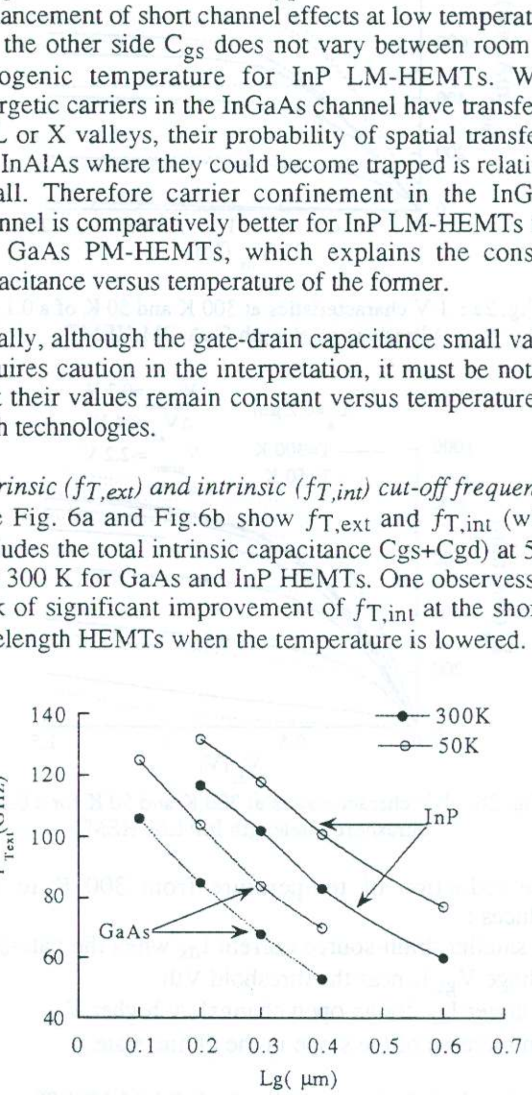

Fig. 6a : $f_{T,ext}$ versus L_g for GaAs and InP HEMTs

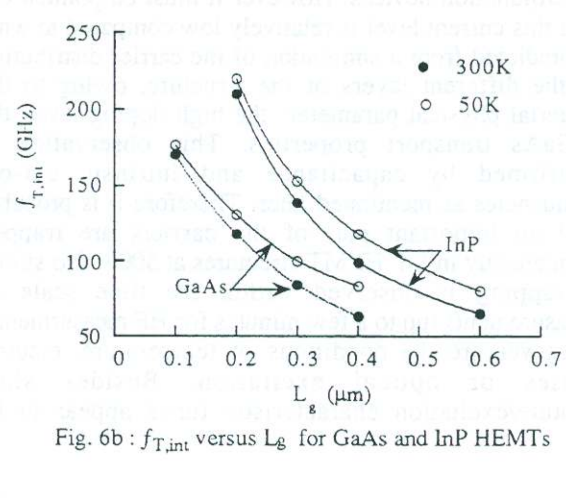

Fig. 6b : $f_{T,int}$ versus L_g for GaAs and InP HEMTs

We also notice :

- For the GaAs and InP HEMTs the difference between $f_{T,ext}$ and $f_{T,int}$ is about 20 % for L_g=0.4 µm; this difference increases at shorter gatelength (40% for L_g=0.1 µm for the GaAs-HEMT) and is the consequence of the importance of parasitic elements. The importance of parasitic elements is largely present in the ultrashort gatelength InP-HEMTs compared with the GaAs-HEMTs; a difference near 70 % is observed between $f_{T,ext}$ and $f_{T,int}$ for the 0.2 µm gatelength InP-HEMT. The intrinsic capacitanes are small (<1 pF/mm at L_g=0.2 µm) and the electrostatic capacitances constitute a large part of the total capacitance.

- When the temperature is reduced, the $f_{T,ext}$ improvement is significant compared to the increase of $f_{T,int}$. This is due to reduction of the parasitic elements and particularly the access resistances explain this difference.

- As a consequence of smaller capacitances for InP-HEMTs, we obtained higher cut-off frequencies. $f_{T,int}$ near 220 GHz is obtained for InP-HEMT with a 0.2 µm gatelength. The extrinsic cut off frequency, for this same device is 130 GHz.

Intrinsic transconductance :

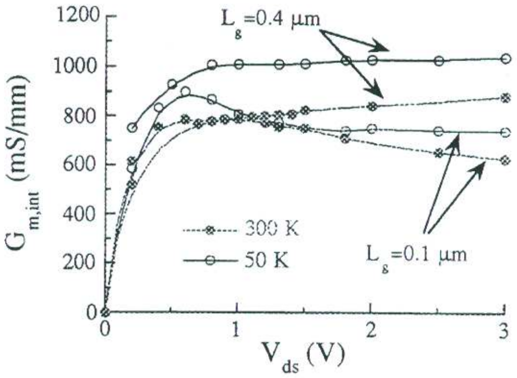

Fig. 6a : $G_{m,int}$ versus V_{ds} at 50 K and 300 K. L_g=0.2 µm and L_g=0.6 µm. GaAs-HEMTs.

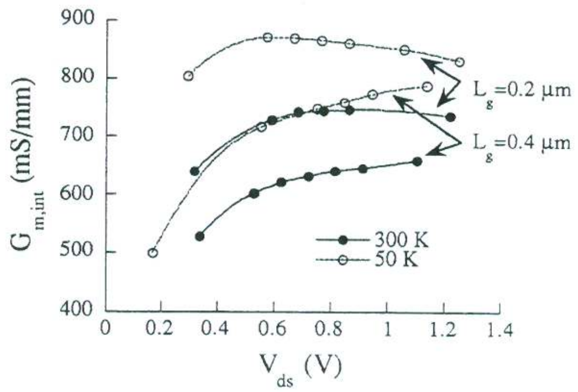

Fig. 6b : $G_{m,int}$ versus V_{ds} at 50 K and 300 K. L_g=0.2 µm and L_g=0.6 µm. InP-HEMTs.

The Fig. 7a and Fig. 7b show for the two technologies the maximum intrinsic transconductance $G_{m,int}$ as a function of V_{ds} at 50 K and 300 K in the case of ultrashort gatelength (0.1 µm and 0.2 µm) and short gatelength (0.4 µm) devices. The transconductance is the product of two terms corresponding respectively to carrier control by the gate and to carrier speed. The C_{gs} capacitance is well representative of the first term, while the cut-off frequency $f_{T,int}$ features well the device average carrier speed. The evolutions of C_{gs} and $f_{T,int}$ allow to explain the transconductance variations.

In the GaAs longer gatelength HEMTs, the C_{gs} reduction at low T is small and the average carrier speed increases which translates in the increase of $G_{m,int}$ (Fig.7a). The short gatelength GaAs HEMTs present a more complex case. At small Vds the reduction of temperture is not detrimental to the channel current control (C does not change) , the carrier speed improves only slightly, and there is only a small increase of $G_{m,int}$. At large Vds, the degradation of C_{gs} is noticeable while the average carrier speed increases as v_{sat} and again $G_{m,int}$ increases slightly.

On the other side in InP LM-HEMTs, $f_{T,int}$ improves in all cases while the capacitance Cgs does not vary upon cooling, which translates in the increase of $G_{m,int}$ for both long and short devices at low or high drain voltages(Fig.7b).

Conclusion

Comparative evolutions versus temperature of the important parameters for millimeter applications have been discussed both for GaAs and InP HEMTs. They give a new insight of short channel and trapping effects. The limited carrier density in the channel of InP-HEMTs due to permanent carrier trapping is a problem yet to be solved. Double heterojunction HEMTs bring an improvement which is a compromise. A stronger doping increases the transconductance as observed experimentally but at the same time it degrades the gate capacitance and may lead to a reduction of the current gain cut-off frequency. GaAs-HEMTs do not present this inconvenience but, due to the intrinsic properties of the $In_{0.2}Ga_{0.8}As$, their applications are limited to nearly 60 GHz.

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