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Low temperature low voltage operation of HEMTs on InP

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Abstract: Pseudomorphic single recessed $\text{Al}_{0.48}\text{In}_{0.52}\text{As}/\text{Ga}_{0.30}\text{In}_{0.70}\text{As}/\text{AlInAs}$ pseudomorphic HEMTs (PM-HEMT) on InP with planar doping and gatelength $0.2\mu\text{m}$ are investigated at cryogenic temperatures (50K) for their high frequency intrinsic transport properties at low drain bias voltage. Transient drain current measurements are compared with DC characteristics and show the evolution of trapping effects versus drain voltage. HF measurements show that at low temperature drain current saturates at drain voltage as low as 0.5V with nearly maximum transconductance ($\approx 800\text{mS/mm}$) and very high intrinsic cut-off frequency ($\approx 190\text{GHz}$). In these ultrashort gate HEMTs, cryogenic temperatures bring the best relative improvement of intrinsic device transport properties ($\approx 60\%$) at very low drain voltages (0.5V).

Introduction

Very high frequency transconductances and cut-off frequencies have been obtained in nanometer gatelength pseudomorphic HEMTs on InP at room temperature[1]. The larger band discontinuities and better carrier confinement result in superior device performances. Anomalous characteristics and associated with deep-level traps have also been investigated [2-3] relatively to optoelectronic applications at 300K. We have shown recently that the high frequency performances of 50K cooled HEMTs on InP with gatelength in the $0.2\mu\text{m}$ range benefited from considerable carrier transport improvement compared to 300K operation [4]. Very low noise cryogenically-coolable amplifiers with lattice-matched HEMTs on InP have been reported at 18K with noise temperature of 47K at 70GHz [5], which is comparable to SIS receiver performance in this frequency range corresponding to the atmospheric window at 3mm wavelength. Although progress in the epitaxial growth of these device multilayers have been made, the published results show that low temperature characteristics are still influenced by trapping centers and other detrimental effects. We emphasize here the operation of pseudomorphic HEMTs on InP in very low drain bias conditions ($\leq 1\text{V}$) at low temperatures from 300K down to 50K. We present preliminary drain current transient measurements ranging from short times ($\approx 10\text{ns}$) up to DC conditions which bring new informations on the effect of traps versus biases and temperature. They show that further progression in

low temperature performances may be expected at low drain voltage ($V_{ds} = 0.5V-1V$). We describe first the device structure and the electrical characterizations. Then we discuss the evolution of DC, pulsed and HF electric parameters as a function of temperature, of drain and gate biases.

Experimental conditions

The device is an $Al_{0.48}In_{0.52}As/Ga_{0.30}In_{0.70}As/AlInAs$ pseudomorphic HEMT (PM-HEMT) on InP substrate (Fig.1). It consists on an InP substrate, a 2500Å $Al_{0.48}In_{0.52}As$ buffer layer, a 150Å n.i.d. $Ga_{0.30}In_{0.70}As$ channel, a 40Å $AlInAs$ spacer, a Si delta-doped ($4.5 \cdot 10^{12}cm^{-3}$), a 250Å n.i.d. $Al_{0.48}In_{0.52}As$ layer, and a 100Å Si doped ($4 \cdot 10^{18}cm^{-3}$) $Ga_{0.47}In_{0.53}As$ cap layer. The gatelength is 0.2µm, the gatewidth is 100µm and the source-drain separation is 2µm. The gate structure is single recessed with no recess optimization on the drain side for high drain breakdown voltage. Electrode pads and mesa area are patterned optically, and the gate is e-beam patterned with JEOLJBX5DII.

Fig. 1 Schematic device structure

All DC, transient and HF measurements are performed in the same cryogenic station with microwave coplanar picoprobes and optical access allowing sample illumination. The transient measurements use wide bandwidth coaxial components and impedance calibration structures, a 2ns rise time generator driving the HEMT drain voltage. Then drain current transients are measured on the time scale from 10ns to 600ns. The temperature control of the cooled probes near the sample holder temperature, the in-situ RF full calibration at the HEMT temperature of operation using an OSTL procedure and a standard substrate at the same temperature, give accurate and reproducible S-parameter measurements up to 45GHz, smooth S parameter variations versus frequency, temperature and biases. These features allow a direct determination of the device current and power gains and an extraction of equivalent circuit parameters versus temperature.

Experimental results and discussion

We first discuss the evolution of drain current amplitude versus time from transient to DC conditions in Fig.2-6. At 300K the DC IV characteristics (not shown) present very small kink, and are rather insensitive to illumination. This corresponds to what is usually referred as a low trap density structure. The Fig.2 shows the DC IV characteristics at 130K. As the structure has not been optimized for large breakdown voltage, the V_{ds} investigation is limited at 1.5V. The HP4142 supply corresponds to a $\approx 1\text{ms}$ acquisition time per point. The Fig.2 shows for open channel conditions ($V_{gs} \approx -0.7\text{V}$ corresponds to maximum transconductance), a moderate kink effect occurs at $V_{ds} \geq 0.5\text{V}$ due to trapping in the InAlAs layers. This trapping occurs mostly in the InAlAs buffer as some I_{ds} collapse is visible at negative gate voltage ($V_{gs} = -1.3\text{V}$) near threshold. The amount of trapping in the InAlAs buffer would be smaller in HEMTs with the same epilayer structure and a deeper recess giving a less negative threshold voltage. Characteristics taken in three different illumination conditions (dark, medium light intensity of binocular white light illumination, full intensity) indicate a small influence of intensity illumination. However all characterizations have been performed under constant illumination to minimize trapping.

The Fig. 3-4 present I_{ds} transient amplitudes at $T=130\text{K}$ as in Fig.2 and at constant V_{gs} bias versus V_{ds} which is pulsed as described earlier. I_{ds} amplitudes are presented at times $t=10\text{ns}$ and 600ns .

The IV characteristic corresponding to $t=10\text{ns}$ transients (Fig.3) does not show any visible anomaly in the 0.5V drain region as it will be confirmed later in the corresponding transconductance (curve Fig 9). On the other side in the I_{ds} curves at $t=600\text{ns}$ (Fig 4) some kink effect at small V_{ds} is already observable. This verifies experimentally that part of electron capture is a fast process in the several tens nanoseconds. Besides Fig.3 shows that some extra drain current appears at $V_{ds} \geq 0.8\text{V}$ already

Fig. 2 DC I_{ds} versus V_{ds} ($T=130\text{K}$)

Fig. 3 Transient I_{ds} amplitude at $t=10\text{ns}$ versus V_{ds} ($T=130\text{K}$)

Fig. 4 Transient I_{ds} amplitude at $t=600\text{ns}$ versus V_{ds} ($T=130\text{K}$)

at $t=10\text{ns}$ which amplitude grows further with time (see Fig.4 and Fig 2). We shall come back on this point when discussing the gate current evolution. Different time scales are apparent from the observation of Fig 2-4 and further time domain investigation is necessary to characterize them more accurately.

Fig 5 Transient I_{ds} amplitude vs V_{ds} at $t=10\text{ns}$ and 600ns ($T=300\text{K}$)

Fig. 6 Transient I_{ds} amplitude vs V_{ds} at $t=10\text{ns}$ and 600ns ($T=50\text{K}$)

The Fig.5 and Fig.6 complement Fig.3 and Fig.4 to show the I_{ds} amplitude evolution with time versus temperature from 300K down to 50K. They indicate that the I_{ds} amplitude at $t=10\text{ns}$ and 600ns crossover at different V_{ds} depending on V_{gs} and T . It may be already said that at the larger V_{ds} where $I_{ds}(t=10\text{ns}) < I_{ds}(t=600\text{ns})$, both carrier detrapping and impact ionization contribute to the increase of I_{ds} amplitude versus time.

Fig. 7 I_{ds} versus V_{gs} and temperature ($V_{ds}=0.5\text{V}$)

Fig. 8 I_{gs} versus V_{gs} , V_{ds} and temperature

The Fig.7 presents the DC transfer characteristics $I_{ds} = f(V_{gs})$ versus temperature at $V_{ds}=0.5\text{V}$. A more important $I_{ds\text{max}}$ at 50K is obtained : 25% higher than $I_{ds\text{max}}$ at 300K (480mA/mm vs 400mA/mm). We can notice in Fig.7 a shift of the threshold voltage $\approx -0.2\text{V}$ from 300K to 50K. This shift is translated in the V_{gs} value corresponding to $G_{m\text{max}}$ (-0.7V at 50K and -0.5V at 300K).

The evolution of gate current I_{gs} is presented versus V_{gs} in Fig.8 at V_{ds} values of 0.5V, 1V and 1.5V versus temperature. At 0.5V and 1V, all I_{gs} data points lie along a continuous line at all temperatures from 300K down to 50K. On the other side at $V_{ds}=1.5\text{V}$ and gate voltage with strong pinch-

off near threshold, the high energy of the carriers in the small-gap InGaAs channel create an additional gate current component which is associated with impact ionization. Fig.8 shows that at $V_{ds} \leq 1V$ and low temperatures, $I_{gs} \leq 20\mu A/mm$. Such a low value shows that the pseudomorphic structures with $In=0.6$ are very promising for very low noise operation [5].

Access lines and device access resistances are extracted from HF measurements at a special bias condition ($V_{ds}=0V$, $V_{gs}=1V$) for each temperature. A coherent set of values is obtained for the whole temperature range (see Table 1). A precise line model including skin effect is used for the 100 μm access line. Unlike the access line losses, access resistances R_s , R_d and R_g experiment only a 50% decrease with temperature. This indicates that they include non metallic losses.

Table 1 : Temperature dependence of access elements

Temp (°K)	R_s ($\Omega.mm$)	R_d ($\Omega.mm$)	R_g (Ω/mm)	Gate. access Length (μm)	Drain access Length (μm)	Access lines (Ω/mm)
300	0.35	0.4	240	87	90	18
50	0.25	0.3	160	90	86	3.5

The main HF parameters are presented versus V_{gs} at $V_{ds}=0.5V$ (Fig.9-10) and versus V_{ds} (Fig.11-12). An overall good agreement between modeling and measurement is obtained for all biases up to 40 GHz. Extrinsic transconductance determined from HF extracted equivalent circuit compares favorably with DC transconductance (Fig 9) which confirms the small influence of traps at $V_{ds}=0.5V$. The DC extrinsic transconductance exhibits a maximum value G_{mmax} of 600mS/mm and 440mS/mm at $V_{ds}=0.5V$ for the temperatures 50K and 300K respectively. The current density under the G_{mmax} condition is 280mA/mm(50K) and 100mA/mm(300K). The increase of the transconductance at low temperature indicates a better gate control of the current and a possible increment of the average carrier velocity. Intrinsic cut-off frequency versus V_{gs} (Fig.10) follows closely the evolution of transconductance with a slight maximum shift towards negative V_{gs} due to capacitance increase with gate voltage.

Fig. 9 G_{mext} versus V_{gs} at 50K

Fig. 10 F_{in} and G_{mint} versus V_{gs} at 50K

We now focus on evolution of G_{mint} and F_{in} versus V_{ds} (Fig.11-12). Fig.11 shows the evolution of intrinsic transconductance G_{mint} versus V_{ds} at optimum V_{gs} bias ($\approx -0.7\text{V}$). This G_{mint} reaches 800mS/mm at 50K for $V_{\text{ds}}=0.5\text{V}$ and does not increase more than 5% beyond this value. The large increase of G_{mint} at $V_{\text{ds}}=0.5\text{V}$ reflects the improvement of carrier transport under the gate largely related to the increase of average carrier velocity which at low temperature is primarily due to higher mobility in the low field region of the device.

Fig. 11 G_{mint} versus V_{ds}
at 50K and 300K

Fig. 12 F_{in} and F_{meas} versus V_{ds}
at 50K and 300K

Intrinsic cut-off frequency $F_{\text{in}} = G_{\text{mint}} / (2\pi(C_{\text{gs}} + C_{\text{gd}}))$ and extrapolated (6dB/octave slope) cut-off frequency F_{meas} are presented in Fig.12. The large difference between intrinsic and measured F_{in} (30% at 300K and 50% at 50K) is partly related to a high value of output conductance which increases at low temperature. F_{in} steadily increases with V_{ds} , but is only below 20% of its maximum value at $V_{\text{ds}}=0.5\text{V}$.

The device has attractive intrinsic transconductance near 800mS/mm and cut-off frequency f_{in} near 190GHz. This illustrates that at cryogenic temperatures, HEMTs on InP have good intrinsic properties for high frequency performances at very low drain bias.

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References

- [1] L.D. Nguyen, A.S. Brown, M.A. Thompson and L.M. Jelloian, "50-nm self-aligned-gate pseudomorphic AlInAs/GaInAs high electron mobility transistors", IEEE Trans. Elect. Devices, vol.39, pp.2007-2014, 1992.
- [2] C. Heedt, F. Buchali, W. Prost, D. Fritzsche, H. Nickel, F.J. Tegude, "Characterization of impact-ionization in InAlAs/InGaAs/InP HEMT structures using a novel photocurrent-measurement technique", Indium Phosphide and Related Materials Vth Conf., Paris, pp.247-250, 1993.
- [3] W. Kruppa and J.B. Boos, "Sinusoidal and transient response of traps in double-recessed InAlAs/InGaAs/InP HEMTs, same IPRM Conf., Paris, pp.251-254, 1993.
- [4] A. Sylvestre, P. Crozat, R. Adde, A. De Lustrac, Y. Jin, J.C. Harmand, M. Quillec, "Cryogenic investigation of gate leakage and RF performances down to 50K of 0.2μm AlInAs/InGaAs/InP HEMTs", Elect. Lett., vol.29, pp.2152-54, 1993.
- [5] M.W. Popieszalaki, W.J. Lakatos, R. Lai, K.L. Tan, D.C. Streit, P.H. Liu, R.M. Dia, J. Velebir, "Millimeter-wave cryogenically-coolable amplifiers using AlInAs/GaInAs/InP HEMTs", IEEE MTT Symposium Digest, pp.515-518, 1993.