4B2 **Gallium Arsenide Application Symposium GAAS®96** **Paris CNAM**
5-7 June 1996

A high-gain coplanar GaAs PHEMT K-band dual-gate amplifier

Y. Baeyens, D. Schreurs, B. Nauwelaers,
*K. Van der Zanden, *M. Van Hove, *W. De Raedt and *M. Van Rossum

K.U.Leuven, div. ESAT-TELEMIC, Kardinaal Mercierlaan 94, B-3001 Leuven, Belgium
*IMEC, Kapeldreef 75, B-3001 Leuven, Belgium

Abstract

In this paper, the performance of both GaAs and InP-based 0.15µm dual-gate HEMTs in a cascode configuration is demonstrated by the successful design and realisation of a number of coplanar amplifiers. For a reactively matched single-stage GaAs PHEMT amplifier a gain of 20.9dB is obtained at 23GHz. At millimetre-wave frequencies, this gain can be further improved by using InP-based HEMTs as is shown by the realisation of a single-stage LM HEMT dual-gate amplifier with a stable gain of 16.4 dB and a good in- and output matching at 58.5 Ghz.

Introduction

GaAs and InP-based HEMTs with very short gatelengths have demonstrated excellent performance in a variety of analog and digital applications [1]. The use of dual-gate HEMTs connected in a cascode configuration gives additional advantages such as a higher and controllable gain [2]. Since the invention of the dual-gate FET [3], these advantages have been reported in literature both for MESFETs, GaAs-based PHEMTs [4, 5] and for 0.7µm gatelength InP-based lattice matched (LM) HEMTs [6].

In this work, we first compare the characteristics of 0.15µm gatelength GaAs and InP-based single-gate and dual-gate HEMTs and then show their potential to realise in a very compact way the high gain amplifiers needed in the next generation of millimetrewave communications and detection systems.

Device technology

Using the standard GaAs and InP-based MMIC technology developed at IMEC [7], dual-gate HEMTs were fabricated both on GaAs-based pseudomorphic $Al_{0.25}Ga_{0.75}As/In_{0.2}Ga_{0.8}As$ layers and on InP-based LM $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ layers. Two different device layouts were evaluated: the T-layout and the fingered layout. A SEM picture of a dual-gate HEMT with a fingered layout is shown in Fig. 1. In this layout, the 0.15µm long T-shape gates are separated by an ohmic metal area between the gates. This ohmic intermetal helps to further reduce the extrinsic parasitics. The second gate is RF grounded by a MIM-capacitor, connected to a DC-pad controlling the voltage on this gate. In this way, the dual-gate cascode configuration can be realised while only occupying about the same area as a single-gate transistor [4].

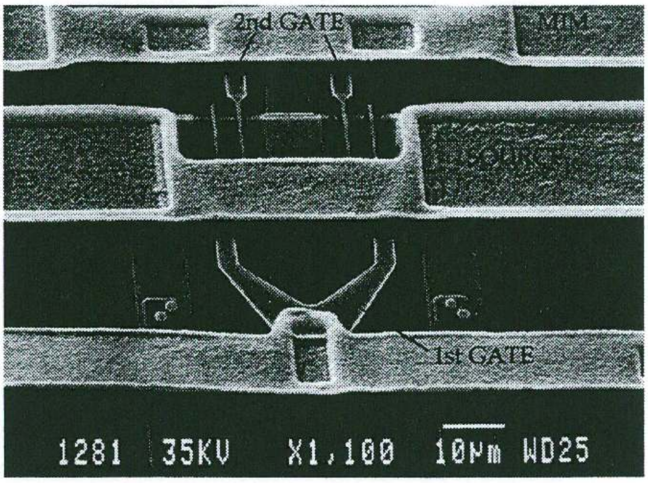

Fig. 1: SEM-picture of a dual-gate HEMT with 2 fingers and an ohmic intermetal separating the two gates

Device performance

The typical DC and RF performance of GaAs and InP-based HEMTs, measured after passivation with 200nm silicon nitride, is compared in Table 1. The peak transconductance and cut-off frequency of the dual-gate devices is about 10% lower than that of comparable single gates. This is caused by the loading of the first FET by the second one and by the increased access capacitances and resistances.

By putting two devices in cascode, the maximal available gain at 10 GHz increases from 17.5 to 25dB and from 22.5 to 28.5dB for respectively GaAs and InP dual-gate HEMTs. These values are to our knowlegde the highest gain ever reported for dual-gate devices. Also at millimetrewave frequencies a very high gain is obtained. Due to the high isolation of the devices however it is difficult to accurately determine this gain from measurements.

The increase of the microwave gain can be studied by looking at the change in the C_{gs}/C_{gd} and g_m/g_{ds} ratios, two ratios which are strongly influencing the microwave gain. The C_{gs}/C_{gd} ratio is already high for InP-based single-gate devices due to their low feedback capacitance leading to a high f_{max} value of 350GHz for LM InP-based single-gate HEMTs. By putting two devices in cascode, this ratio can be further improved but this improvement is ultimately limited by the parasitic feedback capacitance directly from the first gate to the drain.

Indeed, by examining the scaling behaviour of the measured feedback capacitance C_{gd} as a function of the width, one can see that for a dual-gate C_{gd} mainly consists of a fixed parasitic capacitance, typically 1 or 2fF. This parasitic capacitance is one of the main limitations on the further increase of the microwave gain. By using InP dual-gate devices with larger gate widths an increase of the microwave gain to more than 30dB at 10GHz should be feasible.

GaAs single-gate PHEMTs have in general a higher C_{gd}. The C_{gs}/C_{gd} and gain improvement at 10 GHz when going from a single-gate to a dual-gate devices is therefore somewhat more pronounced for GaAs compared to InP-based devices.

For the dual-gates no maximum oscillation frequency f_{max} is given in table 1 as this figure of merit is difficult to determine from measurements due to the different slopes which have to be used when extrapolating the gain at the highest frequencies. When using the extrapolation of the low-frequency unilateral gain with a slope of -20dB/decade values of respectively 450 GHz and almost 1THz are obtained for GaAs and InP-based devices.

Table 1: Summary of the performance of 0.15µm single-gate and dual-gate GaAs PHEMTs and InP LM HEMTs, measured after passivation; the threshold voltage is -0.8V for this comparison,

	dim.	GaAs SG	GaAs DG	InP SG	InP DG
DC g_m	ms/mm	650	600	800	730
Extrinsic f_T	GHz	110	95	140	120
C_{gs}/C_{gd} ratio	-	3.5	38	20	80
g_m/g_{ds} ratio	-	13	80	17	110
Extrinsic f_{max}	GHz	160	-	350	-
MAG@10GHz	dB	17.5	25	22.5	28.5

MMIC amplifier design

To illustrate the potential of using dual-gate HEMTs in amplifiers, both GaAs and InP-based coplanar MMIC circuits were designed and successfully fabricated.

Apart from giving higher yield and lower dispersion, a coplanar layout is especially advantageous for dual-gate circuits since it allows to realise the low-inductance capacitors needed to effectively AC short the second gate to the ground. In this way, potential instabilities at higher frequencies can be avoided. In the coplanar circuits, airbridges are extensively used in order to suppress slotline modes at bends and other discontinuities [8]. Their influence is small due to the very small ground-to-ground separation of 50µm.

In the design, the small-signal behaviour of the dual-gate HEMTs is modelled by the cascode connection of two intrinsic single-gate equivalent circuits, together with the extrinsic parasitics of the dual-gate layout and the different access resistances [9].

Both distributed broadband amplifiers, reported in [9], and reactively matched smallband amplifiers were realised. A GaAs K-band and an InP-based V-band amplifier are discussed here in more detail.

The layout of the GaAs-based dual-gate amplifier operating at 23 GHz is shown in Fig.2. The input is matched by a series transmission line and a lumped MIM parallel capacitor, while for the output matching, which is quite critical due to the high output impedance of the cascode stage, the combination of a series transmission line and a stub RF shorted on top of a MIM capacitor is used.

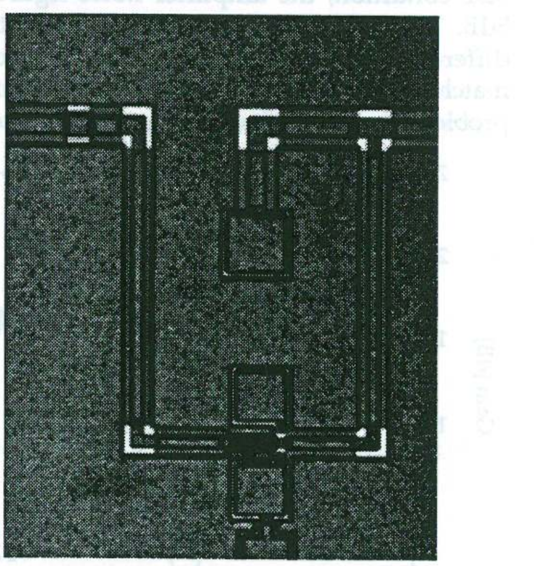

Fig. 2: Layout of the coplanar single-stage GaAs PHEMT dual-gate K-band amplifier

The layout of a second example, an InP-based V-band amplifier is shown in Fig. 3. The input is matched by a series transmission line and a lumped MIM parallel groundcapacitor placed underneath the T-junction connecting the quarter wavelength bias-stub. For the output matching, the combination of a series transmission line and a double stub RF shorted on top of a MIM capacitor is used. The total size of this circuit is 0.9x0.7mm^2 including bias networks.

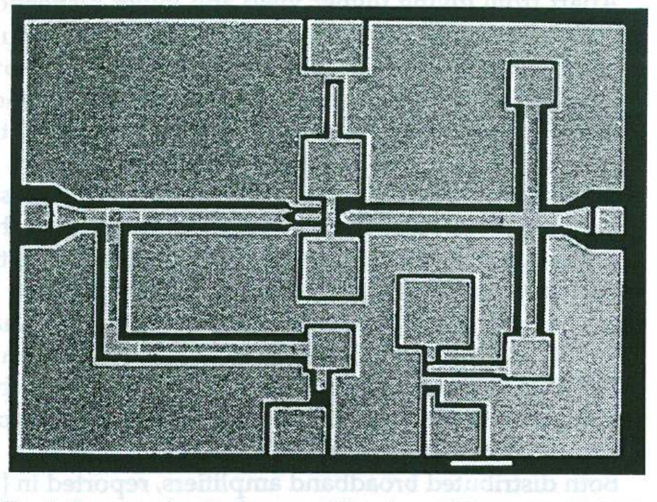

Fig. 3: Layout of a single-stage V-band amplifier using LM InP-based dual-gate HEMTs

Amplifier results

Measurements of the GaAs-based K-band amplifier amplifier are shown in Fig.3 as a function of the frequency. At 23 GHz, a maximal gain of 20.9dB is measured. At this frequency also a good input and output reflection of less then -15dB is obtained. At this bias condition, the amplifier noise figure is around 5dB. This is mainly caused by the relatively large difference between the optimal noise and conjugate match source reflection for the dual-gate device. This problem could be solved by using inductive feedback.

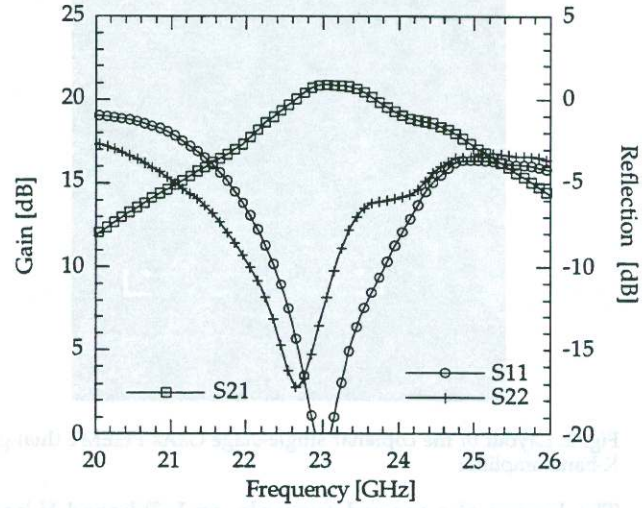

Fig. 4: Measured gain and reflection of the single-stage K-band amplifier as function of frequency (V_d=3V, V_{g2}=1V)

By changing the DC voltage on the second gate from +1V to -1V the gain at 23 GHz can be varied from +20dB up to -27dB. As can be seen in Fig. 5, due to the rather critical matching, a good amplifier reflection (<-10dB) can only be guaranteed for a gain variation from +20dB down to 0dB. This is however sufficient for most variable gain applications.

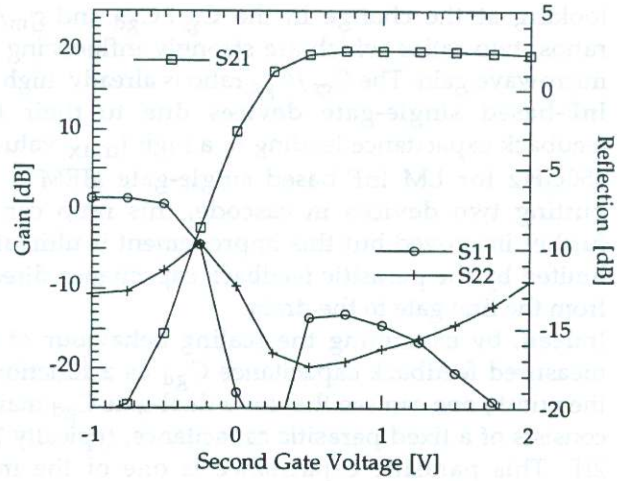

Fig. 5: Measured gain and reflection of the GaAs-based amplifier as function of Vg2 (Vd=3V, Freq.=23 GHz)

Measurements on the InP-based V-band amplifier are shown in Fig. 6 as a function of the frequency. At 58.5 GHz, a maximal gain of 16.4dB is measured, to our knowledge the highest gain reported for a single-stage MMIC amplifier in V-band. At this frequency, also an excellent input and output reflection of less then -20dB is obtained. Additionally, the amplifier is stable from 1GHz up to the highest measurement frequency.

The gain can varied in a similar way as the GaAs-based K-band amplifier by changing the DC voltage on the second gate. For this amplifier however the gain variation while maintaining a good reflection is limited to less then 10dB due to the very critical output matching.

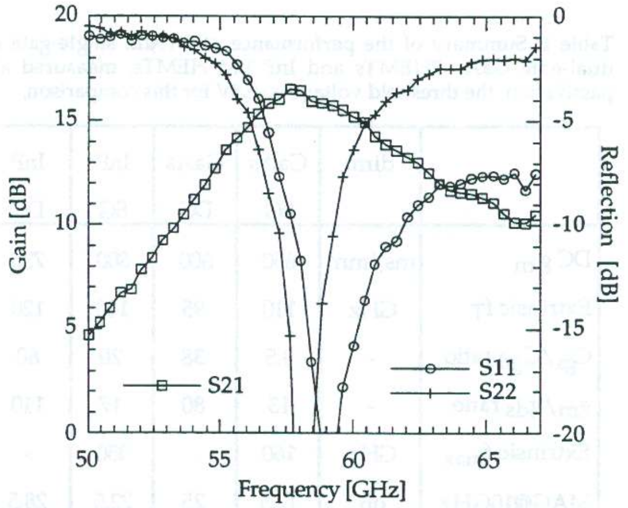

Fig. 6: Measured gain and reflection of the single-stage InP-based amplifier as function of frequency (V_d=3V, V_{g2}=1V)

Apart from the V-band amplifier, also two InP-based dual-gate amplifiers operating in Q and W-band were designed and fabricated. The gain obtained on these amplifiers, is summarised in Fig. 7.

The measured characteristics are in good agreement with the simulated curves apart from a small and consistent shift (2-4%) of both the reflection and gain towards the lower frequencies. This shift is mainly caused by the slightly higher feedback capacitance of the HEMTs processed in a first run.

At 91GHz, a stable gain of more than 10 dB together with a good in- and output matching is obtained from a single InP-based cascode HEMT.

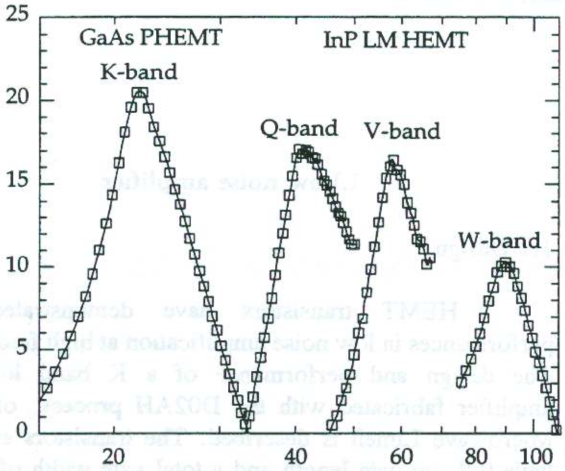

Fig. 7: Measured gain of realised GaAs and InP-based single-stage dual-gate amplifiers in K, Q, V and W-band

Conclusions

At microwave frequencies an extremely high gain can be obtained using either GaAs or InP-based dual-gate cascode HEMTs. Due to the high f_T and f_{max} of the InP-based HEMT, a high and stable gain can be obtained even at millimetrewave frequencies. This was demonstrated by the design of a V-band single-stage amplifier with a gain of 16.4 dB at 58.5 GHz. This very compact amplifier shows the feasibility to use InP-based technology to realise in a cost-effective way the amplifiers needed in future communication systems. It also demonstrates the potential of InP-based technology for amplification beyond 100GHz.

Acknowledgements

IMEC wishes to acknowledge the financial support of ESA/ESTEC for its research activities on GaAs and InP-based HEMT technology. Measurements up to 67 GHz were performed at the IMST in Kamp-Lintfort, Germany, the W-band measurements were performed by Dr. Dambrine at the IEMN in Lille, France. Paul Richardson is acknowledged for his skilful PHEMT device and MMIC development; Rik Jonckheere, Jos Moonens and Hans Costermans for the e-beam direct write work.

References

[1] L. D. Nguyen, L. E. Larson and U. K. Mischra, "Ultra-High-Speed Modulation-Doped Field-Effect Transistors: A Tutorial Review," Proceedings of the IEEE, Vol. 80, No. 4, pp. 494-518, 1992

[2] C. A. Liechti, "Performance of Dual-Gate GaAs MESFET's as Gain-Controlled Low-Noise Amplifiers and High-Speed Modulators," IEEE Trans. Microwave Theory Tech., Vol. 23, No. 6, pp. 461-469, 1975

[3] J. Turner, A. Waller, E. Kelly and D. Parker, "Dual-gate GaAs microwave FET," Electronics Letters, Vol. 7, No. pp. 661-662, 1971

[4] J. Wenger, P. Narozny, H. Dambkes, J. Splettstosser and C. Werres, "Low-Noise Pseudomorphic Dual-Gate Cascode HEMT's with Extremely High Gain," IEEE Microwave Guided Wave Lett., Vol. 2, No. 2, pp. 46-48, 1992

[5] M. Schlechtweg, W. H. Haydl, A. Bangert, J. Braunstein, P. J. Tasker, L. Verweyen, H. Massler, W. Bronner, A. Hülsmann and K. Köhler, "Coplanar millimeter-wave ICs for W-band applications using 0.15µm pseudomorphic MODFETs," to be published in IEEE Journal of Solid State Circuits, October 1996

[6] F. Gueissaz, R. Houdré and M. Ilegems, "DC and RF Characteristics of InAlAs/InGaAs Dual-Gate TEGFET's," Electronics Letters, Vol. 27, No. 8, pp. 631-632, 1991

[7] Y. Baeyens, T. Skrabka, M. V. Hove, W. D. Raedt, B. Nauwelaers and M. V. Rossum, "Performance of 0.2µm planar doped pseudomorphic and lattice matched HEMTs on GaAs and InP", Proceedings of the 23rd European Solid State Device Research Conference (ESSDERC'93), pp. 753-756, Grenoble, France, 1993

[8] I. Wolff, "Design rules and realisation of coplanar circuits for communication applications", Proceedings of the 23rd European Microwave Conference, pp. 36-41, Madrid, 1993

[9] Y. Baeyens, D. Schreurs, B. Nauwelaers, M. V. Hove, W. D. Raedt and M. V. Rossum, "Ultra-broadband distributed variable gain amplifiers using lattice matched and pseudomorphic InP cascode HEMTs", Proceedings of the Microwave and Optronics Conference '95 (MIOP'95), pp. 345-349, Sindelfingen, Germany, 1995