Potential of Metamorphic HEMT with 0.25 µm Refractory Metal Gate for Power Application in Ka-Band

F. Benkhelifa, R. Quay, R. Lösch, K. Schäuble M. Dammann, M. Mikulla, G. Weimann

Fraunhofer Institute for Applied Solid State Physics (IAF), Tullastrasse 72, D-79108
Freiburg, Germany
Mail: **benkhelifa@iaf.fhg.de**

Abstract

Metamorphic high electron mobility transistors (MHEMT) on 4-inch GaAs substrates, with a 0.25 µm refractory metal gate, fabricated by optical stepper lithography and SiN sidewalls spacer, are demonstrated for power application. Single recess MHEMT exhibits a reverse gate to drain breakdown voltage of – 11.5 V, a saturation current density of 680 mA/mm and a f_T of 83 GHz at a drain bias of 1V. At 30 GHz, the device produced an output power of 395 mW/mm with a maximal power added efficiency of 29 %. A maximum output power of 455 mW/mm and 8 dB maximum power gain has also been demonstrated with the device at 30 GHz.

Introduction

GaAs-based metamorphic HEMTs (MHEMT) have been the subject of considerable research and development, demonstrating state-of-the-art mm-wave low noise, high power, and low DC power consumptions[1,2]. We demonstrated high performance and thermally stable (no gate sinking at drain bias of 1 V and 2 V) 0.25 µm MHEMTs using refractory metal self-aligned gates and SiN sidewalls [3]. Metamorphic HEMTs with high on-state and off-state breakdown voltages and large power densities, with 30% to 45 % In contents, have been realized using e-beam lithography [1]. In this paper, an investigation of power performance of 0.25 µm gate length $In_{0.40}Al_{0.60}As$ / $Ga_{0.60}In_{0.40}As$ MHEMTs, for power application in Ka-band, is presented. Here we use conventional lithography and a spacer sidewalls process for low production costs.

Fabrication

Epitaxial growth was carried out in an MBE system on 4-inch semi-insulating GaAs substrates. The metamorphic buffer is grown at 450°C and its composition is graded from $Al_{0.48}Ga_{0.52}As$ to $Al_{0.60}In_{0.40}As$ over 1 µm by increasing the In flux and simultaneously decreasing the Ga flux. A 250 nm $Al_{0.60}In_{0.40}As$ layer is subsequently grown on this buffer. The structure consists of a double heterojunction layer in which planar doping is placed both above and below the undoped $In_{0.40}Ga_{0.60}As$ channel, an $In_{0.40}Al_{0.60}As$ Schottky layer and a doped InGaAs cap layer. After the mesa-isolation, gate manufacturing starts by PECVD SiN deposition. Then, resist openings are formed by optical lithography, with an i-line stepper, having a numerical aperture of 0.4, and are transferred to the SiN film by dry etching using an ICP system. The gate recess is etched using succinic acid and followed by the deposition of SiN sidewall spacer. Dry etching the dielectric spacer enables a final gate length of 0.25 µm. Next, thermally stable refractory metal is sputtered for gate metal. Gate fingers are reinforced by a broader overlay metal to reduce the gate resistance. Finally, unused parts of refractory metal are removed using dry-etching. AuGeAu ohmic contacts are established self-aligned to the T-gate and annealed on hotplate.

Device Characteristics

The output I-V and transfer characteristics of the 0.25 x 20 μm^2 MHEMT are shown in figs. 1 and 2. The device exhibits a good pinch-off in the I-V, an open channel resistance of 0.8 Ω.mm and I_{DSmax} = 680 mA/mm. The average maximum DC transconductance at 1 V drain bias is 600 mS/mm and the threshold voltage is - 1.1 V.

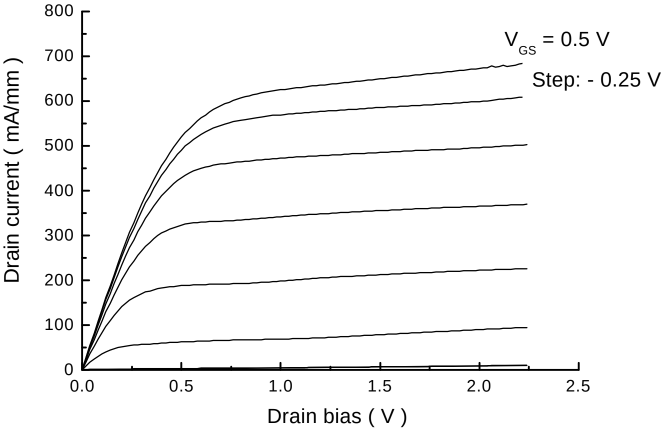

Fig.1 : I-V characteristics of 0.25 µm x 20 µm MHEMT.

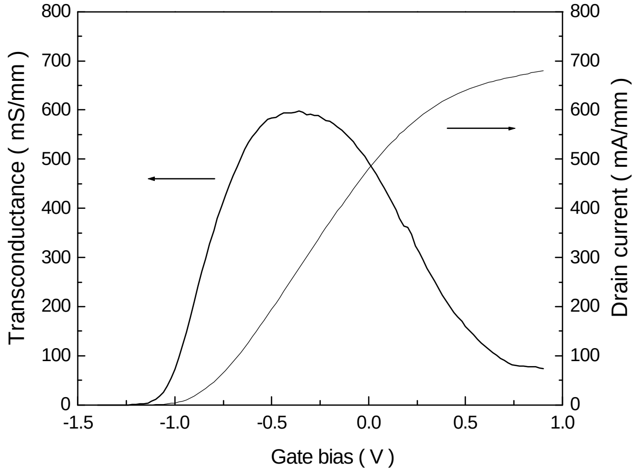

Fig.2 : Transfer characteristics of 0.25 x 20 µm^2 MHEMT.

On a 4∀ substrate, the standard deviation of peak-g_m and V_{th} is 32 mS/mm and 37 mV, respectively, at V_{ds} = 1 V. The uniformity of the parameters is due to both, high selectivity of the gate recess and the excellent uniformity of our MBE growth process. The Schottky characteristic curve for the MHEMT is shown in Fig. 3, the forward drain-gate diode turn-on voltage is 0.88 V and a gate breakdown voltage of - 11.8 V at a gate current of 1 mA/mm is obtained. Improvements in the Schottky barrier are due to the high band gap of the $In_{0.40}Al_{0.60}As$ and to the refractory metal gate. Better large signal operation is so possible, suitable for power applications. For a 0.25x20 µm^2 MHEMT on-state avalanche breakdown voltage (burnout) occurred at V_{DS}= 5.4 V and I_{DS} = 230 mA/mm.

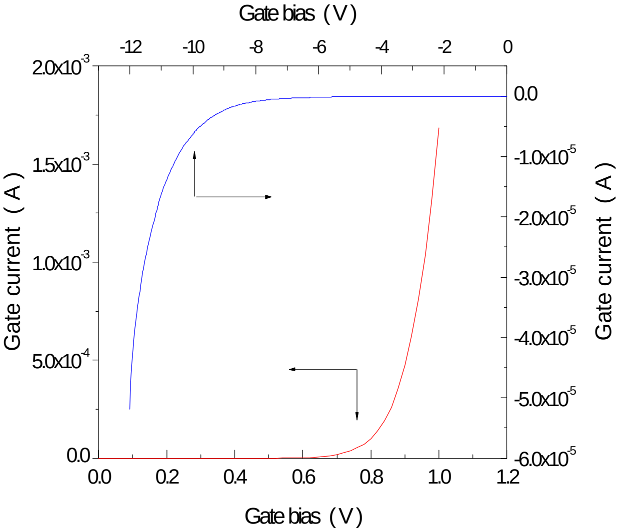

Fig.3 : Schottky characteristics of 0.25 x 20 µm^2 MHEMT.

S-parameters were measured from 1-120 GHz, using on wafer probing for a 2x60 µm wide MHEMT with 1.3 µm drain-source spacing. Maximum stable gain (msg) and current gain, at drain bias of 1 V and 2 V are plotted in fig. 4. An f_T of 83 GHz and f_{max} of 250 GHz is obtained at V_{ds} = 1 V, and at V_{ds} = 2 V f_{max} of 340 GHz is extrapolated. On a 4-inch wafer the standard deviation of the extrinsic current cutoff frequency is 3 GHz. The I-V characteristics of 20 µm gate width MHEMT device, with output power compliance of 1 W/mm, is shown in Fig. 5. A 12 V channel breakdown voltage and 640 mA/mm maximum drain current (at V_{GS} = 0.5 V) is achieved. These results, combined with the maximum available gain of 16.5 dB at 30 GHz , make the 0.25 µm MHEMT very promising for power application in the Ka-Band.

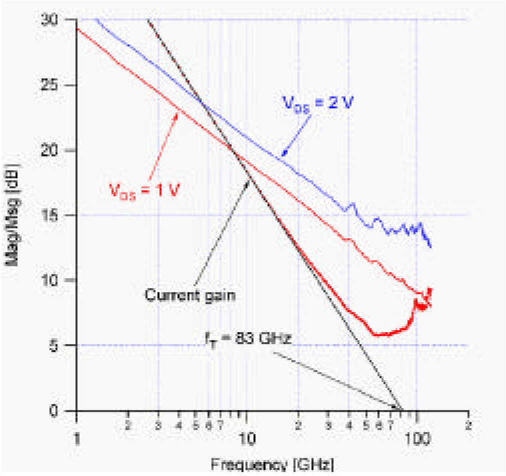

Fig.4 : Measured gain of 0.25 µm MHEMT (W_g= 2x60 µm) at V_{ds} = 1 V and 2 V from 1 – 120 GHz.

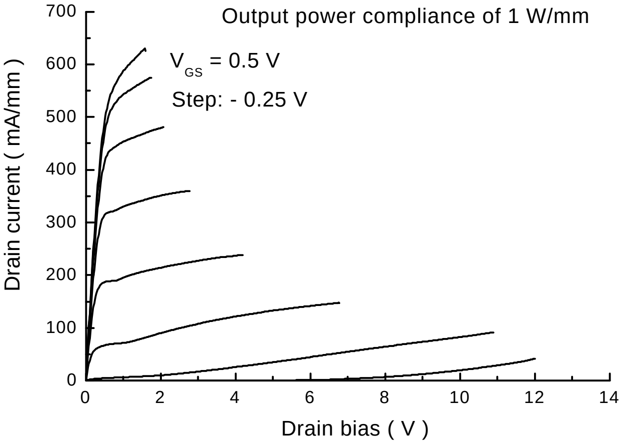

Fig.5 : I-V characteristics of 0.25 x 20 µm^2 MHEMT with 1 W/mm output power compliance.

Power performance and thermal stability

The MHEMTs were tested for large signal performance by load pull measurements (a 40 GHz large signal double reflectometer waveform measurement system), at 30 GHz with 180 µm gate peripheral. Class B biasing regime has been considered. The MHEMT produced 395 mW/mm of output power, 6 dB of associated gain and 29 % maximal power added efficiency (PAE) at V_{DS} = 4 V and I_{DS} = 90 mA/mm , at 0 dB gain compression. The output power, PAE and associated gain are presented in Fig. 6. A maximum output power of 455 mW/mm and a maximum associated gain of 8 dB was achieved. To evaluate the long term stability in class B operation, at 30 GHz, the device was biased at V_{DS} = 4 V, net input power of 11.8 dBm, which drives the device at 3.5 dB gain compression (high condition of stress). After 40 hours, we observed 0.65 dBm decrease in the output power, as seen in Fig. 7. This result is very promising for RF and thermal stability of our MHEMT. Measurements were done on 600 µm thick substrate, thinning the wafer will reduce the thermal dissipation and enhance the RF stability, further. It also shows that the interface semiconductor-silicon nitride is very stable.

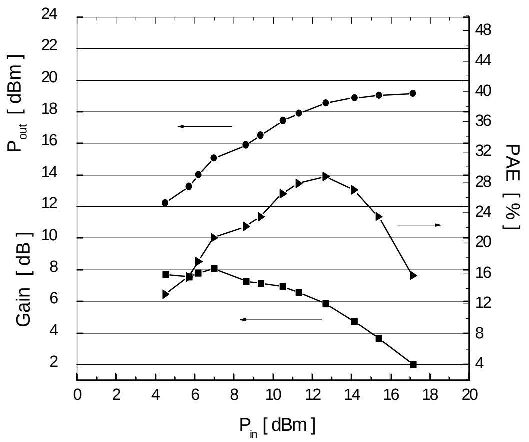

Fig.6 : Measured 30-GHz output power, PAE and gain of a 2x 90 µm MHEMT at V_{DS} = 4 V, class B operation.

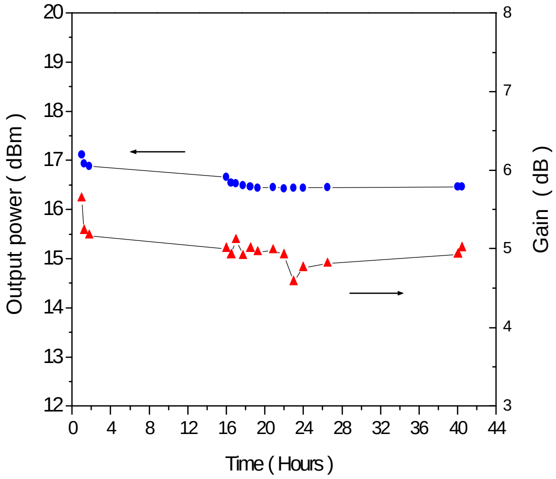

Fig.7 : Change in output power and gain of a 2x 90 µm MHEMT at 3.5 dB gain compression and V_{DS} = 4 V.

A wafer stabilization bake in nitrogen ambient is introduced as part of device fabrication to stabilize the device parameters [4]. Accelerated DC life-time tests were carried out on MHEMTs with 40% In in the channel at V_{DS} = 4 V and I_{DS} = 120 mA/mm. The FETs were stressed in air at 150°C, the drain current was monitored in-situ every 1 hour. The relative change in I_{DS} is plotted in fig. 8. The devices stressed at 480 mW/mm DC power dissipation show a good thermal stability. Figure. 9 shows the transfer characteristics of 0.25 µm MHEMT measured, at drain bias 1 V, before and after the DC life-time test at 150°C for 450 hours. This step leads to a shift in threshold voltage of 39 mV and the degradation in R_S and R_D was only 4.2 % and 1.2 %, respectively.

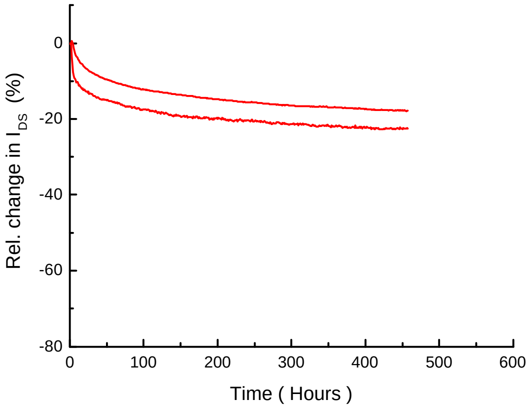

Fig.8 : Relative change in drain current of MHEMTs stressed in air at V_{DS} = 4 V and I_{DS} = 120 mA/mm and T_a = 150°C.

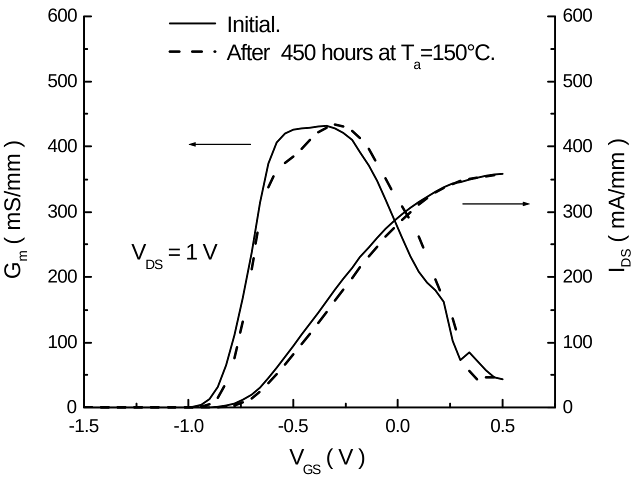

Fig.9 : Transfer characteristics of MHEMT at V_{DS} = 1 V , before (solid line) and after temperature stress at V_{DS} = 4 V and I_{DS} = 120 mA/mm (dashed line).

Conclusion

Single recess Metamorphic HEMTs with 40% In in the channel and 0.25 µm gate length, fabricated with i-line stepper and sidewalls spacer, exhibit good Schottky diode breakdown, a saturation current density of 680 mA/mm and a f_T of 83 GHz. At 30 GHz, a maximal PAE of 29% with an associated power gain of 6 dB and an output power of 395 mW/mm were obtained, demonstrating the potential for power application and low cost manufacturing.

Acknowledgment

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References

[1] C. S. Whelan, P. F. Marsh. W. E. Hoke, T. E. Kazior, “ GaAs metamorphic HEMT: the ideal candidate for high performance, millimeter wave low noise and power applications ”, GaAs Manufacturing Technology Conference, Washington, USA, May 1 – 4, 2000, pp. 237-240.

[2] P. C. Chao, K. C. Hwang, D. W. Tu, J. S. M. Liu, O. Tang, K. Nichols, “ Very high efficiency and low cost power metamorphic HEMT MMIC technology ”, GaAs Manufacturing Technology Conference, Washington, USA, May 1 – 4 , 2000, pp. 57-60.

[3] F. Benkhelifa, M. Chertouk, M. Dammann, H. Massler, R. Lösch, M. Walther, G. Weimann, “ High performance metamorphic HEMT with 0.25 µm refractory metal gate on 4” GaAs substrate ”, GaAs Manufacturing Technology Conference, Las Vegas, USA, May 21 – 24, 2001, pp. 230-233.

[4] M. Chertouk, H. Massler, M. Dammann, K. Köhler, G. Weimann, “ Manufacturable 0.15 µm InP-based HEMT MMIC process with high yield and reliability on 2-inch InP substrate ”, GaAs Manufacturing Technology Conference, Las Vegas, USA, May 21 – 24, 2001, pp. 230-233.