Monolithic Fabrication of a Planar Gunn Diode and a pHEMT side-by-side

V. Papageorgiou, A. Khalid, M. J. Steer, C. Li, and D. R. S. Cumming

School of Engineering
University of Glasgow
UK
v.papageorgiou.1@research.gla.ac.uk

Abstract—**This work presents the implementation of planar Gunn diodes and pseudomorphic high electron mobility transistors (pHEMTs) on the same wafer for the first time. The AlGaAs/InGaAs/GaAs heterostructures were designed for the realisation of pHEMTs on a Gallium Arsenide - based wafer. T-gate technology has been used for the maximisation of the transistor performance. Devices with a 70 nm long gate foot showed excellent DC and small-signal characteristics, with 780 mS/mm peak transconductance and 200 GHz f_{max}. Planar Gunn diodes were fabricated in parallel with the pHEMTs, sharing most of the fabrication steps. The diodes produce oscillations with 87.6 GHz maximum frequency and -40 dBm maximum output power.**

I. INTRODUCTION

The first planar Gunn diodes demonstrated that devices providing oscillations in the millimetre – wave frequency range can be integrated in a single chip as part of monolithic microwave integrated circuits (MMICs) [1]. Efforts in subsequent years have focused on increasing the Gunn diode maximum oscillation frequency and increasing the output power. The power was doubled and the phase noise significantly decreased after the introduction of extra delta-doping layers [2]. The introduction of $In_{0.23}Ga_{0.77}As$ channel layers led to an increase of the maximum oscillation frequency to 116 GHz [3].

The latest development of the planar Gunn diode incorporates $In_{0.53}Ga_{0.47}As$ channel layers on an Indium Phosphide (InP) substrate. Due to the superior characteristics of the material, the maximum oscillation frequency of the fundamental mode has been boosted to 164 GHz with -10 dBm output power [4].

The next challenge to maximize the output power is the integration of the Gunn diode with an amplifying device in a MMIC. The integration technology of HEMTs with other active devices has demonstrated very important results, like the integration of HEMTs with resonant tunneling diodes (RTDs) [5], or p-i-n photodiodes [6]. GaAs-based pHEMTs have been used extensively for the implementation of MMICs such as 60 GHz transmitters and receivers [7], Q-band high power amplifiers [8] and balanced distributed mixers with high conversion gain [9]. Therefore, the realization of planar Gunn diodes with pHEMTs on the same wafer, could potentially be a very significant development for the improvement of the oscillation characteristics. The integration of the diode with a pHEMT amplifier is expected to maximize the output power, while the use of a mixer circuit would lead to the extraction of signals in much higher frequencies. For the above reasons, the monolithic fabrication of the two devices is essential for the implementation of high-power, high-frequency oscillators.

Previously it has not been possible to integrate Gunn diodes with field effect transistors (FETs) on the same chip since the former is typically a vertical transport device, whereas the latter is a lateral transport device. However, Gunn instabilities on a pHEMT substrate have been reported in the past indicating the high possibility of the successful fabrication of both devices using the same active layers [10]. We show the implementation of a planar Gunn diode and a FET side-by-side on the same substrate for the first time. The layer structure of the substrate was designed for the implementation of GaAs-based pHEMTs. In the next section, the fabrication procedure and the characterization techniques of the planar Gunn diode and the pHEMT, are described in detail. A 70 nm T-gate technology was incorporated for the optimization of the DC and the small-signal characteristics of the transistor.
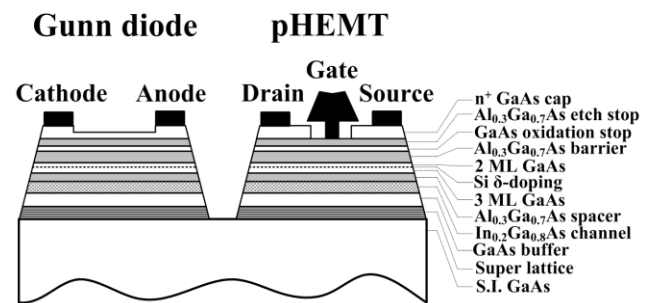

Figure 1.   The pHEMT layer structure and the side-by-side devices.

II. FABRICATION PROCEDURE

The pHEMT layers were grown on a 640 μm thick GaAs substrate, using molecular beam epitaxy (MBE). The first lithographic step on the complete wafer is the definition of the mask windows before the evaporation of the metal for the Ohmic contacts. A bi-layer of 12 % dissolved polymethyl methacrylate (PMMA) and 2.5 % PMMA was spun at 5 k rpm and baked at 154 ^{o}C on a hot plate for 90 s. All the patterns in this work were defined by electron beam lithography (EBL) using a Leica Microsystems VB6 vector beam exposure tool. After development, a multi-layer stack of various metals was evaporated for the formation of the Ohmic contacts of the devices. In this step, the drain and source electrodes of the transistor were deposited at the same time along with the anode and cathode electrodes of the diode. The metal stack used consists of 14 nm Au/14 nm Ge/14 nm Au/11 nm Ni/70 nm Au which is well known for providing low contact resistance on highly doped GaAs cap layers. After annealing the samples at 320 ^{o}C for 20 s followed by 400 ^{o}C for 30 s, the contact resistivity of the electrodes was equal to 0.32 Ω.mm. The second lithographic step is the definition of the mesa areas of the two devices. Again, a PMMA mask layer was used in order to protect the active layers, while the surrounding area was etched away by a 10:1 - $C_6H_8O_7:H_2O_2$ citric acid solution. The 12 % PMMA mask was hard baked for two hours in a convection oven at 180 ^{o}C, to ensure that it would not get damaged by the etching solution.

The third lithography step is the fabrication of the T-gate and the recess etching of the top, highly doped, cap layer. A 3D EBL technique has been applied for the formation of the T-shaped profile on the resist. Two layers of 4 % PMMA were deposited for the definition of the narrow foot of the T-gate. Afterwards, a more electron sensitive layer of 12 % PMMA was deposited on top for the creation of the wide head. A final layer of 2.5 % PMMA was deposited for the creation of the undercut that is needed for the lift-off process. All the above PMMA layers were spun and baked on a hot plate under the same conditions mentioned earlier. The foot areas were exposed to a high dose of electrons to ensure that the beam penetrates the total resist stack with 850 nm height. The large head areas were exposed to a lower dose, so that the electron beam does not penetrate further than the 12 % PMMA layer. After developing the resist layers the recess etching was performed, using a succinic acid solution with adjusted PH at 5.9 for 20 s. Finally, a metal stack of 15 nm Ti/15 nm Pt/400 nm Au was evaporated to form the Schottky contact of the T-gate.

After the fabrication of T-gates, the metal layers of 20 nm Ti/500 nm Au were deposited, to form the coplanar waveguide (CPW) pads for both devices, having the characteristic impedance of 50 Ω. The final step of the total fabrication procedure is the partial etching of the cap layer between the electrodes of the Gunn diode. The transistors were covered by PMMA to protect from further etching and the same etching solution of succinic acid was applied for 7 s to the Gunn diodes. Thus, the current of the diodes was reduced by small etching steps to prevent burning out, that can be caused by the high electric field occurring at the Ohmic contacts. The current was finally reduced to the same level as the current of

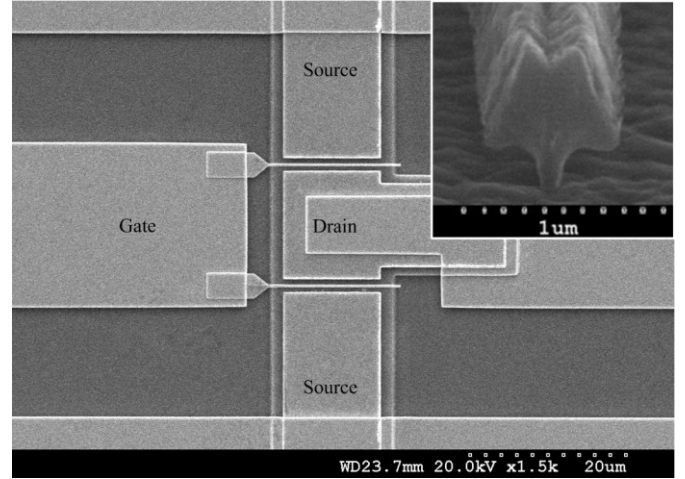the transistor operating at the bias conditions with maximum transconductance.

Figure 2. Scanning electron microscope pictures of the fabricated 12 μm wide HEMT and the 70 nm long T-gate. The drain-source seperation is 1.5 μm and the head of the T-gate is 650 nm long.
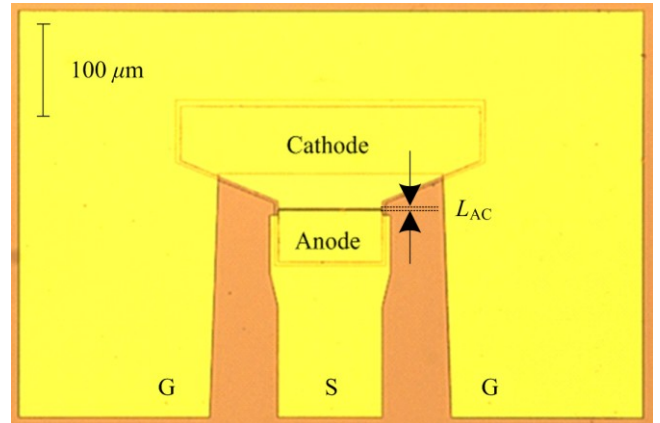

Figure 3. Optical image of Gunn diode with 60 μm width and 1.3 μm L_{AC}. The signal pad is 60 μm wide and the signal-ground gap of the CPW is 40 μm.

III. RESULTS AND DISCUSSION

The DC characterization of the devices was performed using an Agilent Technologies B1500A semiconductor analyser. The drain current versus the applied drain voltage of the fabricated T-gate HEMTs is illustrated in Fig. 4 where various voltages were applied to the gate. The devices show excellent current density with a maximum drain current of about 780 mA/mm when applying 1 V gate bias. The pinch-off of the devices is achieved by applying a gate voltage below -600 mV. The transistors provide the maximum transconductance of 780 mS/mm at a gate and drain bias of 250 mV and 1.0 V respectively (Fig. 5). The two plots indicate that the devices operate at enhancement mode as a small bias to the gate is required to increase the drain current and maximize the transconductance. Therefore, a shorter

recess etching treatment could be applied in future experiments, to improve the performance of the devices.
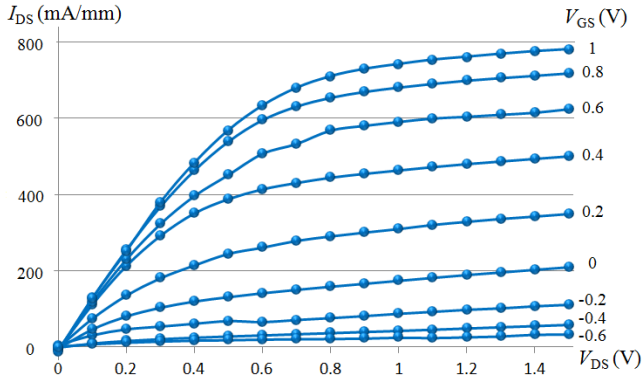

Figure 4. Current-voltage (I_{DS} - V_{DS}) characteristics of the 70 nm T-gate pHEMT with variable V_{GS} .
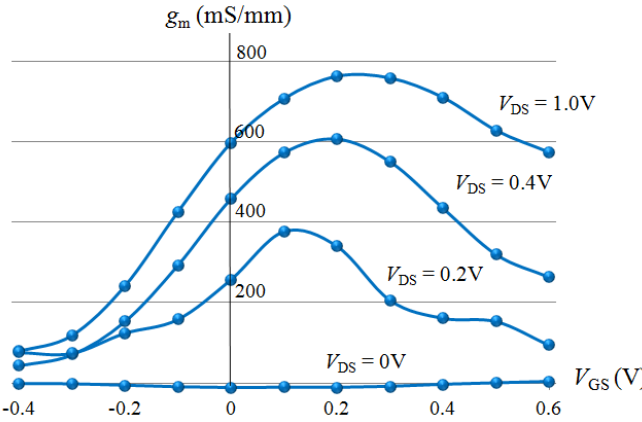

Figure 5. Transconductance-voltage (g_m - V_{GS}) characteristics of the 70 nm T-gate pHEMT with variable V_{DS} .

The small-signal characteristics of the devices were measured using an Agilent vector analyser from 10 MHz to 110 GHz. The frequency dependence of the current gain $H(2,1)$ and the maximum available/stable gain (MAG/MSG) for a 12 um - wide device are illustrated in Fig. 6. The gate was biased at 200 mV and the drain at 1 V. By following the -20 dB/decade extrapolation, the cut-off frequency (f_T) of the transistor was equal to 90 GHz and the maximum frequency of oscillation (f_{max}) was equal to 200 GHz. The DC and the small-signal performance of the pHEMTs fabricated in this work are very satisfying in comparison with the state-of-the-art GaAs pHEMTs using a 0.15 μm [11] and a 0.1 μm [12] T-gate technologies.

The current versus the applied voltage (I-V) of a fabricated planar Gunn diode is shown in Fig. 7. The device has a width of 60 μm and the anode to cathode seperation (L_{AC}) is equal to 1.3 μm. The negative differential resistance (NDR) of the diode appears after biasing the device with voltage

between 2.5 V and 2.7 V. Due to the impact ionisation effect and the relatively high resistivity of the Ohmic contacts, the NDR of the device is difficult to observe.
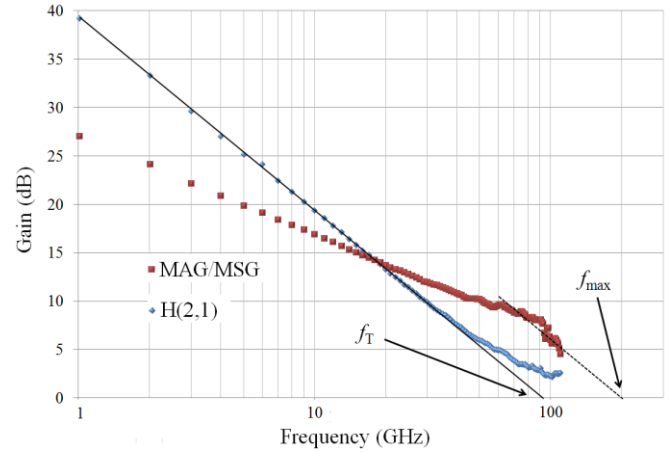

Figure 6. Frequency dependence of the current gain and the maximum available gain/maximum stable gain for the 2-finger, 12 μm wide HEMT with 70 nm long T-gate. The maximum frequency of oscillation is approximately 200 GHz and the cut-off frequency is 90 GHz when the gate is biased at 200 mV and the drain at 1 V.

The oscillation of the diode was investigated using an E4448A Agilent Technologies spectrum analyser and an ACP 110-100 GSG CascadeMicrotech W-band probe. A WHMP-10 Faran Technology W-band mixer was used for the extension of the measured frequency range of the spectrum analyser. A PM4 Erickson power meter was also used for the accurate measurement of the generated power level. The measured spectrum of the 1.3 μm device is presented in Fig. 8. The device oscillates at 87.6 GHz with a maximum output power of -40 dBm when the device is biased at 3.42 V.
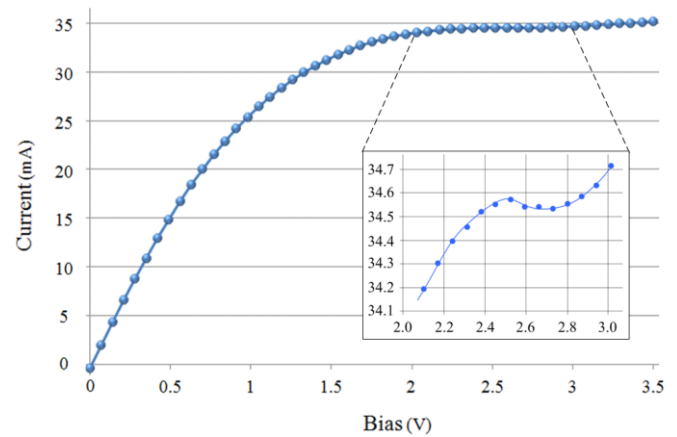

Figure 7. Current-voltage (I-V) characteristics of the 60 μm wide Gunn diode with 1.3 μm L_{AC}. The negative differential resistance of the device is hardly observed, due to to the impact ionisation effect and the relatively high contact resistivity of the electrodes.
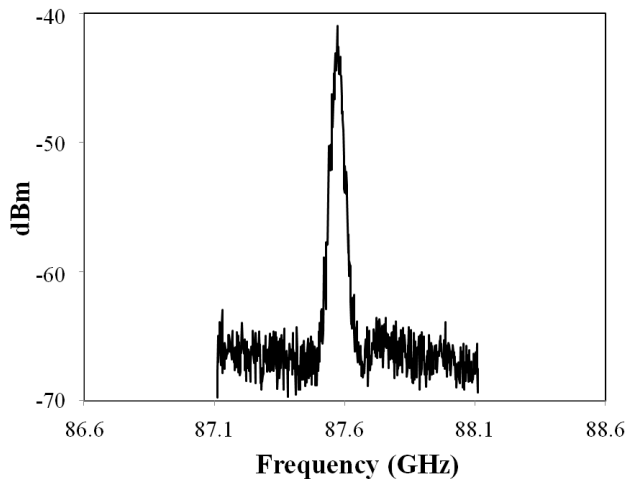
Figure 8. Measured spectrum of a 60 μm wide Gunn diode with 1.3 μm L_{AC}.

The performance of the device is very promising considering that the layer structure of the substrate was not designed for a Gunn diode. Although the oscillation frequency is lower than expected from this geometry, the power level is comparable with the one generated by the first planar Gunn diode [1]. In addition, it is estimated that the generated power is limited by the relatively high access resistance provided by the simply highly-doped GaAs cap layer. A future development of the layer structure, by including graded layers of InGaAs as a cap layer, would lead to a significant reduction of the contact resistance [13]. In addition, the introduction of extra delta-doping layers would significantly improve the performance of the Gunn diode [2]. These modifications are expected to enhance the performance of pHEMT as well. The reduction of the access resistance is expected to increase the gain of the transistor and the maximum frequency of oscillation.

IV. CONCLUSION

We have presented the implementation of a planar Gunn diode and pHMET side-by-side for the first time. The pHEMT using a 70 nm T-gate technology provides a peak transconductance of 780 mS/mm with a 200 GHz f_{max}. A 60 μm wide planar Gunn diode with 1.3 μm anode to cathode separation oscillates at 87.6 GHz with a maximum output power of -40 dBm. The future development of the layer structure is expected to significantly improve the performance of both devices leading to the implementation of MMIC for high power oscillators.

V. ACKNOWLEDGEMENTS

REFERENCES

[1] A. Khalid, N. J. Pilgrim, G. M. Dunn, M. C. Holland, C. R. Stanley, I. G. Thayne, and D. R. S. Cumming, "A planar Gunn diode operating above 100 GHz," *IEEE Electron Device Lett.*, vol. 28, no. 7, pp. 849–851, Oct. 2007.

[2] Chong Li, A. Khalid, Sonia H. Paluchowski Caldwell, N. J. Pilgrim, M. C. Holland, G. M. Dunn, and D. R. S. Cumming, "Enhancement of power and frequency in HEMT-like planar Gunn diodes by introducing extra delta-doping layers," *Microwave and Optical Component Letters,* vol. 53, no.7, pp. 1624-1626, Jul. 2011.

[3] Chong Li, Ata Khalid, Sonia H. Paluchowski Caldwell, Martin C. Holland, Geoff M. Dunn, Iain G. Thayne, and David R. S. Cumming, "Design, fabrication and characterization of In0.23Ga0.77As-channel planar Gunn diodes for millimeter wave applications," *Solid State Electronics,* vol. 64, no. 1, pp. 67-72, Oct. 2011.

[4] A. Khalid, C. Li, V. Papageogiou, G. M. Dunn, M. J. Steer, I. G. Thayne, M. Kuball, C. H. Oxley, M. Montes Bajo, A. Stephen, J. Glover, D. R. S. Cumming, " Planar Gunn Diodes Operating at a Fundamental Frequency of 164 GHz," *IEEE Electron Device Letters,* vol. 34, no. 1, pp. 39-41, Jan. 2013

[5] K. Maezawa, T. Mizutani, "InP-based resonant tunnelnig diode/HEMT integrated circuits for ultrahigh-speed operation," *Conference Proceedings - International Conference on Indium Phosphide and Related Materials 2006.*

[6] K. Takahata, Y. Muramoto, H. Fukano, K. Kato, A. Kozen, S. Kimura, Y. Imai, Y. Miyamoto, O. Nakajima, and Yutaka Matsuoka, "Ultrafast monolithic receiver OEIC composed of multimode waveguide p-i-n photodiode and HEMT distributed amplifier," *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 6, no. 1, pp. 31-37, 2000.

[7] S. E. Gunnarsson, C. Kärnfelt, H. Zirath, R. Kozhuharov, D. Kuylenstierna, A. Alping, and Christian Fager, "Highly Integrated 60 GHz Transmitter and Reaceiver in a GaAs pHEMT Technology," *IEEE Journal of Solid-State Circuits*, vol. 40, no. 11, pp. 2174-2186, Nov. 2005.

[8] F. Y. Colomb, and A. Platzker, "A 3-Watt Q-Band GaAs pHEMT Power Amplifier MMIC For High Temperature Operation," in *IEEE Int. Microwave Symp. Dig.*, pp 897–900, June 2006.

[9] F.-C. Chang, P.-S. Wu, M.-F. Lei, and H. Wang, "A 4–41 GHz Singly Balanced Distributed Mixer Using GaAs pHEMT Technology," *IEEE Microwave and Wireless Components Letters*, vol. 17, no. 2, pp. 136-138, Feb. 2007.

[10] G. M. Dunn, A. Phillips, and P.J. Topham, "Current instability in power HEMTs," *Semiconductor Science and Technology*, vol. 16, no. 7, pp. 562-566, 2001.

[11] D. C. Dumka, M.-Y. Kao, E. Beam, T.-M. Chou, H.-Q. Tserng, and D. M. Fanning, "Development of Ka-band GaAs pHEMTs with Output Power over 1 W/mm," *Compound Semiconductor Integrated Circuit Symposium 2010.*

[12] C. Teyssandier, H. Stieglauer, E. Byk, A.-M. Couturier, P. Fellon, M. Camiade, H. Blanck, and D. Floriot, "0.1μm GaAs pHEMT Technology and Associated Modelling for Millimeter wave Low Noise Amplifiers," *Proceedings of the 7th European Microwave Integrated Circuits Conference 2012.*

[13] N. Takumi, I. Hiroshi, N. Osaake, and I. Tadao, "Non-alloyed Ohmic contacts to n-GaAs using compositionally graded InxGa1-xAs layers," *Japanese Journal of Applied Physics*, vol. 27, no. 9, p. 1718, 1988.