The Development of Planar Gunn Diodes for the realisation of MMIC Oscillators

V. Papageorgiou, A. Khalid, C. Li, G. M. Dunn, and D. R. S. Cumming
School of Engineering
University of Glasgow
UK
v.papageorgiou.1@research.gla.ac.uk

Abstract

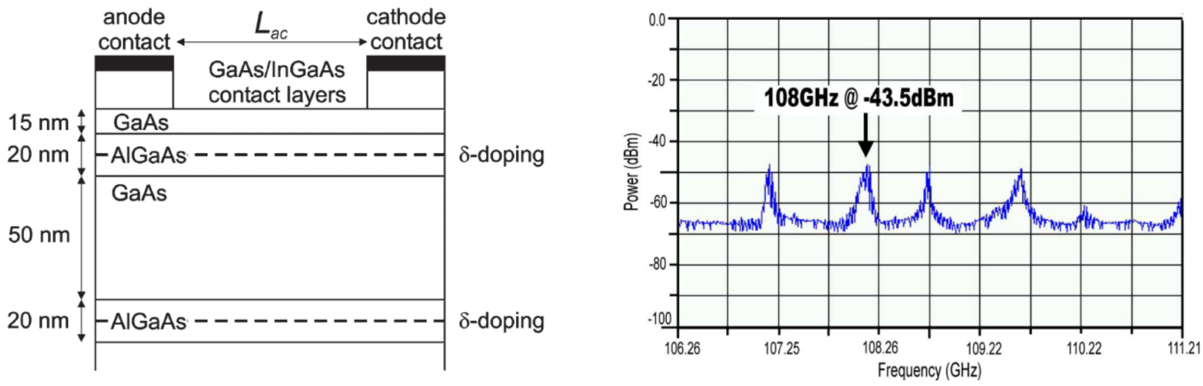
This paper presents the development of planar Gunn diodes over the last few years for the implementation of millimetre-wave sources. The fabrication procedure incorporates electron beam lithography and the oscillation frequency is determined by the anode-to-cathode distance. The evolution of the material design for the maximisation of the maximum frequency of oscillation and the enhancement of the generated power is presented in this paper. The recent implementation of a planar Gunn diode with a high-electron mobility transistor on the same substrate is also described in this work.

Introduction

After the discovery of Gunn oscillations [1] Gunn diodes have been established as low-noise sources for the mm-wave regime where GaAs and InP based devices demonstrate up to hundreds of milliwatts of generated power [2]. Vertical diodes based on GaAs have recently been presented for automotive applications where the devices generate oscillations at 77 GHz [3]. Similar oscillator systems have been presented based on InP, demonstrating oscillations beyond 150 GHz in the fundamental mode of operation [4]. However, the implementation of conventional diodes requires increased complexity, size and cost, and there is no compatibility with the monolithic microwave integrated circuit (MMIC) technology.

A significant development of vertical Gunn diodes has recently been presented, demonstrating a simplified fabrication procedure for the realisation of MMIC-compatible devices [5]. The latter presents oscillations at 37.2 GHz with 2.5 mW maximum generated power. Although vertical Gunn diodes generate high output power, the maximum oscillation frequency is determined by the fixed thickness of the epitaxial layers. Thus, the oscillation frequency is characteristic for every wafer where limited tuning can be applied through the external circuits. In addition, the lowest channel thickness for functional devices is limited due to the increased heating caused by the enormous current flowing through the structure.

The demonstration of the first field-effect controlled transferred electron devices (FECTEDs) [6] and the observation of Gunn instabilities in power HEMTs [7] have been the base for the realisation of high frequency planar mm-wave sources. Based on the above configurations, Khalid et al. [8] presented the first planar Gunn diodes based on GaAs, generating oscillations above 100 GHz. In subsequent years, a significant development on the design of the epitaxial layers has been conducted for the maximisation of the generated power. The individual improvements in the layer design are presented in this work, as well as the realisation of planar Gunn diodes and pHEMTs on the same substrate. The possible implementation of HEMT-based amplifiers using power combiners for the enhancement of the oscillation power is described at the end of this paper.



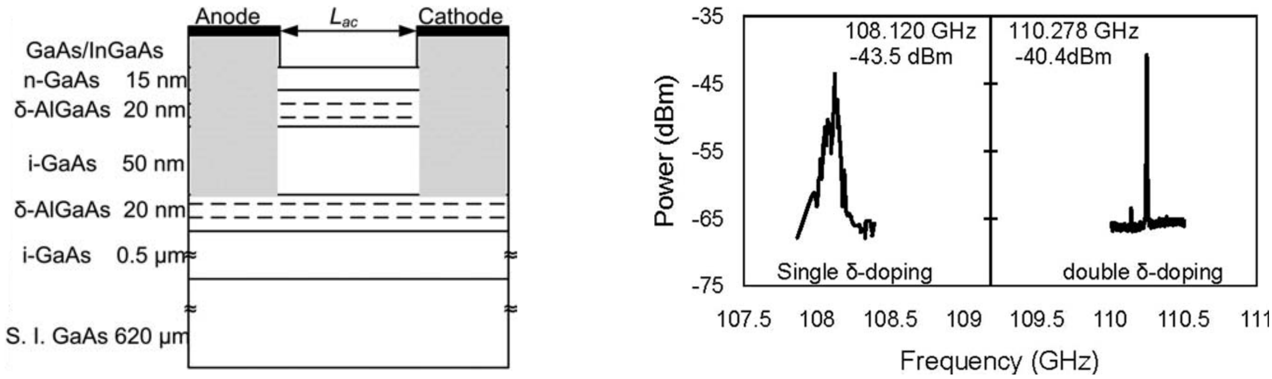
(a) (b)

Figure 1. (a) Layer structure of the AlGaAs/GaAs planar Gunn diode. (b) Measured spectrum for a 60 μm wide device with 1.3 μm anode-to-cathode separation. The pointed peak is the real signal where the rest are spurious signals [8].

<u>Planar Gunn Diodes oscillating above 100 GHz</u>

The layer structure of the first AlGaAs/GaAs planar Gunn diode operating above 100 GHz is illustrated in Figure 1.a. The channel layer is sandwiched between the two barrier layers which include the delta-doping layers providing the electrons for the channel. On top of the structure, multiple graded GaAs/InGaAs layers are grown for the formation of low resistive Ohmic contacts. These layers between the electrodes are etched so that the current is driven through the channel. The measured spectrum of a fabricated device with 60 μm width and 1.3 μm anode-to-cathode separation (L_{ac}) is depicted in Figure 1.b. The diode generates a signal at 108 GHz presenting a maximum power of -43.5 dBm. A significant advantage of the planar configuration is the accurate determination of the oscillation frequency through the control of the lithographic dimensions.

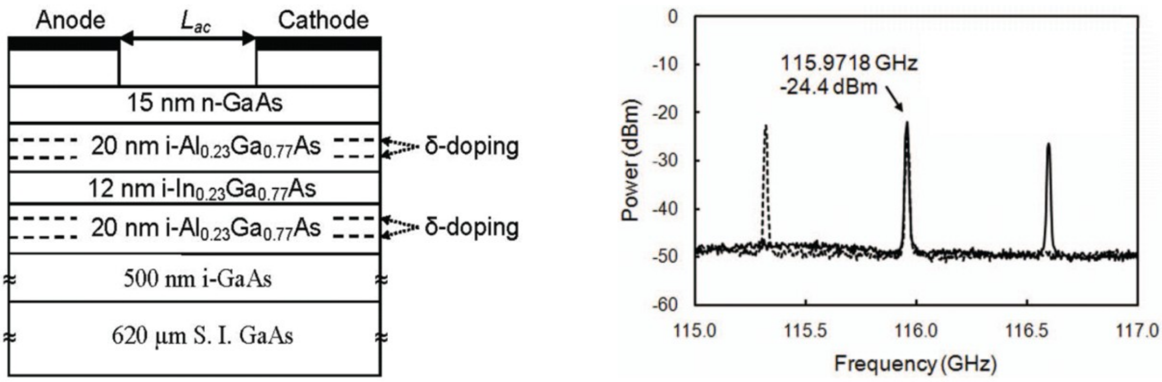
The relatively low generated power by the planar Gunn diodes described above, led to the modification of the layer structure for the enhancement of the device characteristics. The first development of the layer design incorporates the introduction of one extra delta-doping layer in each barrier layer for the increment of the electron population in the channel [9]. The modified layer structure is demonstrated in Figure 2.a. As a result, the operating current of the device is increased by a factor of approximately 2 with a proportional enhancement for the generated power. Additionally, better phase noise characteristics have been achieved after the introduction of the extra doping layers as illustrated in Figure 2.b.



(a) (b)

Figure 2. (a) Layer structure after the introduction of extra delta-doping layers. (b) Comparison between the performance of devices with single and double delta-doping [9].

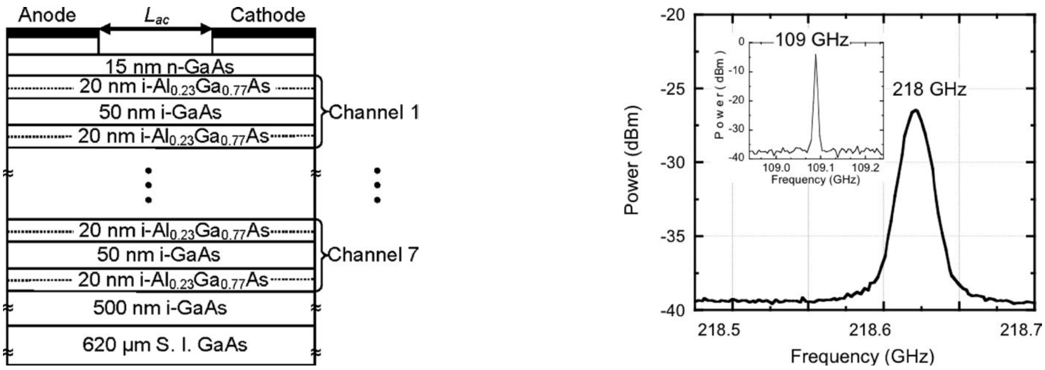
The performance of the planar Gunn diode has been boosted after the introduction of strained channel layers of $In_{0.23}Ga_{0.77}As$ on a GaAs substrate [10]. Due to the superior low-field mobility and effective conduction band density of states of the $In_{0.23}Ga_{0.77}As$ channel layer versus GaAs, the devices present a maximum generated power of -24.4 dBm at 116 GHz frequency of oscillation. The layer structure depicted in Figure 3.a also includes additional delta-doping layers.



(a) (b)

Figure 3. (a) Layer structure after the introduction of the $In_{0.23}Ga_{0.77}As$ channel layer. (b) Measured spectrum of a 1.3 μm long device [10].

The latest improvement of the layer structure for GaAs-based devices incorporates the introduction of additional quantum well channels [11]. The layer structure of the devices is depicted in Figure 4.a where seven channel layers have been used for the enhancement of the power characteristics. The current devices present a current density which is ~5-6 times higher in comparison with the single channel devices presented in [8]. As a result, 7-channel planar Gunn diodes with 1.14 μm L_{ac} generate oscillations with -4 dBm maximum power at 109 GHz. The extraction of the second harmonic of oscillation provides a signal at 218 GHz with -26.6 dBm output power.

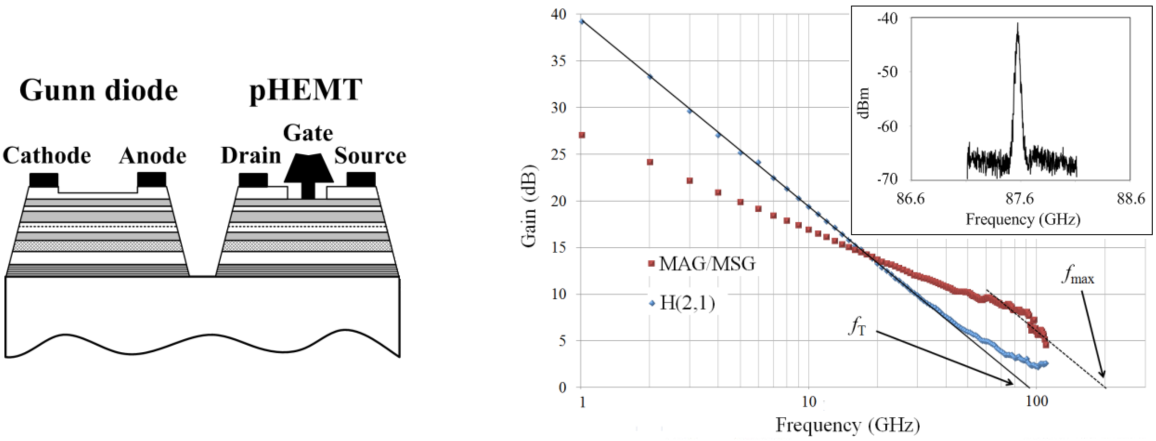


(a) (b)

Figure 4. (a) Layer structure of the seven-channel devices. (b) Measured spectrum of the fundamental (inset) and the second harmonic of a 1.14 μm long device [11].

<u>Integration of planar Gunn Diodes and a pHEMTs</u>

More recently, the potential for implementing a planar Gunn diode and a FET on the same substrate has been studied [12]. Therefore, the pHEMT can be used in the future for the realisation of MMIC amplifiers or mixers reinforcing the frequency and power characteristics of the Gunn oscillations. The layer structure used in this work has been designed for the implementation of pHEMTs. Since the two devices are implemented side-by-side, the total fabrication procedure does not require any modifications as the same steps can be applied for both the diode and the transistor. The small-signal characteristics of the pHEMT with 70 nm long T-gates and 2x12 μm width is presented in Figure 5.b. The measured spectrum of a planar Gunn diode with 1.3 μm L_{ac} and 60 μm width is also presented in Figure 5.b.



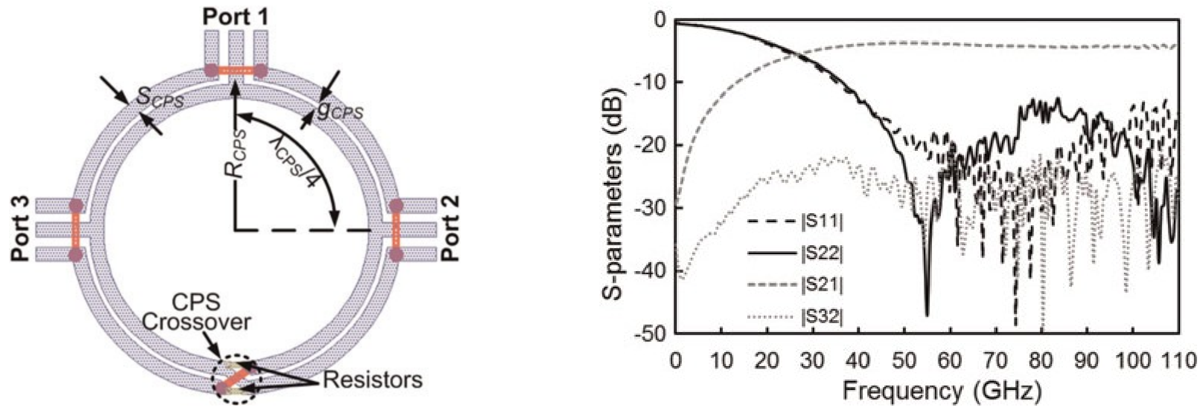
(a) (b)

Figure 5. (a) Integration of the two devices. (b) Small-signal characteristics for a pHEMT with 70 nm long T-gates and 2x12 μm width. (Inset) Measured spectrum of a 60 μm wide Gunn diode with 1.3 μm L_{ac} [12].

<u>Future realisation of MMIC oscillators</u>

Planar Gunn diodes and HEMTs can be combined in the near future with passive components for the realisation of high-power, high-frequency MMIC oscillators. Recently presented mm-wave power dividers have demonstrated excellent performance for a very broad frequency range from 44 to 110 GHz (Figure 6) [13]. The dividers, which also operate as combiners, can be connected with the HEMT devices for the composition of balanced amplifiers. This is expected to enhance significantly the power of the signal generated by the diode.

The side-by-side approach could also be applied on InP-based wafers for higher frequencies of operation since Gunn diodes fabricated on InP substrates have recently demonstrated exceptional results with fundamental-mode oscillations at 164 GHz [14].



(a) (b)

Figure 6. (a) Power combiner configuration. (b) Measured S-parameters from a 80 GHz divider [13].

Acknowledgements

The authors would like to thank the staff of the James Watt Nanofabrication Centre at the University of Glasgow for helping fabricating the devices reported in this paper. This work was supported by UK EPSRC and e2v Technologies (UK) Ltd.

References

[1] J. B. Gunn, "Microwave oscillations of current in III–V semiconductors," *Solid State Communications*, vol. 1, no. 4, pp. 88–91, Sep. 1963.

[2] H. Eisele, et al., "Submillimeter-Wave InP Gunn Devices," *IEEE Transactions of Microwave Theory and Techniques*, vol. 52 no. 10, pp. 2371-2378, Jun. 1998.

[3] A. Foster, et al., "Hot electron injector Gunn diode for advanced driver assistance systems," *Applied Physics A: Materials Science & Processing*, vol 87, no. 3, pp. 545-558, 2007.

[4] H. Eisele, et al., "High-Performance InP Gunn Devices for Fundamental-Mode Operation in D-Band (110-170 GHz)," *IEEE Microwave and Guided Wave Letters*, vol. 5, no. 11, pp. 385-387, Nov. 1995.

[5] S. Montanari, "Fabrication and characterization of planar Gunn diodes for monolithic microwave integrated circuits," in *Institute ISG1*. 2005, Forschungzentrum Julich: Julich. p. 158.

[6] L. Springer, et al., "Transferred electron effect in AlGaAs/GaAs multi-quantum-well structures," in *Proc. 27th Eur. Solid-State Device Res. Conf.*, Sep. 22–24, 1997, pp. 296–299.

[7] G. M. Dunn, et al. "Gunn instabilities in power HEMTs," *Electronics Letters*, vol. 37, no. 8, pp. 530–531, Apr. 2001.

[8] A. Khalid, et al., "A Planar Gunn Diode Operating Above 100 GHz," *IEEE Electron Device Letters*, vol. 8, no. 10, pp. 849-851, Oct. 2007.

[9] C. Li, et al., "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, July 2011.

[10] Chong Li, et al., "An In0.23Ga0.77As-based pHEMT-like planar Gunn diode operating at 116 GHz," *The 35th Intern. Conf. on Infrared, Millimeter and THz Waves,* Rome, Italy, 5th -10th September 2010.

[11] A. Khalid, et al., "A 218-GHz Second-Harmonic Multiquantum Well GaAs-Based Planar Gunn Diodes," *Microwave and Optical Technology Letters*, vol. 55, no. 3, pp. 686-688, Mar 2013.

[12] V. Papageorgiou, et al., "Monolithic Fabrication of a Planar Gunn Diode and a pHEMT side-by-side," *The 43rd European Solid-State Device Research Conference*, Bucharest, Romania, 16th-20th September 2013.

[13] C. Li, et al., "Millimeter-wave coplanar stripline power dividers," *International Journal of Microwave and Wireless Technologies*, vol. 5, no. 3, pp. 205-212, May 2013.

[14] 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.