Numerical and Experimental Investigations of Self-mixing Effect of a Planar Gunn Diode Oscillator

Ming Yan Zhong[1], David R. S. Cumming[2], and Chong Li[3]

James Watt School of Engineering, University of Glasgow, UK

[1]m.zhong.1@research.gla.ac.uk, {[2]davd.cumming.2, [3]chong.li}@glasgow.ac.uk

***Abstract* — In this paper, we investigate the self-mixing effect of planar Gunn diode oscillators numerically and experimentally. The simulation shows a 4 µm long GaAs-based heterostructure planar Gunn diode can generate not only an oscillation frequency of 27.5 GHz but also a down-converted signal of 2.5 GHz when an external signal of 30 GHz is injected to the diode. The conversion loss varies between 14 dB and 20 dB depending on the biasing condition as well as the amplitude and frequency of the input signal. Experiments confirmed the simulation results. The self-mixing effect of planar Gunn oscillators show a great potential for simplifying RF frontends for millimeter-wave applications such as 5G and beyond communications, radar, and imaging systems.**

***Keywords* — Gunn diode, self-mixing effect, heterodyne, down-conversion.**

I. Introduction

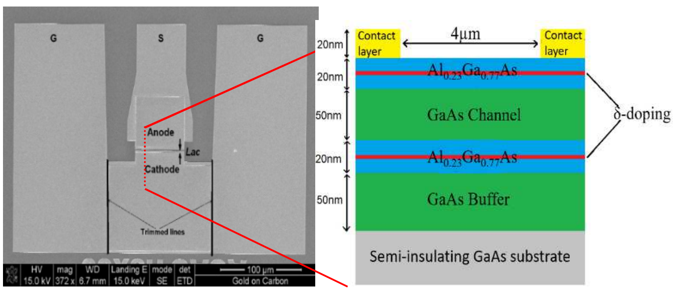
Millimetre-wave (mm-wave) refers to the frequency band in the electromagnetic spectrum from 30 GHz to 300 GHz. It has been applied in many fields in the recent years such as wireless communications, security imaging and remote sensing, radio astronomy, and earth science [1]. Compared with microwave, mm-wave has shorter wavelength, meaning it is suitable for dense communication networks, such as personal area networks (PLANs) to enhance spectrum utilization and data rate [2]. As the core of mm-wave systems, the front-end module, which generally contains local oscillators (LOs), mixers, amplifiers, and filters, becomes more and more challenging due to smaller size and lower efficiency. New devices and front-end architectures with higher efficiency and simplicity are always desirable. For example, in a heterodyne system, the incident signal (RF) is mixed, also called down-converted, with a defined local oscillation signal to an intermediate frequency (IF) signal, that always requires an external mixer and a local oscillator (LO) [3]. At mm-wave frequencies, it's extremely challenging to obtain high performance LOs and mixers using a single semiconductor technology. The separation of mixers and local oscillators requires bulky and costly hybrid integration. Fortunately, planar Gunn diodes could be a game changer because it has a heterostructure structure that is compatible with high electron mobility transistors (HEMTs). Plus their intrinsic nonlinearities in conductance and capacitances make them ideal as mixers like other nonlinear devices [4]. Thus, fully integrated monolithic mm-wave frontends with all active devices fabricated on a single substrate using the HEMT-like planar Gunn diode technology is possible [5] [6] [7].

In this paper, we'll investigate the self-mixing effect of a planar Gunn diode using a commercially available physics-based numerical modelling tool. The DC characteristics, time-domain waveforms and the spectrum of self-oscillation and self-mixing effect of the device are successfully predicted by the numerical tool. Experimental results further confirm and validate the simulation results, indicating planar Gunn diodes have the potential to simply mm-wave frontends for many applications.

II. The Planar Gunn Diode

A. Device Structure

A planar Gunn diode having a GaAs channel that is sandwiched by two silicon δ-doped $Al_{0.23}Ga_{0.77}As$ layers was investigated in this study. Fig.1 illustrates a scanning electron microscopy (SEM) image of the fabricated diode, constructed in a coplanar waveguide (CPW) test structure, and the cross-sectional view of its epitaxial layers. The anode-cathode distance, L_{ac}, and the velocity of Gunn domains, v_{domain}, determine the oscillation of frequency of the diode. The relationship is approximately as $f_{osc}=(L_{ac}-L_{dead})/v_{domain}$ if the dead-zone L_{dead} is considered [5]. For a given material structure as shown in Fig. 1 and a fixed L_{ac}, f_{osc} varies as change of bias voltage. This is because the domain velocity varies as bias voltage changes.



(a) (b)

Fig. 1. (a) Scanning electron micrograph of a typical planar Gunn diode oscillator with coplanar waveguide (CPW) test structure. (b) Illustration of the epitaxial layers of the Gunn diode used in this study.

B. Numerical model in COMSOL

The Gunn diode is modelled using a commercial software COMSOL. COMSOL solves carrier transport equations, Poisson's equation and the carrier continuity equations using the finite element method (FEM). A 2D model was constructed to save computing time. The anode and cathode electrodes are modelled with good Ohmic contact that has a metal contact boundary condition and a 20 nm highly doped GaAs with carrier concentration of 2×10^{20} cm^{-3} underneath. Two $Al_{0.23}Ga_{0.77}As$ barrier layers are lightly doped with electron concentration of 5×10^{16} cm^{-3}. The GaAs channel and buffer are modelled unintentionally n-doped with electron concentration of 10^{2} cm^{-3}. Gunn Effect occurs under high electric field however COMSOL has no such built-in mobility model, a user defined high-field mobility model was used [9]:

$$\mu_h = \frac{\mu_0 + (\frac{V_{sat}}{E})(\frac{E}{E_0})^4}{1+(\frac{E}{E_0})^4} \quad (1)$$

where μ_0 is the low field mobility of GaAs, v_{sat} is the saturation velocity, E_0 is the reference electric field and E is the dependence electric field. When a device is biased with a voltage greater than the threshold voltage i.e., $E > E_0$, the electron transfer effect will occur and result in reduction of overall mobility, and therefore lowered current. The built-in continuity/heterojunction condition is used with continuous quasi-Fermi level model. In addition, trap-assisted recombination condition is used with Shockley-Read-Hall model and the electron/hole lifetime is 0.1 µs. Fig. 2 illustrates the band structures and electron concentration distribution of the diode when the bias voltage is 0 V. A triangle quantum well and a 2DEG are visible at the interface between the top $Al_{0.23}Ga_{0.77}As$ barrier and the GaAs channel. Other material properties used in the modelling are shown in Table 1.

Table 1. Summary of other properties of the materials used in the simulation.

Parameters		GaAs	AlGaAs
Relative permittivity		12.9	12.2
Bandgap (eV)		1.414	1.71
Affinity (eV)		4.07	3.82
Effective conduction band density of states (cm^{-3})		4.7×10^{17}	5.9×10^{17}
Low field mobility ($\mathrm{cm}^2\cdot\mathrm{V}^{-1}\mathrm{s}^{-1}$)		8500	4000
Electron saturation velocity ($\mathrm{cm}\cdot\mathrm{s}^{-1}$)		1×10^{7}	0.8×10^{7}

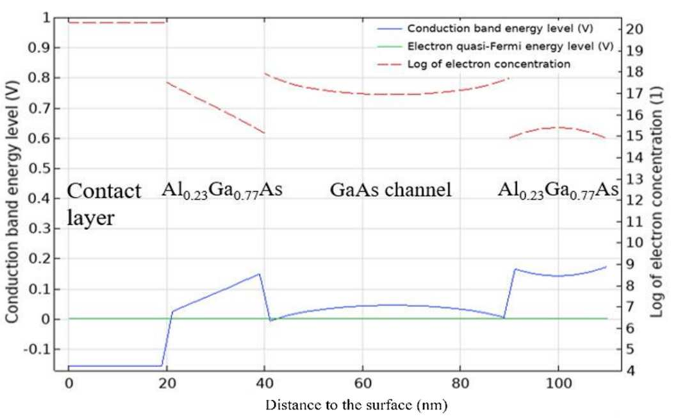


Fig. 2. Band structures and electron distribution of a 4 µm planar Gunn diode.

C. Device fabrication

The anode and cathode are defined by using electron beam lithography (EBL). Ohmic contacts are formed by evaporating Pd/Ge/Au/Pd/Au and annealed at 400 ºC for 60 seconds. Additionally, 1:1:10 H_2O_2:H_2O:H_2SO_4 was used to etch the mesa for 90s. 200 nm gold was evaporated to form CPW pads for RF and DC measurements. At last, the unwanted GaAs cap between electrodes were etched away by dipping in 3:1 citric acid:H_2O_2 solution for 20 seconds. More detailed fabrication process can be found elsewhere [11].

III. EXPERIMENTAL AND NUMERICAL RESULTS

A. Stationary simulation

Stationary study provides IV characteristics of the diode. By using auxiliary sweep function, the IV curve of a 4 µm device is derived and plotted against the experimental results as shown in Fig.3. When the bias voltage reaches around 3V, the Gunn diode starts exhibiting negative differential resistance or NDR where the current decrease as the voltage increase. The slight discrepency between the measured and simulated resutls is probably due to the self heating which would be considered in the future study.

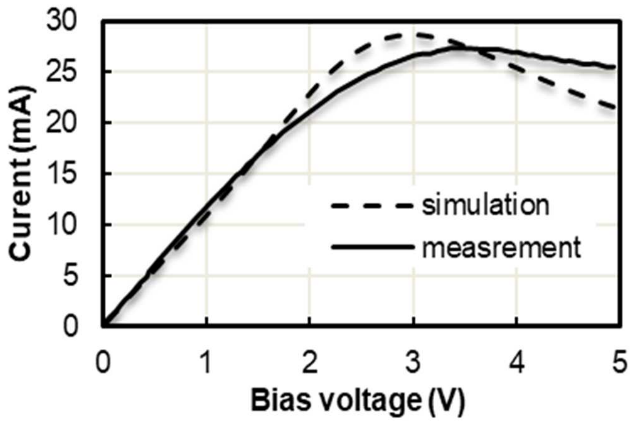


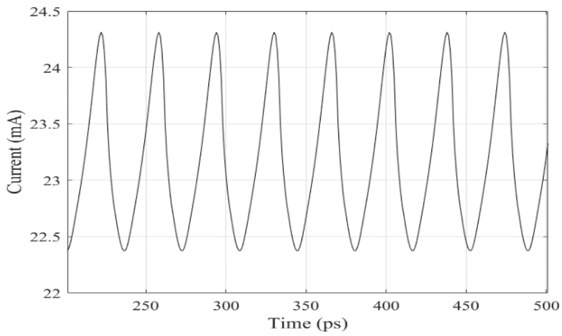
Fig. 3. Measured and simulated I-V characteristics of a 4 µm planar Gunn diode.

B. Modelling the self-oscillation of Gunn diode

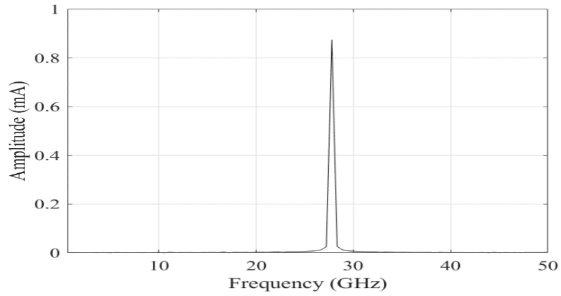
Self-oscillation simulation of the Gunn diode is modelled using COMSOL's time-dependent solver. A ramp up function for bias voltage was used and the slope was set to be $1\mathrm{x}10^{10}$ which means the bias voltage ramps up to 4.5 V in 100 ps. Fig. 4 shows the simulated waveform in time domain and its Fourier Transform in frequency domain. Note the amplitude shown here is current. The diode oscillated at 27.5 GHz at 4.5 V bias voltage, which marched the experimental results very well.

C. The self-mixing effect

Gunn diodes have intrinsic nonlinearities in their conductance and capacitance that make them possible to mix with incoming signals in addition to their self-oscillations. In COMSOL, we deliberately injected a 30 GHz (f_{RF}) sinusoidal signal with an amplitude of 10 mV between the anode and cathode when the bias voltage was set at 4.5 V and the corresponding waveform and its spectrum are shown in Fig. 5 where both self-oscillation (f_{LO}=5 GHz) and self-mixing effect (f_{RF} - f_{LO} =30 GHz-27.5 GHz = 2.5 GHz) are seen. The 2nd order mixing ($2f_{LO}$-f_{RF}=25 GHz) is also visible in Fig. 5b.

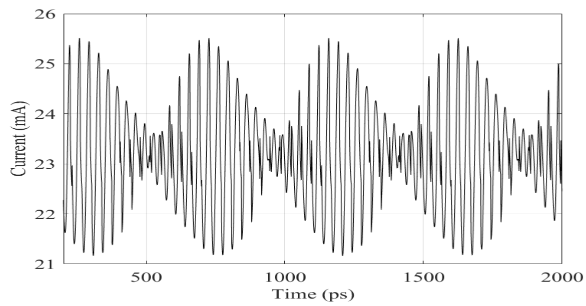


(a)

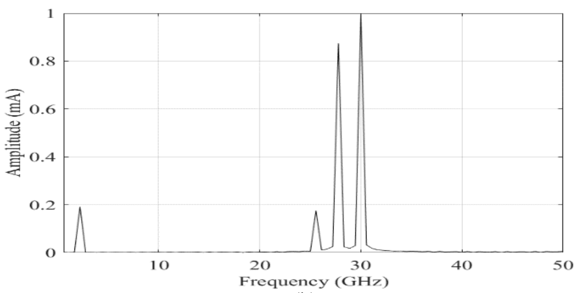


(b)

Fig. 4. (a) waveform in time domain and (b) the corresponding spectrum modelled in COMSOL.



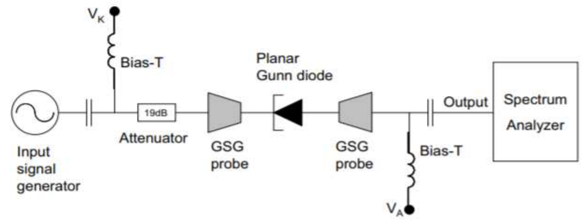
(a)



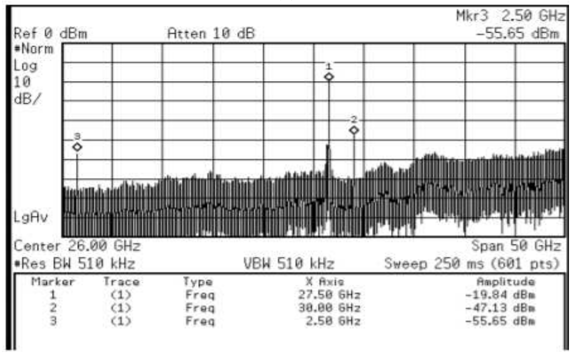
(b)

Fig. 5. Simulated self-mixing effect of a planar Gunn diode when it is biased at 4V (a) waveform in time domain and (b) its frequency spectrum.

To verify the simulation results, we trimmed the side grounds of the coplanar waveguide and converted the one-port Gunn diode to be a two-port device (Fig.1a). The trimmed diode was measured in a setup shown in Fig. 6. The diode was biased through two bias-tees (Anritsu 250V). The incident signal was generated by an external signal generator (Wiltron 68369B) to the cathode side of the Gunn diode through a Formfactor's ground-signal-ground (GSG) ACP probe. A spectrum analyzer (Agilent 4448A) was connected to the anode side to measure the output of the diode. Fig. 7 shows a snapshot of the spectrum analyzer where the self-oscillation frequency of 27.5 GHz, incident signal of 30 GHz and the down-mixed signal of 2.5 GHz are shown. Note the diode was biased at 4.22 V and the DC current was 24.5 mA [5]. Discrepancy on bias voltage and current between the simulation and experiment is due to system loss which include probes, cables, and bias tees. The measured conversion loss of target planar diode is around 20±2.5 dB [5].



(a)



(b)

Fig. 6. (a) Illustration of the measurement setup and (b) the spectrum shown on the spectrum analyser, where 1, 2 and 3 indicate the self-oscillation signal frequency of the diode, the incident RF signal and the IF signal.

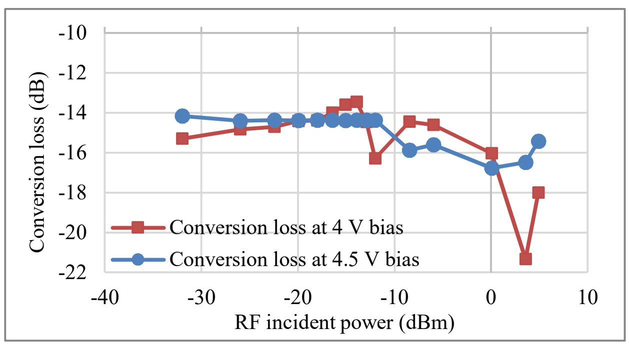


Fig. 7. Conversion loss (dB) VS amplitude of the incident wave (V) at 4.0 V and 4.5 V.

We numerically investigated the relationship between the power of the incident wave and the conversion loss. The power was varied from – 32 dBm to 5 dBm for two biasing conditions 4.0 V and 4.5 V and the results are shown in Fig. 7. One can see the conversion loss remain almost constant while the power of the input signal small however once the input signal's strength is increased. The conversion loss decreases at 4.0 V but tends to be stable at 4.5 V.

Furthermore, we investigated the linearity of the IF output power against the RF input power and the results are shown in Fig. 8. From this we can see that the Gunn diodes has a linear relationship between the input power and down-converted IF signal.

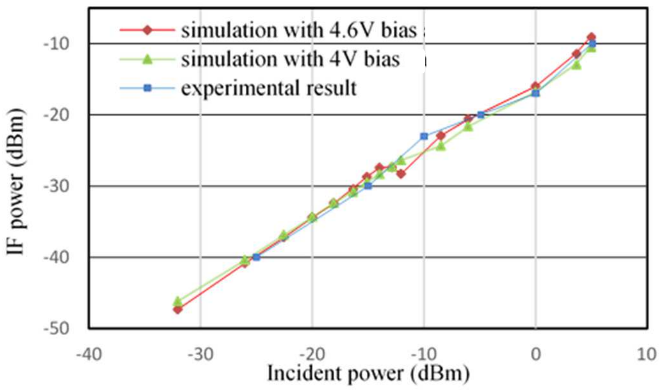


Fig. 8. Relationship with RF power and IF power

Both simulation and experimental results indicate that the conversion loss of the diode is around 20 dB at 30 GHz that is slightly higher than other nonlinear devices such as barrier diode (SBD) and field effect transistor at similar frequency range [12] [13]; however planar Gunn diodes have the advantage of self-mixing that prevents from using external local oscillators. The demonstrated planar Gunn diode has comparable conversion loss to other self-oscillating devices such as resonant tunnelling diodes at the frequency of interest, as shown in Table 2.

Table 2. Performance comparison of self-oscillating mixers

Frequency (GHz)	Conversion loss (dB)	LO power (dBm)	Ref.
11	10	-40	[14]
87	25	-53	[15]
350	10	-11	[16]
30	20	-20	This paper

IV. Conclusions

In this paper we have demonstrated the self-mixing effect of a planar Gunn diode using both numerical and experimental approaches. A 4 μm AlGaAs/GaAs HEMT-like planar Gunn diode generates a 27.5 GHz oscillation and down-converts a 30 GHz RF signal to 2.5 GHz. Approximately 20 dB conversion loss was obtained. Future work can be concentrated on improving the conversion efficiency using more compact design of the device, implementing impedance matching circuit and other materials e.g. InGaAs [17]. Nevertheless, this work shows that Gunn diodes have the potential to be used as self-oscillating mixers to simply RF front-ends in novel mm-wave systems.

References

[1] K. C. Huang and Z. C. Wang, *Millimeter wave communication systems*, John Wiley & Sons, 2011.

[2] D. P. Jaco and S. Saurabh, *Millimeter-wave power amplifiers*, Springer, 2017.

[3] R. A. Lewis, "A review of terahertz detectors," *Journal of Physics D: Applied Physics*., vol. 52, 2019.

[4] 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, pp. 849-851, Oct. 2007.

[5] L. B. Lok, C. Li, A. Khalid, N. J. Pilgrim, G. M. Dunn, and D. R. S. Cumming, "Demonstration of the self-mixing effect with a planar Gunn diode at millimeter-wave frequency," in *IRMMW-THz 2010 - 35th Int. Conf. Infrared, Millimeter, Terahertz Waves, Conf. Guid*., pp. 9–10, 2010.

[6] M. J. Lazarus, E. D. Bullimore, and S. Novak, "A sensitive millimeter wave self-oscillating Gunn diode mixer." *Proceedings of the IEEE*, vol. 59, pp. 812-4, May 1971.

[7] J. Krasavin and H. Hinrikus, "Performance and optimization of Gunn self-oscillating mixer." *IEEE Microwave Guided Wave Letts*., vol. 5, pp. 177-9, Jun. 1995.

[8] M. Ali, "Design and simulation of planar electronic nanodevices for terahertz and memory applications," Ph.D. thesis, Univ. of Manchester, p. 158, 2013.

[9] M. Pokorný and Z. Raida, "Multi-physical model of Gunn diode," in *17th Int. Conf. Microwaves, Radar Wirel. Commun*, pp. 2–5, 2008.

[10] G. Rieke, *Detection of Light*, 2nd ed., Cambridge University Press, pp. 276-300, 2002.

[11] C. Li, "Design and characterisation of millimetre-wave planar Gunn diode and integrated circuits," Ph.D. thesis, Univ. of Glasgow, p. 97, 2012.

[12] A. Rogalski and F. Sizov, "Terahertz detectors and focal plane arrays," *Opto-Electronics Review*, vol. 19, no. 3, pp. 346-404, 2011.

[13] D. Glaab, S. Boppel, A. Lisauskas, U. Pfeiffer, E. Öjefors, and H. G. Roskos, "Terahertz heterodyne detection with silicon field-effect transistors," *Applied Physics Letters*, vol. 96, no. 4, pp. 042106-042106-3, 2010.

[14] G. Millington, R. E. Miles, R. D. Pollard, D. P. Steenson, and J. M. Chamberlain, "A resonant tunnelling diode self-oscillating mixer with conversion gain," in *IEEE Microwave and Guided Wave Letters*, vol. 1, no. 11, pp. 320-321, 1991.

[15] G. Millington, R. E. Miles, R. D. Pollard, D. P. Steenson, J. M. Chamberlain, and M. Henini, "Millimetre-wave self-oscillating mixers using resonant tunnelling devices," *23rd European Microwave Conference*, pp. 255-256, 1993.

[16] Y. Nishida, N. Nishigami, S. Diebold, J. Kim, M. Fujita, and T. Nagatsuma "Terahertz coherent receiver using a single resonant tunnelling diode," *Scientific reports*, vol. 9, no. 1, pp 1-9, 2019.

[17] C. Li, A. Khalid, S. H. Paluchowski Caldwell, M. C. Holland, G. M. Dunn, I. G. Thayne, and D. R. S. Cumming, "Design, fabrication and characterization of In0.23Ga0.77As-channel planar Gunn diodes for millimeter wave applications," *Solid State Electron*., vol. 64, no. 1, pp. 67–72, Oct. 2011.