Ismaeel Maricar, M, Glover, J., Evans, G.A., Khalid, A., Papageorgiou, V., Li, C., Dunn, G., Stephens, A., Montes Bajo, M., Kuball, M., Cumming, D.R.S., and Oxley, C.H. (2013) Planar gunn diode characterisation and resonators elements to realise oscillator circuits. In: International Conference on Advanced Nanomaterials and Emerging Engineering Technologies (ICANMEET-2013), 24-26 Jul 2013, Chennai, India.

Planar Gunn diode characterisation and resonators elements to realise oscillator circuits

M Ismaeel Maricar[1], J. Glover[1], G. A. Evans[1], Ata Khalid[2], V Papageorgiou[2], Li Chong[2], G Dunn[3], A. Stephen[3], M Montes Bajo[4], M Kuball[4], D R S Cumming[2] and C H Oxley[1]

De Montfort University[1], University of Glasgow[2]

University of Aberdeen[3], University of Bristol[4]

Email: choxley@dmu.ac.uk

Abstract: The paper describes the planar Gunn diode, which is well suited to providing milli-metric and tera hertz sources using microwave monolithic integrated circuit (MMIC) technologies. Different planar Gunn electrode geometries are described along with DC, RF and thermal characterisation. To realize the planar high frequency sources there is requirement for high frequency planar resonators, the paper will describe both the radial and new diamond shaped geometries.

Keywords: Planar Gunn diode, thermal microscope, radial resonators, Diamond resonator

I. Introduction

The Gunn diode was discovered by J. B. Gunn in the1960's and offered the opportunity of a low cost stable microwave source. The diode was a vertical structure in which the Gunn diode active and contact semiconductor layers were sandwiched between the anode and cathode metal ohmic contacts. The device structure was compatible with waveguide or coaxial circuits but difficult to integrate into a planar circuit technology, for example microstrip and coplanar waveguide (CPW). In recent years a planar diode has been developed [1- 5], in which the anode and cathode contacts are on the top surface of the semiconductor making it directly compatible with coplanar waveguide technology. This has enabled for the first time Gunn diode technology to be explored in planar form, for example Monolithic Microwave Integrated Circuits (MMICs). The fundamental frequency of the planar Gunn diode operation is controlled by the distance between the cathode and anode contacts and recent work has shown that fundamental frequency of 158GHz [1] can be achieved in gallium arsenide (GaAs). By reducing the gap and exploring harmonic extraction the device could provide a low cost integrated milli-metric and tera-hertz source. It may also be possible to eventually design multi-frequency sources integrated on the same chip. This paper will describe electrical and thermal characterisation of the planar Gunn diode as well as CPW resonator configurations required in oscillator design.

II. Fabrication and Measurement Techniques:

The planar construction of the Gunn diode is shown as a schematic in Figure-1 and was developed by the Universities of Glasgow and Aberdeen [1-4], The device material layers were grown by molecular beam epitaxy (MBE) and from top to bottom in Figure 1 consist of a highly doped GaAs layer (15nm), the active channel region consisting of 50nm of un-doped GaAs between 20nm layers of double δ-doped $Al_{0.23}Ga_{0.77}As$, 50nm GaAs buffer layer grown directly to a 620 µm thick semi-insulating GaAs substrate. The metal anode and cathode ohmic contact regions were defined by electron beam lithography using polymethylmethacrylate (PMMA) resist and formed using Pd/Ge/Au/Pt/Au deposited by e-beam evaporation and annealed at 400°C.

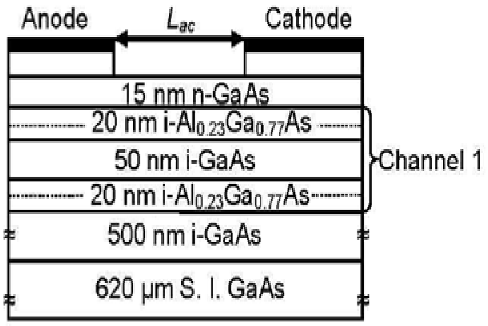


Figure-1Schematic View of material layers

To enable RF connection to the planar Gunn diode it was embedded in a CPW structure. Figure-2 shows an optical image of a planar Gunn diode and the CPW geometry. The CPW lines were fabricated in 100nm thick gold to minimise RF losses.

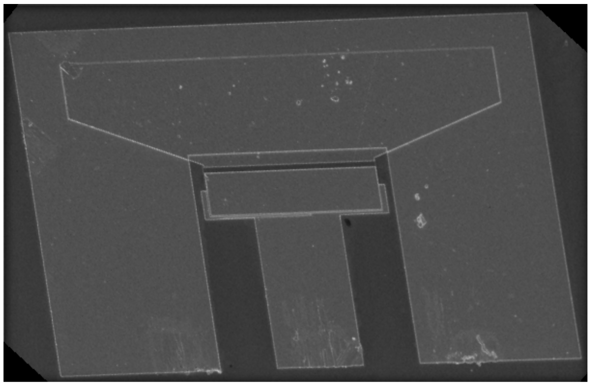


Figure-2 Optical Image of the Planar Gunn Diode with a 50 Ohm feedline

Planar Gunn diodes with different CPW electrode geometries were designed to investigate the effect of parasitics associated with electrode structures. Figure-3 shows four CPW structures which were fabricated in James Watt Nanofabrication Centre at the University of Glasgow. Figure-3 shows the four types of contact geometries designed at De Montfort University [6]. Type (a) represents a base-line design and similar as adopted by Glasgow University. (b) was to investigate a reduced fringing capacitance, (c) was designed to enable the de-embedding of the 50Ω feed line allowing measured s-parameters to more closely represent the active region of the planar Gunn diode and (d) the feed-line is made narrow to enhance the series inductance. By decreasing the width of the CPW line the inductive element will increase which may be sufficient to resonate the diode capacitance. Figure-4 shows how the theoretical inductance increases with decreasing width of the CPW line at two frequencies 60 and 100GHz. However, it should be noted that the Q of the inductance will decrease with reducing CPW width. All of the electrode structures had a range of anode cathode separations of 1, 2, 3 and 4 microns. The width was maintained at 120 microns.

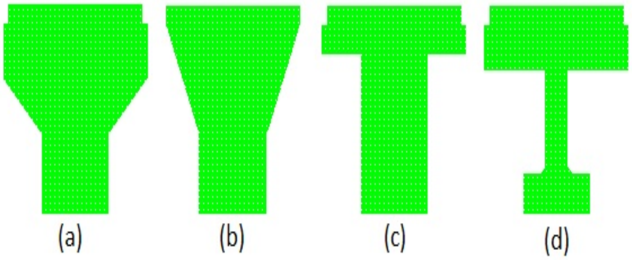


Figure-3 Types of Coplanar Waveguide Structure (a) standard CPW electrode structure (b) CPW model to reduce fringing capacitance(c) CPW model with 50 Ω feedline (d) CPW model with series inductor

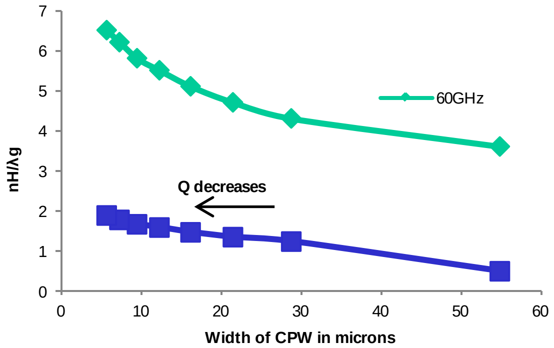


Figure-4 Inductance of CPW line as a function of width

III. Fabrication and Measurement Techniques:

The devices were DC, RF and thermally characterised. The Gunn diode IV characteristics were measured using a probe station connected to a IV plotting system. Figure-5 shows a typical plot of the measured small-signal S11 parameter against frequency for different levels of voltage bias applied to a type c planar Gunn diode with an anode to cathode separation of 4 microns. The RF measurements were made using calibrated CPW probes attached to an Agilent DC to 110GHz network analyser and Figure 5 shows that S11 was greater than 1 over a frequency band of 20 to 50 GHz for a range of DC bias conditions. Preliminary RF measurements using CPW probes and a spectrum analyzer (E8364B from Agilent) were also carried out to find the natural transit oscillation frequency of the structures with different anode to cathode separation; the respective transit oscillation frequency have been calculated in Table 1. RF measurements made on a type c device with 4 microns of electrode separation was found to naturally oscillate at 42GHz, which is higher than expected. The separation between the anode and cathode electrode was measured using scanning electron microscope (SEM) and found to be of the order of 3.4 microns, which partially accounted for the higher oscillation frequency. Also, Li Chong reported [3] that there is a dead space in the transit region which effectively reduces the channel width further, thereby increasing the frequency further.

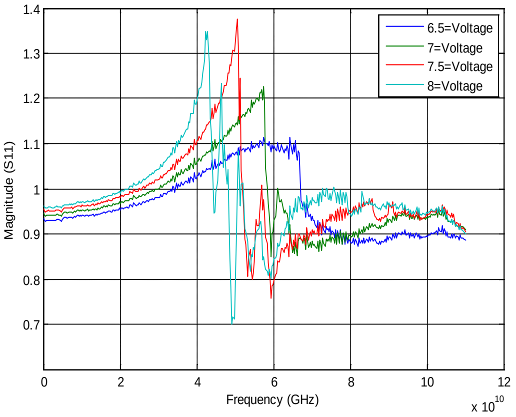


Figure-5 Small signal measurements (a) reflection coefficient (S_{11})

L_{ac} (Anode and cathode separation)	Operating Frequency
1 µm	100 GHz
2 µm	50 GHz
3 µm	34 GHz
4 µm	25 GHz

Table-1 Oscillating frequency of the planar Gunn diode

The thermal characterisation of the planar Gunn diode was carried out using infra-red (IR) microscopy. A difficulty using this technique is that semiconductors are transparent to IR radiation and therefore, when carrying out an emissivity calibration radiation is received by the microscope from the top surface of the device as well as the different interfacial layers leading to anomalous surface emissivity and therefore an incorrect surface temperature. To overcome this problem De Montfort University has developed a technique using a calibrated high emissivity micro-particle sensor [7, 8] and therefore the measurement is independent of the device's surface emissivity map. The particle is placed at the location the temperature measurement is to be made, and the IR radiation measured by the microscope will directly give the temperature at that point. Figure-6 diagrammatically shows the method. The temperature measurements were made on a biased Gunn diode by manipulating the particle sensor from anode across the channel to the cathode Figure 7a and measuring the temperature at each location. The mapped profile temperatures at different Gunn bias level are shown in Figure-7b. The measured thermal impedance was 75^{0}C/W.

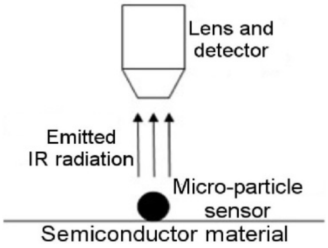


Figure-6 Schematic showing principle of measuring temperature using micro particle

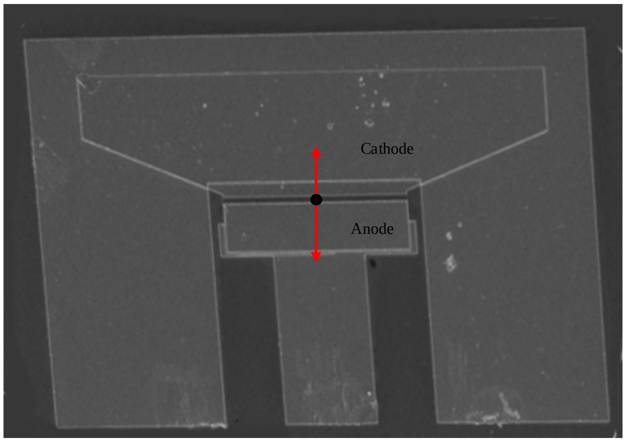


Figure-7a shows the line the micro particle sensor is moved to obtain the temperature profile

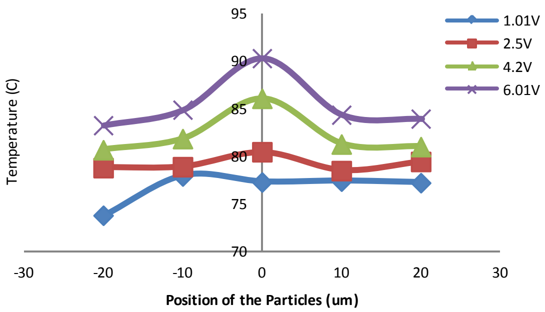


Figure-7b Thermal profile across the type c planar Gunn diode

IV. Oscillator Methodology:

To obtain high frequency oscillator performance from the planar Gunn diode a low loss planar circuit medium is required for this reason CPW was chosen. To maximise the Q of the oscillator the resonator is required to be as close to the diode as possible. The design methodology adopted was similar to that used when matching and resonating a vertical Gunn diode in a waveguide cavity, which is shown in Figure-8. For simplicity the planar Gunn diode was considered as a combination of a capacitor and negative conductance in parallel, these values were directly taken from the s-parameter measurements. The diode capacitance can be resonated (f_0) by a series inductor or a shunt open circuit stub: a CPW resonator (f_0) can be coupled to the circuits to provide a more stable oscillation frequency at (f_0).

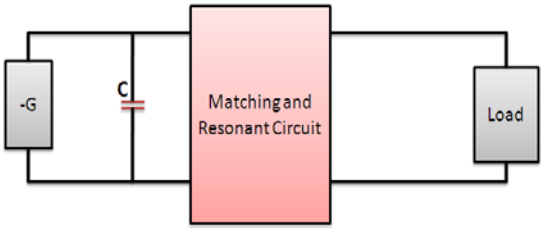


Figure-8 Oscillator methodology

The problem with planar circuits is obtaining a high Q resonator. Initial design work was carried out on CPW open circuited quarter-wave transformer and radial stub resonators. The design work used the Advanced Design System-2009 (ADS) finite element electro-magnetic package. Using the finite element model it was found that the mesh size was of particular importance to obtain realistic return-loss at high frequency. The work showed that the radial stub resonator had superior performance over the quarter wavelength stub, it was shorter in physical length, had a wider bandwidth and a higher Q. Figure-9 shows a typical structure of radial stub with air-bridge to equalise electrode potentials. The simulated result for a 400µm radius radial resonator is shown in Figure-10. The radial resonator was first reported in 1993 by Simons [9] who also used double stub radial resonator [10] to enhance the Q factor however this occupied a lot of chip area. In practical terms it is difficult to calculate the radius of a radial resonator for a particular resonant frequency. In 2012 Li Chong reported a polynomial equation (relating radius and internal angle to the resonant frequency) to enable the design of high frequency radial stub resonators [3]. Separate work has been carried out and similar polynomial equations relating resonator radius and internal angle to resonant frequency have been obtained. Figure 11 and 12 show the computed resonant frequency of the radial stub as a function of radius and angle respectively.

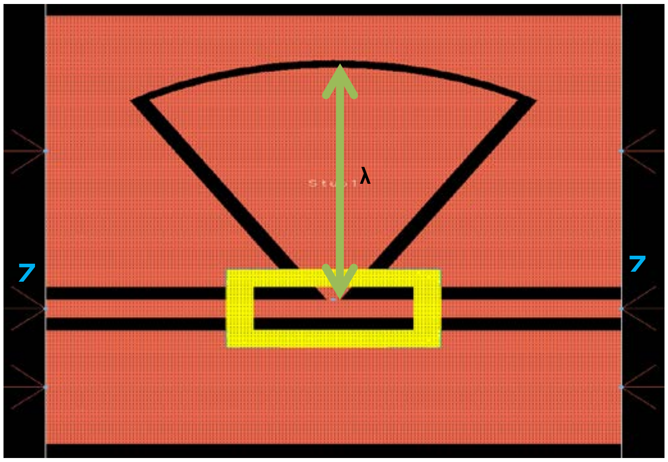
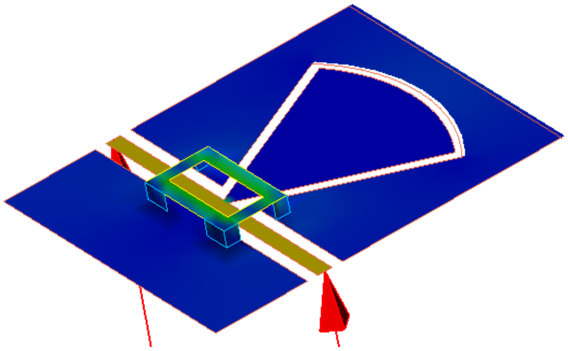


Figure -9a 2-D radial stub resonator



(b)

Figure - 9b 3D view of the radial line resonator

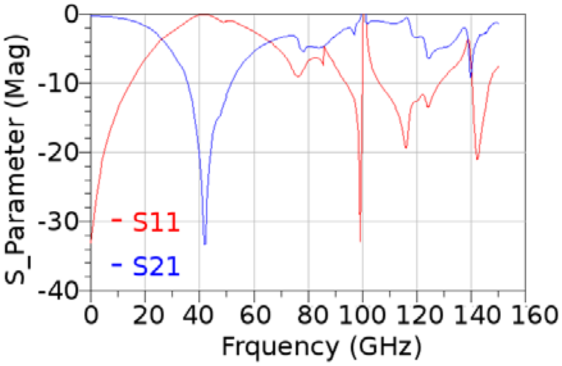


Figure-10 Return loss of the radial stub resonator

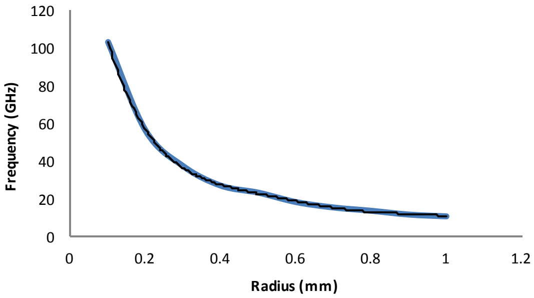


Figure-11 Resonant frequency as a function of the radius of a radial resonator

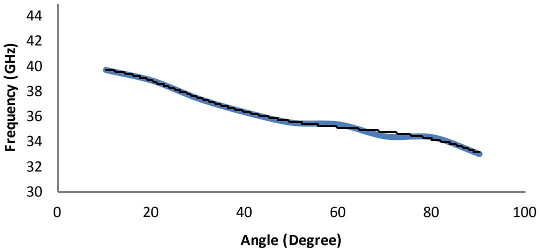


Figure-12 Resonant frequency as a function of the internal angle of a radial stub resonator

The work has led to the development of a simple diamond resonator structure which is physically shorter and has a computed higher Q than the radial stub. Preliminary computed results showing the resonant frequency as a function of the height (h) of the resonator are shown in Figure-13.

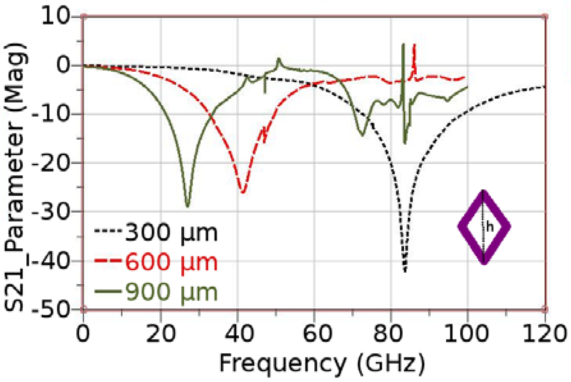


Figure 13 Resonant frequency of a diamond resonator

A number of preliminary planar oscillator designs using the presented resonators will be discussed, and will include open transformer stub and series inductance matching (electrode structure Type-d).

V. Conclusion:

The paper describes the planar Gunn diode and a number of electrode contact geometries including a geometry which enhances the series inductance to resonate the diode capacitance. Thermal measurements have been made across the channel of the device using a novel technique utilising a micro-particle sensor. To realise high frequency planar oscillators a high Q resonators are required. Both radial and a novel diamond shaped resonator have been presented.

Acknowledgements:

The authors would like to thank the staff of the James Watt Nanofabrication Centre at the University of Glasgow for help in fabricating the devices reported in this paper. 'Part of this work was supported by ESPRC'.

VI. Reference

1. Chong Li, A Khalid, N Pilgrim, M C Holland, G Dunn and D S R Cumming '*Novel Planar Gunn diode Operating in Fundamental mode upto 158 GHz*'. Journal of Physics: Conference Series 193 (2009)
2. A.Khalid, Chong Li V.Papageorgiou et all '*A 218 GHz second harmonics multiquantum well GaAs based Planar Gunn diodes*' Microwave and optical technology Letters Volume 55 Issue 3 pp 686-688 (2012)
3. Chong Li. '*Design and Characterizations of millimeter wave planar Gunn diodes and integrated circuits*' PhD thesis (2012).
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 Letters, Vol.28.No.10. (2007)
5. William H. Haydl '*Planar Gunn diode with ideal contact geometry*' Proceeding of the IEEE, Volume 61, Issue 4 pp 497 (1973)
6. M Ismaeel M, J Glover, et al. '*Planar Gunn Diode Characterization and Resonators*' 4th Annual Seminar on Passive RF and Microwave Components, 18 March (2013)
7. C H Oxley, R Hopper, D Prime, M Leaper, G Evans and A Levick '*Probe propels IR thermal microscopy to a new level*' Compound Semiconductor, Jan/Feb (2011), pages 33 – 36.
8. J Glover, R.H. Hopper et al. '*Novel infra-red (IR) Thermal Measurement on GaAs Micro-coolers*' ARMMS RF and Microwave society, 19th-20th Nov (2012)
9. R.N.Simons and S.R. Taub., '*Coplanar wave guide radial line stubs*'. Electronics Letters, Volume. 29. No.4 (1993)
10. R.N.Simon and S.R.Taub., '*Coplanar waveguide radial line double stubs and application of filter circuits*' Electronic Letters. Volume 29. No.17. (1993)