Second harmonic extraction of planar Gunn diode by using resonators for mill metric wave applications

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Abstract:
Indium gallium arsenide (InGaAs) planar Gunn diodes with on chip matching circuits were fabricated on a semi-insulating Indium phosphides (InP) substrate. Radial and diamond stub resonators were used as circuit elements to suppress the fundamental frequency and allow the second harmonic frequency to be extracted from the planar Gunn diode. The extraction of the second harmonic will enable the planar Gunn diode to operate at millimetre wave and terahertz frequencies. InGaAs planar Gunn diodes were fabricated with an active channel length (anode to cathode separation) of 4 µm and a width of 120 µm. The experimental results gave a second harmonics signal at 118 GHz with an RF output power of -20 dBm for the radial stub resonator and 121 GHz with an RF output power of -14.1 dBm for the diamond stub resonator. The letter was the highest second harmonic power recorded for a planar Gunn diode. The results indicate the potential of terahertz operation by reducing the channel length to sub-micron and extracting the second or third harmonic from the planar Gunn diode.

1. Introduction:

The first milli-meteric planar Gunn diodes on Gallium Arsenide (GaAs) were designed, fabricated and tested by Universities of Aberdeen & Glasgow in 2007 [1,2]. The devices were experimentally found to oscillate at 108 GHz with an RF output power of -43.5dBm. Later devices used $In_{0.53}Ga_{0.47}As$ which was lattice matched to the InP substrate providing improved properties over the GaAs based devices. It was reported the inclusion of pseudomorphically grown $In_{0.53}Ga_{0.47}As$ layer on a GaAs substrate increased the planar Gunn oscillation frequency to 118 GHz [3]. The indium content is limited to 23% as further increases introduce excessive strain in the device structure. Alternatively an $In_{0.53}Ga_{0.47}As$ layer can be grown on a lattice matched InP substrate to further enhance the material properties [4]–[6]. In 2013 Khalid et al [4] designed, fabricated and tested an $In_{0.53}Ga_{0.47}As$ on an InP substrate planar Gunn diode with an active length of 1.3 µm and experimentally measured fundamental oscillation frequency of 164 GHz with an RF output power of -10 dBm.

The planar Gunn diode can be easily integrated into monolithic integrated circuit (MMIC) technology making the feasibility of including two terminal devices as frequency sources. The frequency of operation of these devices can be increased by reducing the active channel length and/or efficiently extracting the second or third harmonic frequency. This paper presents a novel method to extract the second harmonic from the planar Gunn diode by using coplanar waveguide (CPW) matching elements and a resonator [7]. The work was carried out by using $In_{0.53}Ga_{0.47}As$ Gunn diode on an InP substrate. The diode was fabricated with 4 µm active channel length and 120 µm width providing the fundamental oscillation frequency of 60 GHz. The matching circuits and resonators were designed by using Advanced Design System (ADS-2009) simulation package. The devices and on chip integrated circuits were fabricated and tested at the Nanotechnology Centre at University of Glasgow. The experimental results gave a second harmonics signal at 118 GHz with an RF output power of -20 dBm for the radial stub resonator and 121 GHz with an RF output power of -14.1 dBm for the diamond stub resonator. This is the highest second harmonic power recorded for a planar Gunn diode.

2. Device fabrication:

A. *Fabrication of device by using the GaAs material*

The planar Gunn diode has been developed by the Universities of Glasgow and Aberdeen, and Figure-1 shows a schematic of the cross section of the material layers making up the device. The device material layers were grown by molecular beam epitaxy (MBE) and consisted of a highly doped GaAs layer (15nm), 50nmof un-doped GaAs between 20nm layers of double δ-doped $Al_{0.23}Ga_{0.77}As$ forming the Gunn channel. These are grown on a 500nm GaAs buffer layer grown directly to a 620 µm thick semi-insulating GaAs substrate. The anode and cathode ohmic contact regions were defined by electron beam lithography (EBL) using polymethylmethacrylate (PMMA) resist and formed using Pd/Ge/Au/Pt/Au deposited by e-beam evaporation and annealed at 400ºC.

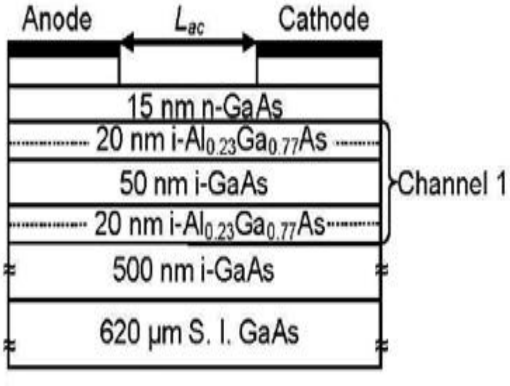


Figure-1 Schematic view of material layers

B. *Fabrication of device by using the InP material*

Figure-2 shows a schematic view of the physical cross-section of the planar Gunn diode. The same fabrication methodology was used to fabricate the InGaAs planar Gunn diode [2], [4], [8], [9].The device material layers were grown by MBE and consisted of a highly doped $In_{0.53}Ga_{0.47}As$ layer ($8x10^{16}$ cm^{-3}) with a 300 nm thick active channel layer, followed by 200-nm-thick cap layer of $In_{0.53}Ga_{0.47}As$, with a doping density of $2x10^{18}$ cm^{-3}. These layers were directly grown on a 600µm thick semi-insulating InP substrate. The nL_{ac} product of both GaAs and InP based planar Gunn diodes device was designed to be greater than 10^{12} cm^{-2}, where n is the free carrier density and L_{ac} is the separation distance between the anode and cathode [10]. The anode and cathode low resistance ohmic contact layer was again defined by EBL using a polymethylmethacrylate (PMMA) resist and formed using Pd/Ge/Au/Pt/Au deposited by e-beam evaporation and annealed at 400 ºC.

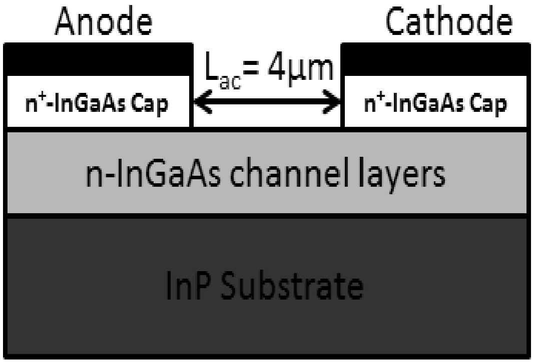


Figure-2 Schematic view of material layers

The devices were fabricated on an InP substrate using a $In_{0.53}Ga_{0.47}As$ planar Gunn diode. Figure-3 (a) shows a SEM image of a 4 µm active channel length hetero-structure InP planar Gunn diode with an integrated CPW open circuit matching stub with a characteristic impedance of 32 Ohm, and line length of 478 µm; the radial stub resonator had a radius of 400µm [11]. The complete structure was fabricated on a 620 micron thick semi-insulating InP substrate. Figure-3 (b) shows the SEM image of a 4 µm active length hetero-structure InP planar Gunn diode with integrated CPW open circuit matching stub with a characteristic impedance of 33 Ohm and electrical length of 478 µm, but this time the novel diamond resonator of length 400 µm was used [12]. The CPW open circuit stub inductive line matches the planar Gunn diode reactive component at the fundamental frequency of 60 GHz and the radial stub resonator suppresses the fundamental component allowing the harmonics to pass to the load via the 50 Ohm CPW line with a pitch of 40-60-40 µm. The device and integrated circuit were passivated by depositing silicon nitride to suppress trapping and minimize surface oxidation [13].

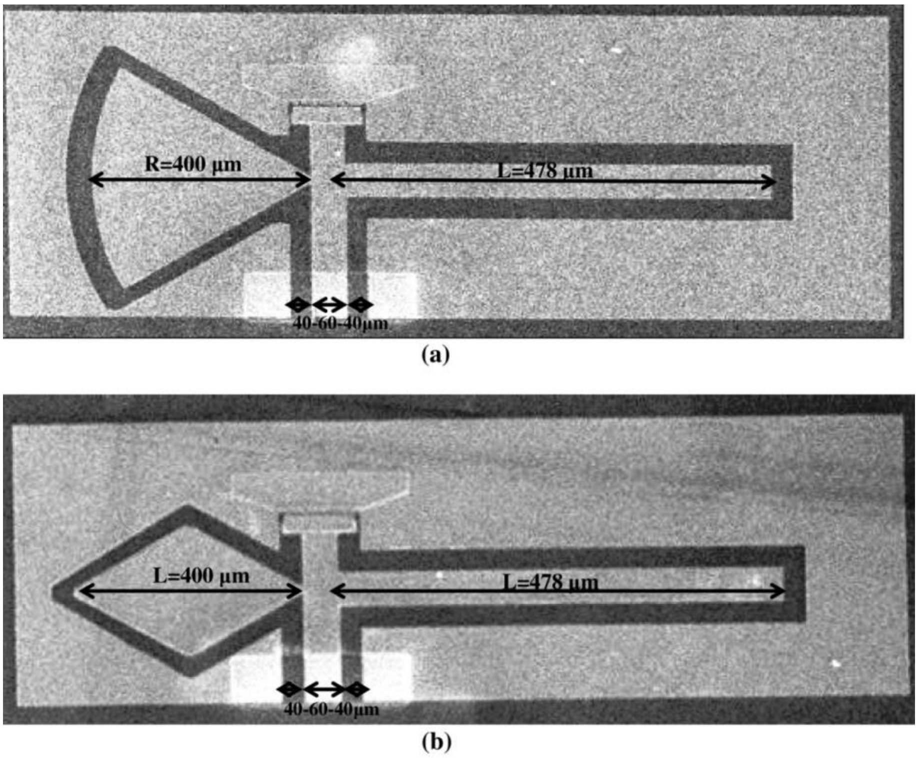
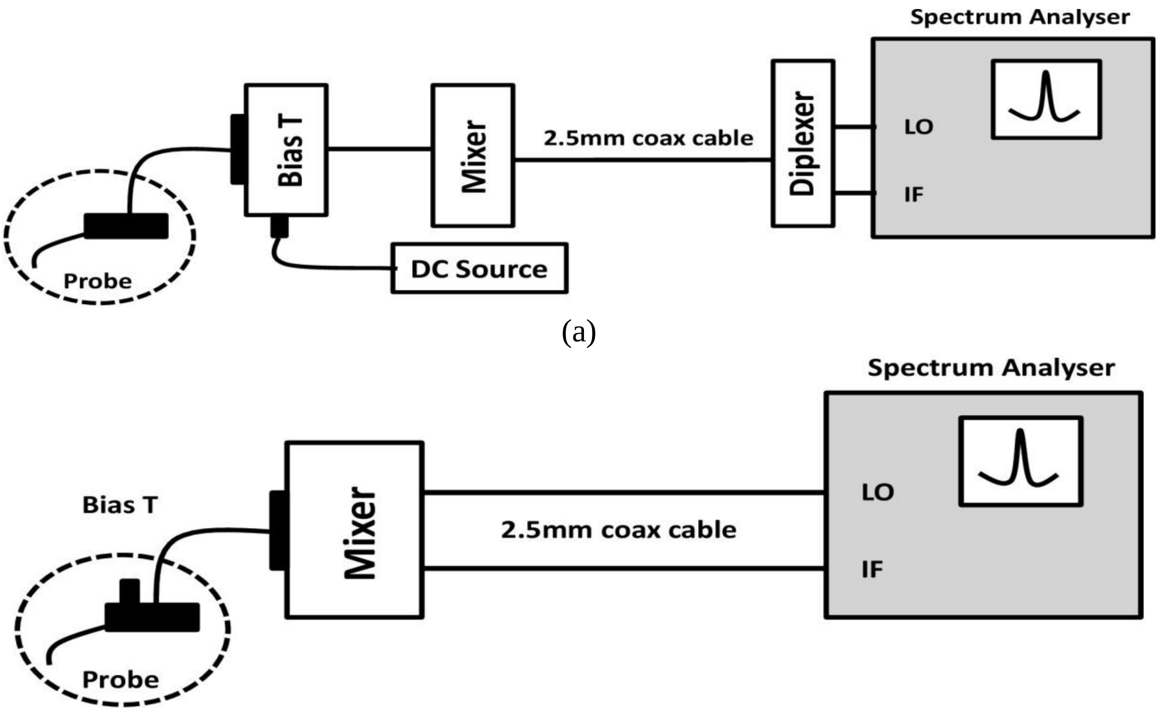


Figure-3. SEM image of planar Gunn diode to extract the second harmonics by using the (a) radial stub resonator and CPW line (b) novel diamond resonator and CPW line

3. Experimental Results:

The fabricated InP based planar Gunn diode circuit was RF characterised by measuring its second harmonic output power and the effectiveness of suppressing the fundamental frequency. The experimental set-up for measuring the second harmonic is shown in Figure-4a. It consisted of a W band RF probe with a G-S-G pitch of 40-60-40 microns, the probe had an integrated bias tee to enable biasing the Gunn diode while coupling the RF signal to a Farran mixer and local oscillator, the base-band frequency was fed directly to an Agilent E4448 spectrum analyser.

The test bench had a RF loss of approximately -50 dB over the ‘extended’ frequency range of 60 to 125 GHz. RF measurements identified a second harmonic signal at 121 GHz with an output power of -14 dBm for diamond stub resonator and 118 GHz with an RF output power of -20 dBm for the radial stub resonator. The fundamental response from the same circuit under identical bias conditions (2.8V and 2.63V) was measured using a similar set-up (Figure 4b) but working over V-band (50 to 75 GHz). The set-up briefly consisted of a V-band RF probe (GGB Technologies) with GSG pitch of 40-60-40 µm, bias tee, feeding a mixer (Farran Technologies) which down converts the signal to the base-band frequency of the spectrum analyser (Agilent E4448). The RF loss of the measurement set up was approximately -50 dB over the frequency range of 50 to 75 GHz. The measurement indicated that the fundamental frequency was in the noise floor of the spectrum analyser. The same CPW open circuit matching stub with planar Gunn diode but without the diamond resonator and radial stub resonator were also fabricated on the same wafer as the second harmonic extraction circuit. The circuit was tested at the fundamental frequency and gave an RF output power of -9 dBm at 66 GHz, showing the effectiveness of the diamond and radial stub resonator suppressing at the fundamental frequency. The apparent small difference in the fundamental frequency between the two circuits was thought to be due to a slight difference in the optimum bias voltages. Figure-5 shows the measured output spectrum centred at 121.688 GHz with the output power of -14.1 dBm for diamond stub resonator (Figure-5a) and 117.870 GHz with RF output power of -19.97 dBm for radial stub resonator (Figure-5b).



(a)

(b)

Figure-4 On-wafer Spectrum analyser measurement setup for (a) V-band frequency and (b) W-band frequency

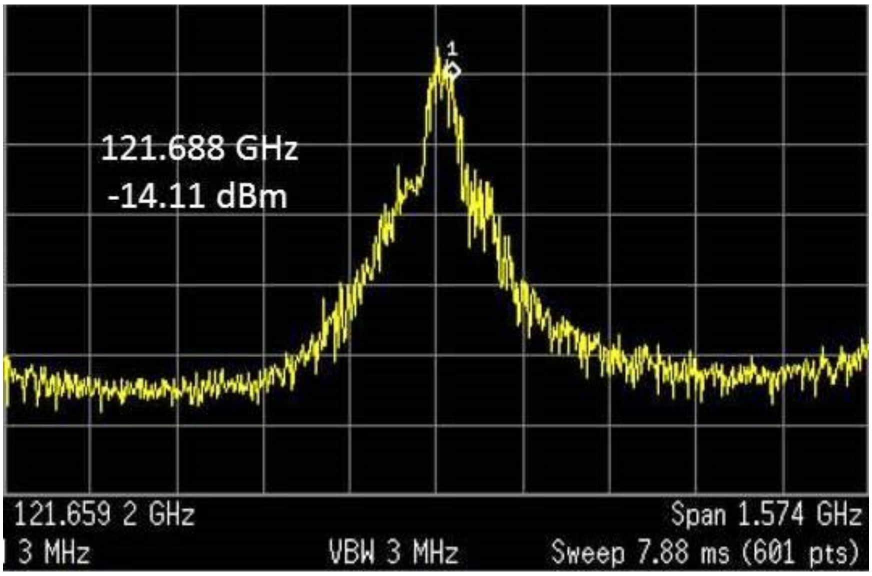


Figure-5a Spectrum analyser measurement for second harmonics frequency using W-band setup

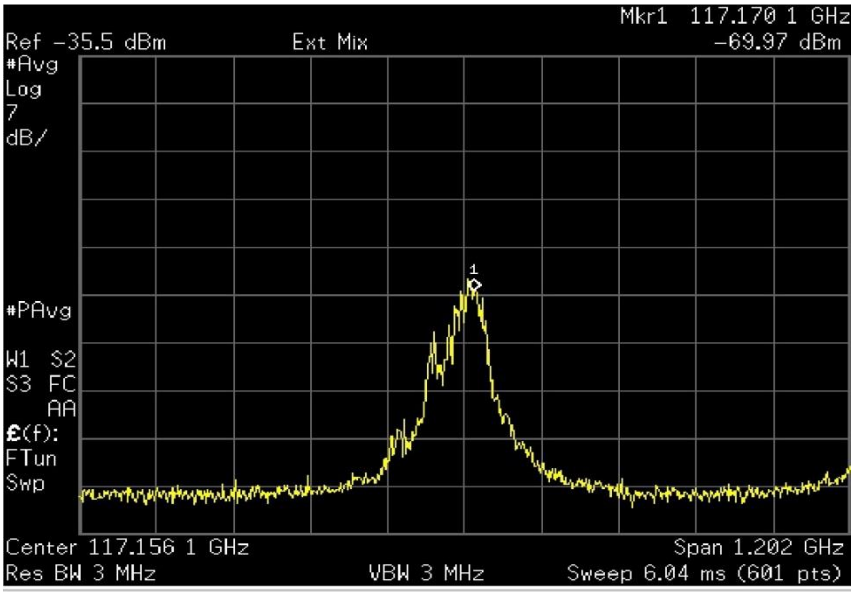


Figure-5b Spectrum Analyser Measurment Second harmonics frequency using W-band setup

4. Conclusion:

The paper describes an $In_{0.53}Ga_{0.47}As$ based planar Gunn diode fabricated on an InP semi-insulating substrate with an integrated matching circuit to extract the second harmonic. Preliminary RF measurements have been presented in which a device with a 4 µm active channel length oscillated with a second harmonic frequency of 121 GHz with a RF outpur power of-14 dBm for diamond stub resonator and 118 GHz with a RF output power of -20 dBm for radial stub resoantor and with good fundamental frequency suppression. When the dimaond and radial stub resonator were removed from the circuit a fundamental frequency of 66GHz and 59 GHz was detected with an RF output power of approximatley -9 dBm.

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