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Extraction of second harmonic from an InP based planar Gunn diode using diamond resonator for milli-metric wave frequencies

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ABSTRACT

Planar Indium Gallium Arsenide ($In_{0.57}Ga_{0.47}As$) Gunn diode was fabricated on a semi-insulating indium phosphide substrate with on chip matching circuit to enable the extraction of second harmonic in millimeter and terahertz frequencies. The $In_{0.57}Ga_{0.47}As$ planar Gunn diodes were designed with an active length of 4 μm, channel width of 120 μm and integrated with a novel diamond resonator to suppress the fundamental and extract the second harmonic. The experimental results gave good fundamental suppression and extraction of second harmonic (121.68 GHz) with an RF output power of −14.1 dBm. This is highest recorded power at the second harmonic from a planar Gunn diode.

1. Introduction

Gunn diodes were first demonstrated by J.B. Gunn in 1963 using a GaAs bar structure with electrical contacts on opposite faces [1]. In 2007 the first millimeter-wave planar Gunn diodes on Gallium Arsenide (GaAs) modelled by Aberdeen University, were fabricated and tested by Glasgow University [2,3]. The experimental results showed devices oscillating in the fundamental mode at 108 GHz with an RF output power of −43.5 dBm. Recent modified devices have achieved RF output powers of −4.5 dBm at a fundamental frequency of 100 GHz [3,4]. 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 [5]. The indium content is limited to 23% as further increase introduces 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 [6–8]. In 2013 Khalid et al. [6] designed and tested a $In_{0.53}Ga_{0.47}As$ planar Gunn diode with an active length of 1.3 μm fabricated on an InP substrate and measured a fundamental oscillation frequency of 164 GHz with an RF output power of −10 dBm [6]. Experimental work on similar InP planar Gunn diodes has shown the saturation domain velocity is 1.93×10^5 m/s^{-1} and the dead-space as 0.21 μm [9] enabling higher frequency devices to be realised when compared to GaAs based planar Gunn diodes.

The planar Gunn diode can be easily fabricated as part of a microwave monolithic integrated circuit (MMIC) making the feasibility of including simple two terminal devices as frequency sources. The frequency of operation of these devices can be potentially increased to the millimeter or terahertz frequencies by reducing the active length below 1 μm and efficiently extracting the second or third harmonic frequency. This paper presents a method to extract the second harmonic from the planar Gunn diode by using coplanar waveguide (CPW) matching elements and a novel diamond stub resonator [10]. The work was carried out using $In_{0.53}Ga_{0.47}As$ Gunn diode on an InP substrate. The Gunn diode was fabricated with an active layer of 4 μm and width of 120 μm providing a fundamental frequency of oscillation around 60 GHz. This geometry was chosen as the lower frequency made it easier to microwave characterize the device. The matching circuit and resonator structures were designed using Advanced Design System (ADS2009) simulation package. The diodes and on chip integrated circuits were fabricated and tested at the Nanotechnology Center at University of Glasgow. Experimental results showed good fundamental suppression at 60 GHz and second harmonic extraction at 121 GHz with an output power of −14 dBm. This is the highest output RF power recorded for second harmonic extraction from a planar Gunn diode.

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2. Device fabrication

Fig. 1 shows a schematic view of a cross section of the planar Gunn diode. The same fabrication technology was used to fabricate the InGaAs planar Gunn diode as was used to fabricate the AlGaAs Gunn diode [10,11]. The device material layers were grown by molecular beam epitaxy (MBE) and consisted of a 300 nm thick active channel layer of $In_{0.53}Ga_{0.47}As$ (8×10^{16} cm^{-3}), followed by 200-nm-thick highly doped cap layer of $In_{0.53}Ga_{0.47}As$, with a doping density of 2×10^{18} cm^{-3}. These layers were directly grown on top of a 600 μm thick semi-insulating InP substrate. The nL_{ac} product of the 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 [12]. The anode and cathode low resistance ohmic contact layer was defined by electron beam lithography using a polymethylmethacrylate (PMMA) resist and formed using Ti/Au deposited by e-beam evaporation; the contacts were not annealed and the measured contact resistivity was found to be 0.12 ohm mm [6].

Fig. 2 shows the optical image of a 4 μm active length planar Gunn diode with integrated CPW open circuit matching stub having a line length of 478 μm and a novel diamond resonator [10] of length 400 μm. The CPW open circuit stub line matches the planar Gunn diode reactive component at the fundamental frequency of 60 GHz and the diamond stub resonator suppresses the fundamental component allowing the even harmonics to pass to the load via a 50 Ω CPW line with a ground (G), signal (S), ground (G) pitch of 40–60–40 μm. The device and integrated circuit were passivated by depositing silicon nitride to suppress trapping and minimize surface oxidation.

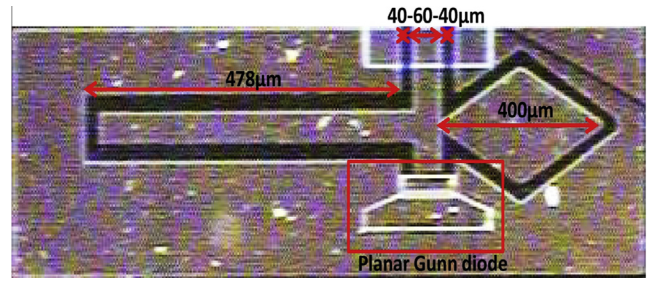

Fig. 2. Optical image of planar Gunn diode to extract the second harmonics by using the a novel diamond resonator and CPW line.

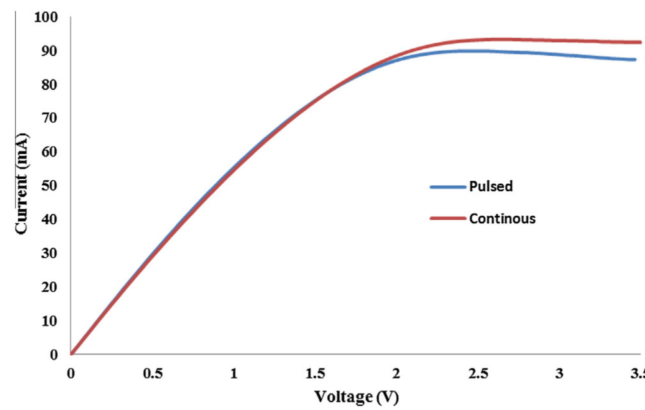

Fig. 3. Measured current–voltage characteristics of a typical 4 μm × 120 μm of the $In_{0.53}Ga_{0.47}As$ planar Gunn diode.

3. Experimental results

The DC characteristics were measured using a semiconductor device analyser (Agilent Technologies B1500A), which was connected to an automated probe station (Cascade Microtech). Fig. 3 shows the pulsed and continuous IV characteristics of a typical InP based planar Gunn diode. It is interesting to note with this device there was only a small indication of negative resistance when compared with measurements carried out on similar GaAs based planar Gunn diodes [13]. The available pulsed measurement was carried out using pulse duration of 1 ms and was not short enough to remove the thermal effects completely and hence show more pronounced negative differential resistance (NDR) region which occurred at an applied bias voltage of approximately 3.15 V with a peak current of 86 mA.

The fabricated InP based Gunn diode circuit was RF characterised by measuring its second harmonic output power, and the effectiveness of the diamond resonator to suppress the fundamental frequency. The experimental set-up for measuring the second harmonic is shown in the test circuit schematic Fig. 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 (2.8 V) 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.

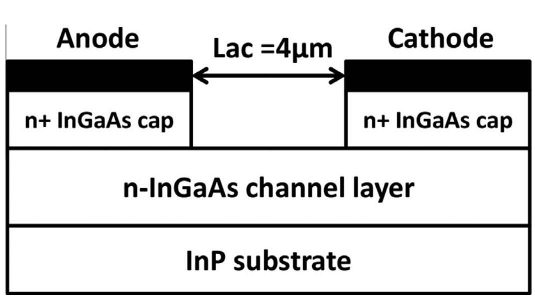

Fig. 1. Schematic view of material layers.

The test bench had a measured RF loss of approximately −50 dB over the 'extended' frequency range of 60–125 GHz. Preliminary RF measurements identified a second harmonic signal at 121 GHz with an output power of −14 dBm. The fundamental response from the same circuit under identical bias conditions (2.8V) was measured using a similar set-up shown in the test circuit schematic Fig. 4b but working over V-band (50–75 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 set up was approximately −50 dB over the frequency range of 50–75 GHz. The RF output measurement indicated that the fundamental frequency signal was in the noise floor of the spectrum analyser (−98 dBm). The same CPW open circuit matching stub with planar Gunn diode but without the diamond resonator was 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 resonator in suppressing the fundamental frequency. The small difference in the measured fundamental frequency between the two circuits is thought to be due to small variations in fabrication giving rise to a slightly different optimum bias voltage (2.6 V) and therefore fundamental frequency.Fig. 5 shows the measured output spectrum centered at 121.688 GHz with the output power of −14.1 dBm. This work shows the potential of using planar Gunn diodes with submicron active channel width and second harmonic extraction to extend the operation of the planar Gunn diode to terahertz frequencies.

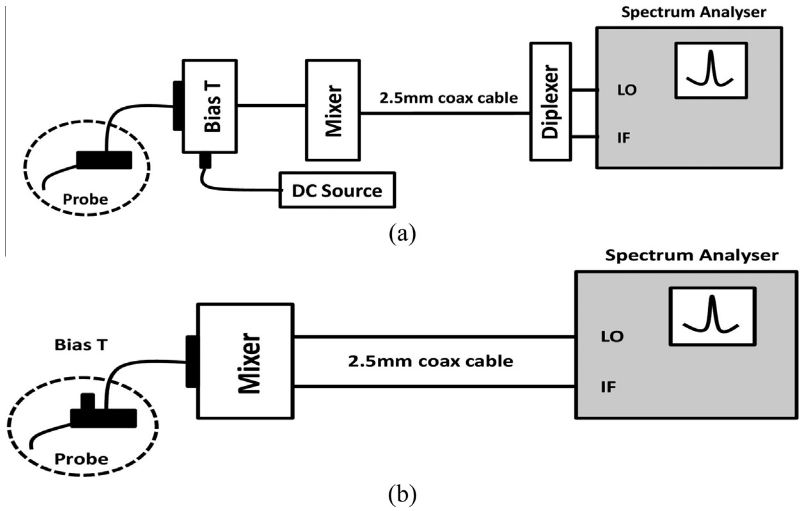

Fig. 4. On-wafer Spectrum analyser measurement setup for (a) V-band frequency and (b) W-band frequency.

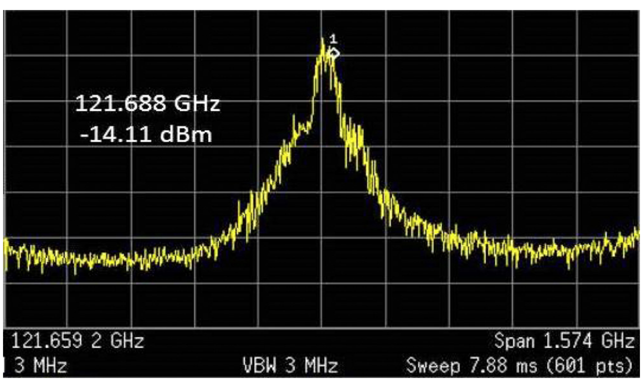

Fig. 5. Spectrum analyser measurement for second harmonics frequency using W-band setup.

4. Conclusion

The letter 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. RF measurements have been presented in which a device with a 4 μm active length oscillated with a second harmonic frequency of 121 GHz and −14 dBm output power which is the highest reported second harmonic output power from a planar Gunn diode. The fundamental frequency was suppressed to the noise floor of the spectrum analyser. When the diamond resonator was removed from a similar circuit a high RF power −9 dBm was measured at the fundamental frequency.

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