Design, characterization and fabrication of an In$_{0.53}$Ga$_{0.47}$As planar Gunn diode operating at millimeter waves

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Abstract: This paper describes the design, characterization and fabrication of a planar In$_{0.53}$Ga$_{0.47}$As based planar Gunn diode on an InP semi-insulating substrate. The planar Gunn diode was designed in Coplanar Waveguide (CPW) format with an active channel length and width of 4 $\mu$m and 120 $\mu$m respectively, and modeled using the Advanced Design System (ADS-2009) simulation package. The initial experimental measurements have given a fundamental oscillation frequency of 63.5 GHz with a RF output power of $-6.6$ dBm, which is the highest recorded power for an InP based planar Gunn diode.

Key words: indium phosphide; planar Gunn devices; millimeter-wave source; semiconductor; power

1 Introduction

The InP hetero-structure planar Gunn diode was first proposed and developed by the University of Aberdeen and University of Glasgow in 2010$^{[1]}$. Later in 2013 Papageorgiou and Ata Khalid published simulation, fabrication and RF measurement results for an InP based planar Gunn diode with a 1.3 $\mu$m active channel length which operated at 164 GHz$^{[2-3]}$. Early in 2014, Ata Khalid published work on a planar Gunn diode with an active channel length(Lac) of 600 nm, which operated at 298 GHz, the highest recorded fundamental frequency from an InP based planar Gunn diode$^{[4-5]}$. The hetero-structure In$_{0.53}$Ga$_{0.47}$As planar Gunn diode was fabricated on a lattice matched InP substrate giving improved RF performance(higher frequency of oscillation and higher output power) when compared with GaAs based planar Gunn diode. This is partly due to the In$_{0.53}$Ga$_{0.47}$As low field electron mobility being much higher than for GaAs, enabling the carriers to reach the saturation velocity at a lower electric field$^{[6]}$. The other advantage of hetero-structures device is higher electron concentration in the active layer which is necessary for high frequency Gunn oscillation$^{[7]}$.

A similar design methodology as used for the planar GaAs devices was adopted to design an In$_{0.53}$Ga$_{0.47}$As planar Gunn diode on a semi-insulating InP substrate. The planar Gunn diode was designed in CPW(Coplanar Waveguide) format with an active channel length and width of 4 $\mu$m x 120 $\mu$m respectively using the Advanced Design System(ADS-2009) simulation package. The devices were fabricated and initial experimental measurements showed a fundamental oscillation frequency of 63.5 GHz with the highest RF output power of $-6.6$ dBm recorded for a planar Gunn diode working at this frequency.

2 Device Fabrication

Fig. 1 shows a schematic view of the cross-section of a planar Gunn diode. The device material layers were grown by Molecular Beam Epitaxy(MBE) and consist of a highly doped In$_{0.53}$Ga$_{0.47}$As layer($8 \times 10^{16}$ cm$^{-3}$) 300-nm-thick active channel, followed by 200-nm-thick cap of In$_{0.53}$Ga$_{0.47}$As with a doping density of $2 \times 10^{19}$ cm$^{-3}$. These layers were directly grown on top of a 600-$\mu$m-thick

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semi-insulating InP substrate. The nLac product of the device was greater than $10^{12} \text{ cm}^{-2}$, where $n$ is the free carrier density and $L_c$ is the separation between the anode and cathode electrodes. The anode and cathode ohmic contact layers 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 400°C.

Fig.2 shows the SEM image of a $4 \mu m \times 120 \mu m$ In$_{0.53}$Ga$_{0.47}$As planar Gunn diode which was fabricated on InP semi-insulating substrate and the electrode structure forming a CPW format with a pitch 40-60-40 $\mu m$ (50 Ohm). The pitch size of the CPW was calculated using ADS-2009 to obtain the 50 Ohm characteristic impedance line. The devices were passivated by depositing silicon nitride to suppress trapping and minimize surface oxidation.

3 Experimental Results

The fabricated InP based planar Gunn diodes were experimentally measured to obtain the fundamental oscillation frequency using a high frequency Vector Network Analyzer (VNA) and Spectrum Analyzer. Initially DC pulsed measurements were made on all the InP based planar Gunn diodes to give an indication of the existence of a Negative Domain Resistance (NDR) region. The pulsed DC characteristic was measured using a semiconductor device analyzer from Agilent technologies (B1500A) connected to an automated probe station manufactured by Cascade Microtech, enabling measurements to be made across the wafer. Fig.3 shows a comparison between the pulsed and continuous IV characteristics of an InP based In$_{0.53}$Ga$_{0.47}$As planar Gunn diode. The measurement shows that the diode pulsed IV characteristic will minimize diode self-heating allowing the NDR region to be more easily detected.

The RF experimental set-up for measuring the fundamental oscillation frequency is shown in Fig.4. It consisted of a V-band RF probe with a ground-source-ground (g-s-g) pitch of 40-60-40 $\mu m$, bias tee, feeding a mixer (Farran Technologies) which down converted the signal to the base band frequency of the spectrum analyzer (Agilent E4448). The RF loss of the measurement set-up was approximately $-50$ dB over the frequency range of 50 GHz to 75 GHz.

It was found that In$_{0.53}$Ga$_{0.47}$As planar Gunn diode started to oscillate when the bias voltage was between 3.1 V to 3.9 V. Fig.5 shows the RF output spectrum of the InP planar Gunn diode with an electrode spacing of 4 $\mu m$. The measurement showed with a bias voltage of 3.76 V, the diode oscillated at a fundamental frequency of 63.5 GHz with an RF output power of $-6.6$ dBm. To obtain the maximum RF output power, the bias voltage was tuned, as in Fig.6, an output power of $-6.6$ dBm is the highest recorded RF power at 63.5 GHz from an InP based planar Gunn diode.
Planar Gunn diodes with an anode to cathode separations of 3 µm were also measured to identify the transit mode oscillation frequency and the corresponding RF output power. Table 1 shows the ‘transit mode’ oscillation frequency and RF output power of the above variants of the In$_{0.53}$Ga$_{0.47}$As planar Gunn diode. The experimental frequency of oscillation was similar to the calculated ‘transit mode’ frequency, assuming the carrier saturation velocity was $2.4 \times 10^5$ m·s$^{-1}$ and the dead space 0.21 µm$^{10}$. 

4 Conclusion

The paper describes an In$_{0.53}$Ga$_{0.47}$As based planar Gunn diode fabricated on an InP semi-insulating substrate. Preliminary RF measurements have been presented, in which a device with a 4 µm active channel length oscillated with a fundamental oscillation frequency of 63.5 GHz gives the highest recorded RF output power of −6.6 dBm for an InP planar Gunn diode.

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