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Simulation investigation of multiple domain observed in $In_{0.23}Ga_{0.77}As$ planar Gunn diode

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ABSTRACT

A numerical study for an AlGaAs/InGaAs-based quantum well structure planar Gunn diodes was performed by initially proposing imperfect metallic contacts that can introduce multiple anode–cathode spacings caused by etching process during the fabrication. Through Fast Fourier transform (FFT) algorithm, the result reveals that, at moderate bias voltage above the threshold, multi-channel planar Gunn diode exhibits multiple oscillations which were consistent with experimental observation due to non-uniformity of contact terminal. A downwards shift of oscillation frequency by varying the applied voltage across terminal was observed due to Gunn effect. The finding may be utilized not only to generate multiple millimeter wave or even terahertz signal sources on single chip, but also to achieve frequency tunability through tuning the applied bias voltage.

Introduction

Gunn diodes are increasingly becoming an ideal solid state millimeter-wave signal source which can be used in imaging, material analysis, wideband wireless communications, and chemical or biological sensing application while keeping relatively small device size, low fabrication costs, low power consumption, and low phase noise [1–7]. There have been a number of studies involving Gunn diodes that have concentrated on "vertical" structures [8–11]. Far too little attention has been paid to explore "planar" structures until new attempts have been made to fabricate AlGaAs/AlGaAs quantum wells on a planar layout, whilst operating in fundamental mode at 83 GHz, and even reach up to 108 GHz [12,13]. It could be easily integrated with monolithic integrated circuit technology, which makes two terminal devices as a frequency source become feasible.

In recent years, the key challenge of planar devices is to further improve output power and oscillation frequency into sub-terahertz region. Two emerging trends have been attempted to meet growing demand for millimeter wave applications or solid-state THz source with high output power. One is to reduce spacing between anode and cathode terminal to sub-micron regime, which is in excess of previously theoretical limits [14–17]. An AlGaAs/GaAs-based planar Gunn diode fabricated with an active channel length of 1 μm can operate above 120 GHz with an output power of −9.14 dBm in fundamental mode, which is highest ever reported for a GaAs Gunn device at this frequency [18].

The other trend is to employ a new semiconductor material system possessing higher electron saturation velocity

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compared to GaAs, such as, $In_{0.47}Ga_{0.53}As$, InN, InSb, GaN and InP [19–23]. An alternative material system like $In_{0.47}Ga_{0.53}As$ lattice-matched to InP based on planar diode has been proved experimentally to increase oscillating frequency up to 164 GHz at fundamental mode [24]. Moreover, a combination of both higher velocity material and sub-micron fabrication, with an active channel of 700 nm, will allow the planar Gunn diode oscillation frequency up to 317 GHz [25].

The most striking result to emerge from the reported data is that multiple-domain oscillations have been observed on either GaAs or InGaAs-based Gunn diode [26,27]. Initially reported explanations have been proposed for this result. Multiple domains nucleation sites dominated by random doping in the channel and electrons injection into layers beneath active layer in high applied electric field accounted for these phenomena [28]. Both just remain in the qualitative analysis instead of providing analysis in quantitative way. To the best of our knowledge, no previous study has investigated the non-uniformity between the anode and cathode metallic contacts that lead to the coexistence of multiple domains, and most studies about planar diode have only been carried out in both DC simulation and experimental fabrication. No studies have been found to focus on transient analysis of III–V compound semiconductor based planar Gunn diode.

In this article, we propose roughness-like metallic contacts, that may result in multiple Gunn domains nucleation sites that correspond to different oscillation frequency. In order to confirm the proof-of-concept, firstly, simulation of top-view planar Gunn diode with single channel has been performed. Afterwards, we investigate and discuss the effect of non-uniform edge on multiple oscillations by means of a two-dimensional (2D) simulation.

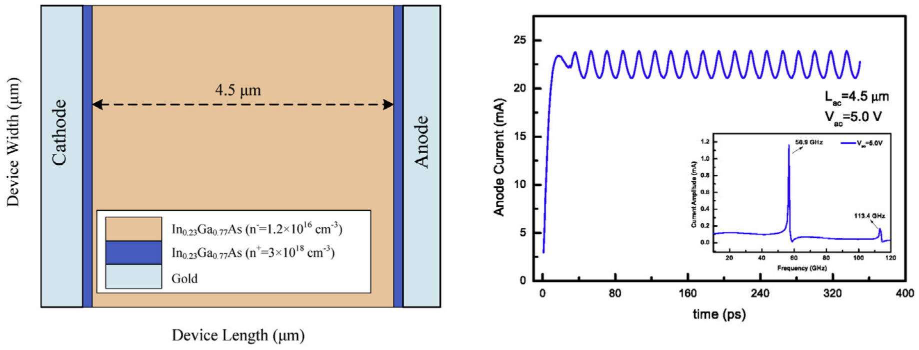
InGaAs planar Gunn diodes with uniform and non-uniform active channel

$In_{0.23}Ga_{0.77}As$ planar Gunn diode with uniform active channel

For supporting the explanation for multiple frequency oscillations, it is important to firstly simulate planar Gunn diode with uniform metallic contact. The detailed design, fabrication is presented in Ref. [29]. The devices have AlGaAs/InGaAs/AlGaAs heterojunctions that were grown on a GaAs wafer using molecular beam epitaxy technology. Fig. 1(a) schematically shows the top view of the simulated structure with W = 60 μm. It includes a 4.5 μm length L_{ac} $In_{0.23}Ga_{0.77}As$ conductive channel with doping concentration of $n = 1.2 \times 10^{16}\ cm^{-3}$, two highly doped $In_{0.23}Ga_{0.77}As$ ($n = 3 \times 10^{18}\ cm^{-3}$) sandwiched by anode, cathode electrodes and conductive channel respectively are modeled to simulate the Ohmic anode and cathode.

For a given material doping level, the diode length should be chosen to satisfy the criteria $N \times L \geq 10^{12}\ cm^{-2}$ that corresponds to the approximate minimum value for sustained Gunn oscillations [30]. Meanwhile a dc bias V_{ac} above the critical terminal voltage defined as the bias level above which space-charge growth occurs in the channel is applied across the diode. The simulation has been carried out using SILVACO that allows for the electrical, optical, thermal characteristics of a semiconductor device to be simulated under given bias conditions to obtain DC, RF and time domain responses [31]. In this simulation, we employ the model of velocity-field dependency proposed by Barnes. This negative differential mobility (NDM) model reveals that carrier drift velocity reaches to peak at a given electric field, and then reduces with increased electric field [32]. For $In_{0.23}Ga_{0.77}As$ material adopted here, permittivity is assumed to be 13.9, bandgap is assumed to be 1.1 eV, affinity is assumed to be 4.26 eV, effective conduction band density of states is assumed to be $2.9 \times 10^{17}\ cm^{-3}$, low field mobility is assumed to be $8000\ cm^2\ V^{-1}\ s^{-1}$, electron saturation velocity is assumed to be $1.8 \times 10^7\ cm\ s^{-1}$ [29].

Current waveform generated for a dc bias is shown in Fig. 1(b). Harmonic analysis of current waveform has been realized by FFT analysis in origin software and shows a fundamental of 56.9 GHz and a second harmonic frequency of 113 GHz, as shown in the inset of Fig. 1(b). Single-oscillation behavior is observed in simulated structure with uniform electrode edge. Fig. 2 shows current amplitude by FFT algorithm from current waveform extracted at the anode of Gunn diode with $L_{ac} = 4.5$ μm at 4.6, 5.0 and 5.4 V respectively. It can be clearly seen, by tuning the voltage across the device, the slight decrease in the oscillation frequency is observed. The



(a)

(b)

Fig. 1 – (a) Top view of simulated $In_{0.23}Ga_{0.77}As$-based planar Gunn diode with uniform 4.5 μm anode–cathode spacing L_{ac}. (b) Transient curve characteristics of $In_{0.23}Ga_{0.77}As$ planar Gunn diodes and its current amplitude through FFT, the width of the active region is 60 μm.