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Enhanced InP-based Gunn Diodes with Notch-δ-doped Structure for Low-THz Applications

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***Abstract* - In this work, Monte Carlo simulation is performed for InP Gunn diode with a notch-δ-doped structure. It is found that the presence of the δ-doped layer has improved the Gunn diode performance significantly as compared to the conventional notch structure. The δ-doped effect caused an increment in the fundamental operating frequency and current harmonic amplitude in InP Gunn diodes by modifying the electric field profile within the device. An InP notch-δ-doped Gunn diode with device length of 800 nm under 3V DC bias is capable of producing AC current signal of 287 GHz, reaching the THz region, with its harmonic amplitude being 5.68×10^8 A/m^2. It is observed that InP-based notch-δ-doped Gunn diode is able to generate signals at a higher operating frequency with a larger output power as compared to that of GaAs due to the higher electron drift velocity and threshold field in InP material.**

Keywords— Gunn diode, δ-doped, Monte Carlo model, Indium Phosphide, Terahertz source

I. INTRODUCTION

The rapid growth of the Internet of Things (IoT) technology over the recent years has escalated the demand for high-frequency wave sources, approaching the Terahertz (THz) spectrum. With the deployment of 5G, the worldwide connection of IoT devices shows an increasing trend from having 3.6 billion in 2015 to 12.3 billion IoT connected devices in 2021 [1]. A lot of IoT devices such as autonomous vehicles (AV), smart devices, smart infrastructures and industrial IoT (IIoT) require high-power and high-frequency applications. This has led to an increasing demand for a portable, efficient, and low-cost THz wave source operating at high frequency and high output power. In view of this situation, further advancements on Gunn diode as a THz wave source can be seen as a key to support the evolving IoT technology.

In the recent years, there have been numerous improvements made on the Gunn diode as a THz source device. Many studies on the fabrication of Gunn diode with different material systems such as GaAs [2] and InP [3] have been performed to utilise their unique material properties. InP has become a preferred material for the design of Gunn diode due to its high efficiency and high operating frequency [4]. The advancement on InP Gunn diode throughout the years has resulted in the extension of fundamental operating frequency of the device being up to 160 GHz [5].

The transferred-electron effect exhibited in the Gunn diode, which can be translated into the nucleation and propagation of high field domain is strongly dependent on the material properties, particularly the band structure. InP is a direct bandgap material like GaAs, capable of demonstrating the Gunn effect. It is reported in the work of Garcia *et al* [6] that the operating frequency of InP Gunn diode with notch structure is 140 GHz, which is higher than the conventional GaAs Gunn diode. Figure 1 shows the electron drift velocity characteristics of GaAs and InP materials. At electric fields below a threshold value of E_{th}, the drift velocity increases to a peak value, which differs for each material, as the applied electric field increases. Once the electric field exceeds the threshold value, the material exhibits a negative

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differential mobility characteristic whereby the drift velocity decreases with an increase in the electric field. This is known as the Negative Differential Resistance (NDR) region, where the Gunn diode will be operating as a DC-to-AC converter to generate current oscillations under a constant bias [7]. From Fig. 1, it is observed that the threshold field of InP (~14 kVcm) is larger than that of GaAs (~4 kV/cm) [8]. This high value of InP E_{th} is due to its larger intervalley (Γ-L) separation energy as compared to GaAs. However, the electron negative differential mobility of InP (up to -65 $cm^2V^{-1}s^{-1}$) is found to be lower than in GaAs (up to 200 $cm^2/V^{-1}s^{-1}$) material. According to the Kroemer criterion [9], the growth rate of a high field domain due to Gunn effect is strongly dependent on the negative differential mobility value of the material which determine the Gunn diode performances.

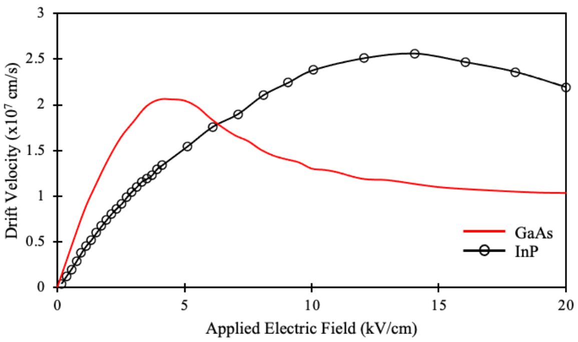

Fig. 1. Electron drift velocity characteristics of GaAs and InP.

In this work, the effect of implementing a notch-δ-doped layer on the device performance of a Gunn diode structure using InP material is investigated. The device performance of InP Gunn diodes with notch-δ-doped structure are optimised in terms of operating frequency and harmonic amplitude and compared to GaAs Gunn diodes. In section II, the ensemble 1-D self-consistent 4-valleys analytical-band Monte Carlo model used for the simulation of Gunn diode in this work is briefly explained. The design structure of a notch-δ-doped Gunn diode along with its parameters are also described in this section. In section III, the simulation results and discussion for InP Gunn diodes with notch-δ-doped structure are presented. The optimisation of the device performance is then presented and compared with GaAs Gunn diode performances. Lastly, a summary of the findings is provided in section IV.

II. METHODOLOGY

A. Monte Carlo Model

In this work, an ensemble 1-D self-consistent 4-valleys analytical-band Monte Carlo model was developed to simulate the electron transport in an InP Gunn diode with notch-δ-doped structure. The Monte Carlo model parameters of InP are taken from [8]. The model is found to be able to simulate the transport of electrons at low and high fields accurately, subjected to the boundary conditions set for the device simulation. In the Monte Carlo device simulation, electrons are distributed in a one-dimensional mesh size of 1 nm according to the Gunn diode doping density profile. At the initial condition, typically, there are more than 10^5 particles to represent the thermally equilibrium electrons in the device. With the aid of a Poisson solver, the electric field profile is calculated based on the electron charge distribution within the device under a DC bias. The electric field is then recalculated to renew the field profile between contacts over a short time step of 1 fs while the electrons continue to drift to ensure a self-consistent model [10].

B. Gunn Diode Structure

The Gunn diode proposed in this study is of a notch-δ-doped structure as illustrated in Fig. 2. The notch-δ-doped Gunn diode consists of a 50 nm contact region at both ends with a doping density of $2{\times}10^{18}$ cm^{-3}, a 100 nm undoped notch followed by a thin δ-doped layer of 5 nm doped at $1{\times}10^{18}$ cm^{-3} and a transit region in a range of 495-895 nm with doping density of $8{\times}10^{16}$ cm^{-3}, as shown in Table I. Device with higher doping density in the transit region is limited by thermal effect thus it is not considered in this work. All simulations are performed at a temperature of 300 K.

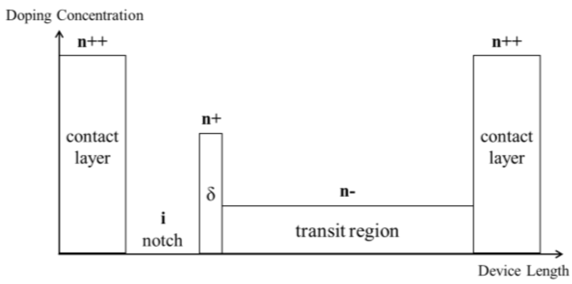

Fig. 2. Gunn diode with notch-δ-doped structure.

Table I: Parameters for the notch-δ-doped Gunn diode.

Layer		Length (nm)	Doping density (cm^{-3})
Contact layer	n^{++}	50	2×10^{18}
Undoped notch	i	100	0
δ-doped layer	n^{+}	5	1×10^{18}
Transit region	n^{-}	495 – 895	8×10^{16}
Contact layer	n^{++}	50	2×10^{18}

III. RESULTS AND DISCUSSIONS

InP Gunn diodes with and without δ-doped layer having the same parameters as in Table I are simulated under different DC biases of 3 V and 4 V for 1000 nm device length. The highest DC bias applied is limited by the impact ionization phenomenon occurred within the device. Figure 3 shows the current waveforms obtained from the InP Gunn diodes with and without the presence of a δ-doped layer under different DC biases. It is observed that the oscillation frequency decreases with increase in applied bias. As the DC bias increases, there is an increment in the electric field across the device which causes the electron drift velocity to be lower in the NDR region. As a result, the operating frequency of the InP Gunn diode is reduced at a high applied bias. In Fig. 3(a), it is shown that the device with a δ-doped layer has a higher peak-to-peak current density of 28.3×10^8 A/m^2 which is almost 1.3 times the value of the device without δ-doped layer at 22.4×10^8 A/m^2. This increment can be attributed to the δ-doped effect on the performance of the InP Gunn diode. The presence of the δ-doped layer helps in modifying the electric field profile within the device which resulted in the increment of the electron energy, mean velocity, electron occupancy in the higher valleys and current density as well as reducing the dead zone at the beginning of the transit region as analysed in [11]. Thus, generating a better Gunn diode performance as compared to the conventional vertical Gunn diode structure.

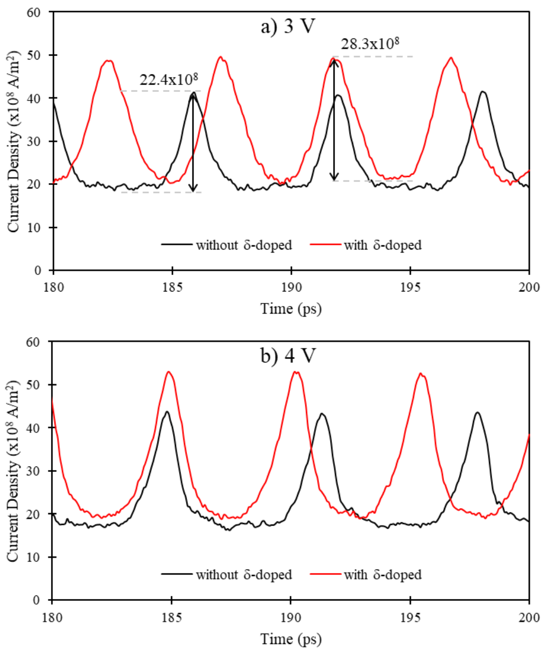

Fig. 1. The current waveforms as a function of time for the InP Gunn diode of 1000 nm length with and without δ-doped layer under DC bias of a) 3 V and b) 4 V.

The performance of InP Gunn diode with and without the presence of a δ-doped layer is then further studied for different device lengths of 700 nm, 800 nm, 900 nm and 1000 nm. The minimum device length is limited to the device capability in sustaining current oscillation with a doping density of 8×10^{16} cm^{-3} in the transit region. Figure 4 shows the Fast Fourier Transform (FFT) of current waveforms for different device lengths under the DC bias of 3 V. It is found that in longer devices with 800 nm, 900 nm and 1000 nm length, InP Gunn diode with δ-doped layer has a higher harmonic amplitude as compared to the device without δ-doped layer. However, the implementation of notch-δ-doped layer in shorter device of 700 nm length shows no improvement on the device performance in terms of harmonic amplitude. On the other hand, the operating frequency shows an increment in the device with notch-δ-doped structure across different device lengths as compared to the device without δ-doped layer.

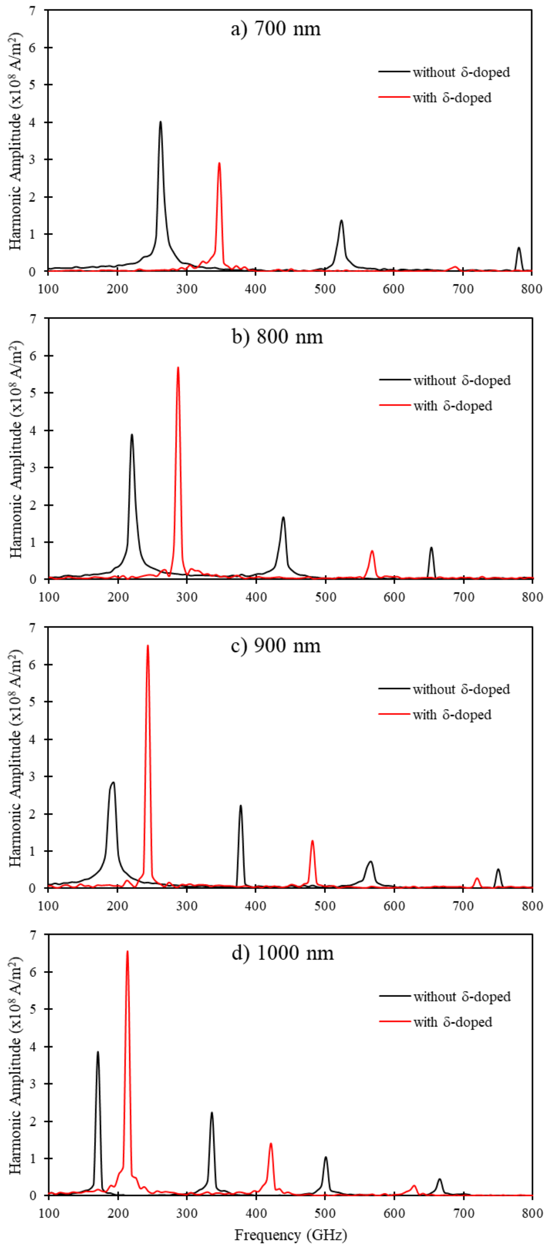

Fig. 2. FFT of current waveforms from the InP Gunn diode with and without δ-doped layer for different device lengths of 700 nm, 800 nm, 900 nm and 1000 nm under an applied DC bias of 3 V.

From the FFT of current waveforms, the fundamental frequency and harmonic amplitude for InP Gunn diode with notch structures are plotted for each of the device length as shown in Fig. 5. It is observed that there is an increment in the fundamental frequency value as the length of the device reduces. When the device length is reduced, the high field domain which is the electron bunch, travels a shorter distance and reach the anode side faster. Thus, generating a higher operating frequency in a shorter device. However, it is observed that the harmonic amplitude decreases as the device length decreases. This is due to the lower negative differential mobility of InP as the operating electric field increases which resulted in a slow growth of electron domain in low-doped InP Gunn diode [9], in addition to the shorter device length.

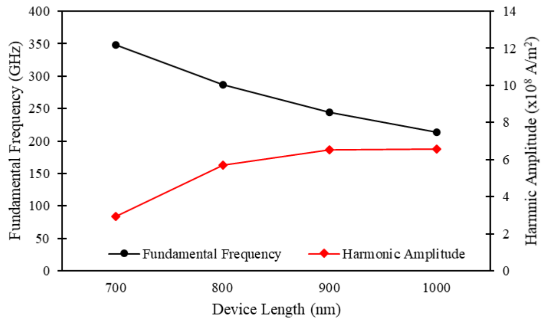

Fig. 3. Fundamental harmonic frequency and current amplitude for different device lengths of 700 nm, 800 nm, 900 nm and 1000 nm under 3 V DC bias.

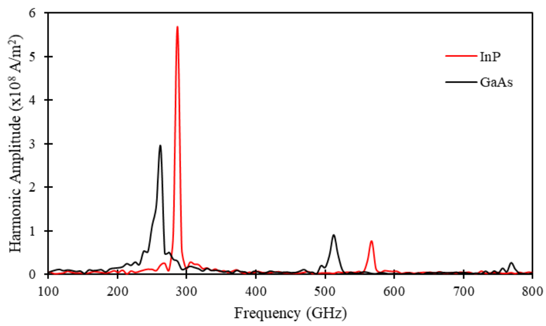

Fig. 4. FFT of current waveforms of the optimized Gunn diode with notch-δ-doped structure for both InP and GaAs devices.

In Fig. 6, the FFT of current waveforms for the InP Gunn diode of 800 nm length with notch-δ-doped structure is compared with the GaAs Gunn diode of 700 nm length which is the shortest device length with a sustainable current oscillation for the same doping density in the transit region i.e. 8×10^{16} cm^{-3}. The optimised GaAs notch-δ-doped Gunn diode is capable of operating at a fundamental frequency of 262 GHz with 2.94×10^8 A/m^2 under a DC bias of 2 V [11]. It is important to note that although the GaAs Gunn diode is shorter in length, its operating fundamental frequency is lower than that of InP 800 nm Gunn diode. This is mainly attributed to the smaller electron drift velocity of GaAs as compared to InP, as shown in Fig. 1. InP material has a higher threshold field value with a larger peak velocity. Thus, InP Gunn diode is expected to be operating at a higher DC bias with higher operating frequency with 1.1 times increment as compared to the GaAs Gunn diode. The InP notch-δ-doped Gunn diode also generates higher harmonic amplitude with almost 2 times the value of that in GaAs Gunn diode.

IV. CONCLUSION

In conclusion, the performances of InP-based Gunn diodes with notch-δ-doped structure have been studied using Monte Carlo method. The device is optimised by applying different DC biases and device lengths to obtain the best device performance in terms of operating frequency and harmonic amplitude. The δ-doped effect on InP Gunn diode is reflected in the significant increase of peak-to-peak current density with 1.3 times increment as compared to the device without δ-doped layer. An improvement on the operating frequency of the InP Gunn diode is also observed with the presence of δ-doped layer within the device. Lastly, the optimised 800 nm InP Gunn diode is found to be operating at 287 GHz, reaching the THz region, with its harmonic amplitude of 5.68×10^8 A/m^2. As expected, the optimised InP device is capable of generating higher operating frequency and larger output power than GaAs Gunn diode due to InP properties.

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