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Mohamed Ismaeel Maricar[1]**, A Khalid**[2]**, G Dunn**[3]**, D Cumming**[2] **and C H Oxley**[4]

[1] School of Engineering and Computer Science, University of Durham, Durham, UK, DH1 3LE
[2] Microsystems Technology Research Group, University of Glasgow, Glasgow, UK, G12 8LT
[3] School of Natural and Computing Science, University of Aberdeen, Aberdeen, UK, AB24 3UE
[4] Department of Electronics Engineering, De Montfort University, Leicester, UK, LE1 9BH

E-mail: choxley@dmu.ac.uk

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Abstract

An experimental method has been used to estimate the dead space of planar Gunn diodes which were fabricated using GaAs and InP based materials, respectively. The experimental results indicate that the dead space was approximately $0.23\,\mu m$ and the saturation domain velocity $0.96 \times 10^5\,\mathrm{m\,s^{-1}}$ for an $Al_{0.23}Ga_{0.77}As$ based device, while for an $In_{0.53}Ga_{0.47}As$ based device, the dead space was approximately $0.21\,\mu m$ and the saturation domain velocity $1.93 \times 10^5\,\mathrm{m\,s^{-1}}$. Further, the results suggest that the saturation domain velocity is reduced or there is an increase in the dead-space due to local field distortions when the active channel length of the planar Gunn diode is less than 1 micron.

Keywords: dead space, planar Gunn diode, GaAs material, InP material

(Some figures may appear in colour only in the online journal)

1. Introduction

THERE is a growing demand for a solid state terahertz source [1, 2] to occupy the small chip area, provide high RF power generation, and at a low operating dc voltage at room temperature. Recently in 2007, Khalid *et al* [3, 4] proposed and fabricated the first $Al_{0.23}Ga_{0.77}As$ based planar Gunn diode operating above 100 GHz. The operating frequency of the planar Gunn diode is determined by the separation between the anode and cathode electrodes, which is known as the active channel length L_{ac}. The active channel length and the saturation velocity v_s determine the transit mode oscillation frequency (v_s/L_{ac}) of the Gunn diode. The first $Al_{0.23}Ga_{0.77}As$ based planar Gunn diodes provided low RF output power of $-43.5\,dBm$ [3] at a fundamental frequency of 108 GHz. In 2011 Li *et al* [5] demonstrated a planar Gunn diode with seven parallel active channels providing an RF output power of $-6.82\,dBm$ at a fundamental operating frequency of 101 GHz.

In recent years planar Gunn diode technology has improved enabling operation in the higher milli-metric and low terahertz regions of the electromagnetic spectrum. $Al_{0.23}Ga_{0.77}As$ based planar Gunn diodes with an anode to cathode separation of $1\,\mu m$ have shown the highest fundamental operational frequency of 121 GHz recorded for a $Al_{0.23}Ga_{0.77}As$ based Gunn diode; the RF output power was $-9.3\,dBm$ [6]. Very recently Khalid *et al* [7] published results for a $In_{0.53}Ga_{0.47}As$ based Gunn diode fabricated on lattice matched InP substrate showing an operational fundamental frequency of 298 GHz with an RF output power of $-25\,dBm$. The anode to cathode separation was $0.6\,\mu m$ and represented the first sub-micron planar Gunn diode. Theoretically the transit fundamental oscillation frequency of the device can be increased by reducing the active channel length L_{ac}. However, Monte Carlo simulations of the planar Gunn diode suggest Gunn oscillations cannot be maintained for active channel lengths which are approximately $0.6\,\mu m$ [8, 9]. The Monte Carlo simulation also indicates the presence of a dead space
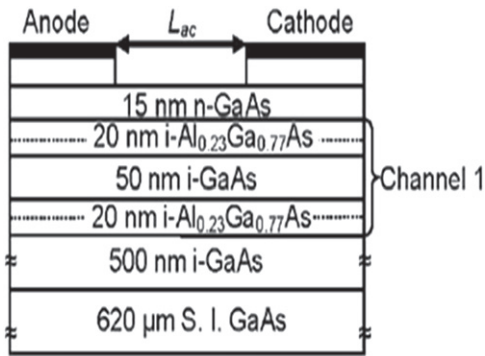
Figure 1. Schematic view of material layers.

Figure 2. Schematic view of material layers.

L_{dead} (the distance it takes the Gunn domain to form in the active region). The simulation indicated the dead space was $\approx 0.25\,\mu$m for both GaAs and InP based planar Gunn diodes [5, 9–11]. A similar dead space has been seen theoretically and experimentally in vertical Gunn diodes [12–14]. The presence of the dead space will affect the transit mode frequency of operation and the efficiency of the planar Gunn diode as it reduces the active channel length and increases the parasitic channel resistance, respectively.

In this paper, both GaAs and InP material based planar Gunn diodes were fabricated with different active channel lengths in order to experimentally determine the active channel dead space. The device fundamental transit frequency was determined using a high frequency network analyzer and for the lower frequencies, the measurement was substantiated using spectrum analyzer measurements. Using the experimental fundamental frequency and knowing the physical active length the dead space was determined. The results indicate that the dead space associated with $Al_{0.23}Ga_{0.77}As$ ($\approx 0.23\,\mu$m) and $In_{0.53}Ga_{0.47}As$ ($\approx 0.21\,\mu$m) based planar Gunn diodes was similar and constant as predicted by the Monte Carlo simulations, provided the active channel length was greater than 1 μm.

2. Fabrication of planar Gunn diodes on GaAs and InP based materials

2.1. Fabrication of device by using the GaAs material

The planar Gunn diode was 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 (15 nm), 50 nm of un-doped GaAs between 20 nm layers of double δ-doped $Al_{0.23}Ga_{0.77}As$ forming the Gunn channel. These are grown on a 500 nm GaAs buffer layer grown directly on 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 400 °C.
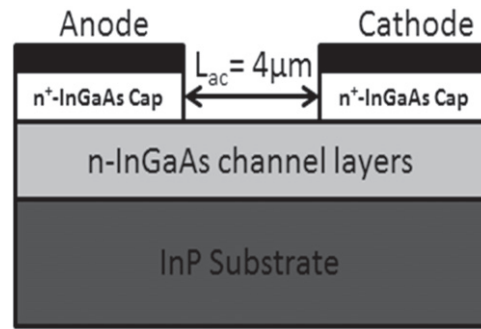
2.2. Fabrication of device by using the InP material

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 $In_{0.53}Ga_{0.47}As$ planar Gunn diode [3, 7, 15, 16]. The device material layers were grown by MBE and consisted of a highly doped $In_{0.53}Ga_{0.47}As$ layer (8×10^{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 2×10^{18} cm^{-3}. These layers were directly grown on a 600 μm thick semi-insulating InP substrate. The nL_{ac} product of both the GaAs and InP based planar Gunn diodes were 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 [17]. 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 °C.

3. Planar Gunn diode measurements

A selection of GaAs and InP based planar Gunn diodes with different active channel lengths were dc and RF characterized. The active channel length of these devices was between 4 and 1 μm in steps of 1 μm. The pulsed *IV* characteristics were first measured using a probe station connected to an automatic pulsed *IV* plotting system (Agilent semiconductor device analyzer B1500). This enabled devices with a negative resistance region to be identified for RF characterization.

The calculated expected transit oscillation frequencies using equation (1) for the different active channel lengths for both the $Al_{0.23}Ga_{0.77}As$ and $In_{0.53}Ga_{0.47}As$ based planar Gunn diodes are given in table 1. The calculation was made assuming the domain velocity was 1×10^5 m sec^{-1} for $Al_{0.23}Ga_{0.77}As$ [3, 6] and 2.25×10^5 m sec^{-1} [7] for $In_{0.53}Ga_{0.47}As$.

$$f = \frac{v_{\text{domain}}}{L_{\text{ac}}} \qquad (1)$$

Single port S-parameter measurements were used to identify the natural transit oscillation frequency using the

Table 1. Oscillating frequency of the planar Gunn diode.

L_{ac}	Operating Frequency of GaAs	Operating Frequency of InP
0.6 μm	166.7 GHz	375 GHz
0.7 μm	142.8 GHz	321.4 GHz
1 μm	100 GHz	225 GHz
2 μm	50 GHz	112.5 GHz
3 μm	34 GHz	75 GHz
4 μm	25 GHz	56.3 GHz

Table 2. DC Operating voltages for $Al_{0.23}Ga_{0.77}As$ and $In_{0.53}Ga_{0.47}As$ devices.

Channel length	dc bias voltage $Al_{0.23}Ga_{0.77}As$	dc bias voltage $In_{0.53}Ga_{0.47}As$
1 μm	2.57–2.96 V	1.31–1.87 v
2 μm	3.26–3.58 V	2.17–2.26 V
3 μm	3.63–3.98 V	2.43–2.71 V
4 μm	4.2–4.85 V	3.51–3.87 V

criterion that the transit frequency corresponded to the maximum magnitude of S_{11}. The $Al_{0.23}Ga_{0.77}As$ and $In_{0.53}Ga_{0.47}As$ device dc operating voltages for the S-parameter measurements are given in table 2. The channel length of these devices stepped from 1 to 4 μm in 1 μm steps.

To verify this criterion spectrum analyser results were used on devices operating at the lower transit oscillation frequencies, i.e. those devices where the active channel length was 4 μm. The single port S-parameters were measured using the VNA as frequencies approaching 220 GHz could be measured which corresponded to the shorter channel length of devices fabricated on $In_{0.53}Ga_{0.47}As$ material (see table 1).

The VNA S-parameter set-up consisted of calibrated 50 Ohm GSG probes attached to an Agilent network analyzer operating from 10 MHz to 110 GHz and 140 GHz to 220 GHz. Single port S_{11} measurements were made on both a GaAs and InP based planar Gunn diodes with a 4 μm active channel length. The measurements indicate natural frequencies of operation of 28 and 62.8 GHz, respectively. These natural oscillation frequencies were verified by using spectrum analyser measurements. The spectrum analyser measurement set-up consisted of Agilent E4448 spectrum analyser, CPW probe and W-band mixer. Figure 3 shows the spectrum analyzer measurements on GaAs and InP based devices with an active channel length of 4 μm. The 4 μm GaAs based planar Gunn diode oscillated (dc = 4.46 V) at 27.67 GHz with an RF output power of −23.4 dBm and the 4 μm InP device (dc = 3.76 V) oscillated at 63.5 GHz with an RF output power of −6.64 dBm. These frequencies were similar to those measured using the VNA and the criterion of maximum S_{11}.

It was found that the oscillation frequency of GaAs and InP device were higher than the figures calculated in table 1. To verify the physical separation between the anode and cathode electrodes a scanning electron microscope (SEM) was used. The electrode separation of the devices selected for RF measurement were measured and found to correspond to the designed active channel lengths. The increase in the measured transit frequency can be explained by the existence of a dead space in the active channel length, which effectively reduces the channel length as reported by Li et al [5, 15]. The dead space can be estimated by using equation (2) and by plotting the measured transit time (1/(transit frequency of

oscillation)) against active channel length L_{ac}.

$$L_{dead} = L_{ac} - \frac{v_{domain}}{f\,(\text{GHz})} \qquad (2)$$

The experimentally estimated dead space for both the GaAs and InP based planar Gunn diodes are shown in figures 4 and 5, respectively. The results indicate for $Al_{0.23}Ga_{0.77}As$ based planar Gunn diodes the dead space was 0.23 μm and the saturation domain velocity was 0.96×10^5 m s^{-1}. This velocity is consistent with the estimated electric field of between 1 to 2 MV m^{-1} for the devices with channel widths of 2 to 4 microns. The dead space appeared to be almost constant between 1.5 to 4 μm active channel lengths. As 1 μm channel length was approached the plot started to show some non-linearity, which indicated a reduction in the saturation domain velocity, or an increase in the dead space. Similar trends were observed for the InP based planar Gunn diode. The experimental results also included the published transit mode frequency for a 0.6 μm [7] and a 0.7 μm [18] active channel length $In_{0.53}Ga_{0.47}As$ planar Gunn diodes. The estimated dead space was 0.21 μm for channel lengths of 4 μm approaching 1μm and the estimated saturation domain velocity was 1.93×10^5 m s^{-1}. This experimental work verifies that the saturation domain velocity for the $In_{0.53}Ga_{0.47}As$ based planar Gunn diode was approximately twice saturation domain velocity of the $Al_{0.23}Ga_{0.77}As$ based planar Gunn diode [7]. Below 1 μm the plot starts to show non-linearity effects indicating a reduction in the saturation domain velocity or an increase in the dead space. The experimental measurements agreed well with Monte Carlo simulation of the planar Gunn diode by Dunn et al [9] who reported a constant dead space for planar Gunn diodes with active channel lengths greater than 1 μm.

4. Conclusion

The paper describes experimental measurements of the dead space for both $Al_{0.23}Ga_{0.77}As$ and $In_{0.53}Ga_{0.47}As$ based planar Gunn diodes on GaAs and InP substrates, respectively. The results verify that the saturation domain velocity for $In_{0.53}Ga_{0.47}As$ was approximately twice that for $Al_{0.23}Ga_{0.77}As$ based planar Gunn diodes. The results also indicated that the dead space for the GaAs based planar Gunn diode was 0.23 μm and 0.21 μm for InP based planar Gunn diode and both constant for the active channel lengths greater than 1 μm, as predicted by Monte Carlo simulations. The
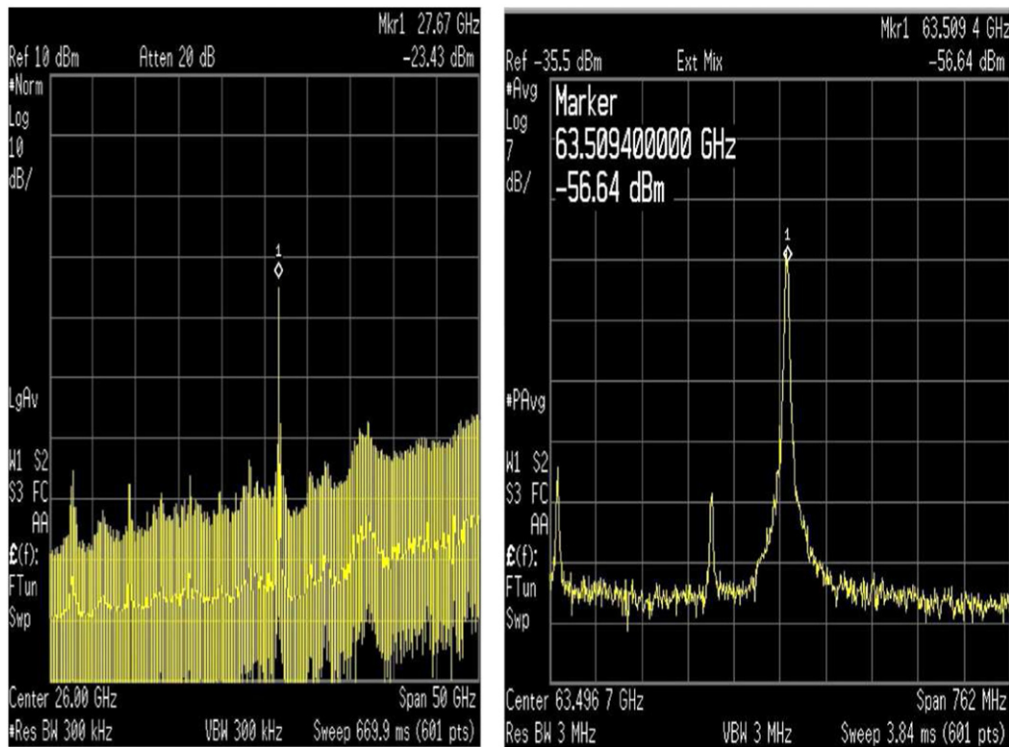
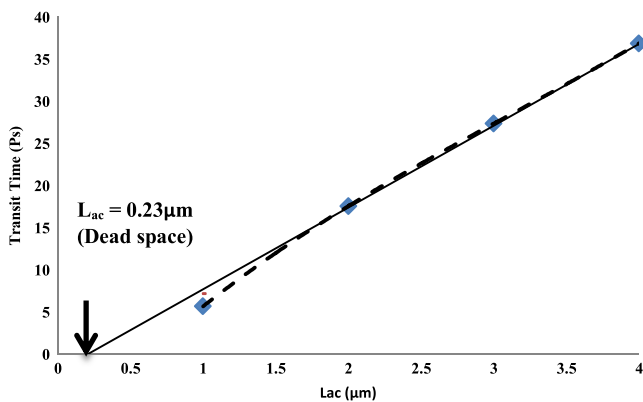**Figure 3.** Spectrum Analyzer measurements results on GaAs and InP materials.

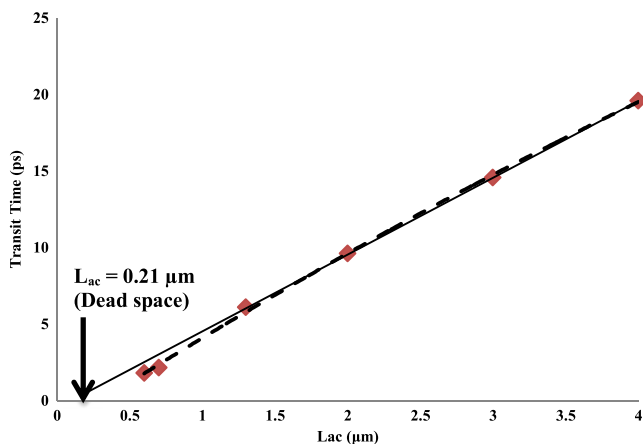

Figure 4. Dead Space for the GaAs based planar Gunn diode.

experimental work also indicated that for active channel lengths of less than 1 μm non-linear effects were seen which could result in an increase in the dead-space, a reduction in the domain velocity or a combination of both effects.

Acknowledgment

Figure 5. Dead Space for the InP based planar Gunn diode.

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