

Gunn Oscillations in Planar Heterostructure Diodes

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Abstract

A significant number of planar Gunn oscillation sources have been modelled and experimentally realized. These offer the prospect of THz operation and increased ease of integration over more traditional vertical structures. Devices were grown by MBE and made using electron beam lithography. Development of devices capable of operation beyond 108 GHz is under way, in tandem with integration into suitable pre-existing cavity designs. Output power is continuously showing improvement and is expected to shortly reach mW power levels.

Introduction

Traditionally, Gunn diodes are constructed in a "vertical" configuration whereby carriers primarily travel perpendicular to semiconductor epilayers and where contacts are made to the top- and bottom-most layers. These structures have been optimised in various ways [1] and serve well at producing significant CW power with low phase noise and so suitable for existing consumer and military radar applications, among others. However in order to achieve efficient operation upwards of ~90 GHz, devices are typically operated in second or higher harmonic modes.

The origin of this frequency limitation lies primarily with thermal dissipation constraints, which impose a maximum ambient charge density typically not much beyond 10^{16} cm^{-3} . Such charge densities determine the size of the domain and consequently, in line with the well-known nL product for Gunn diodes, the minimum length over which the domains are able to

form and transfer. Since this length is directly related to the operating frequency when these devices are operating in a transit-time mode, the heating-imposed density limit corresponds to a frequency limit. Beyond the processing steps required to integrate these vertical devices into a complete oscillation system or with planar integrated circuits, production of sufficient power for common tasks at higher frequencies necessitates additional engineering steps. This may be due to the need to incorporate power combining technology to mitigate the reduced efficiency from individual devices, or investigation into promising alternative material systems. These approaches incur additional unwelcome costs and complexity, whether in development or on a per unit basis.

With the push to develop systems operating at higher microwave frequencies and into the terahertz range, the aforementioned limitations have resulted in the investigation of various alternative technologies. Reported here are details of

an ongoing exploration of a route to bypassing these constraints yet maintaining the benefits of Gunn devices, namely transitioning to a planar architecture.

Historically such explorations have been largely unsuccessful, which has been attributed to growth and fabrication issues such as high impurity or trap densities [2-3]. One notable planar design, however, is the Field Effect Controlled Transferred Electron Device "FECTED" of Thim and Kuch [4-6], designed to operate in transit time independent mode by exploiting the negative differential resistivity (NDR) of a domain trapped under the gate of the device. The possibility of Gunn instabilities forming in FET and HEMT structures has been commented on by a number of authors [7,8], yet this idea has not become established. Furthermore, a number of recent papers [9] have concluded that the well-known "kink effect" in HEMTs [10] could be explained by the presence of Gunn domains, the sudden drop in drain current at certain points in the IV characteristics being due to the onset of associated instabilities. In summary, the great majority of development has at least recently focused on the already established vertical device technology.

The potential advantages of a planar Gunn architecture are significant. Firstly, the charge densities achievable in existing working planar heterostructure devices are substantially higher than those possible in vertical Gunn devices, suggesting that thermal issues will pose less of a problem. This holds the promise of higher frequency operation, following the argument made above. Secondly, integration into planar circuits and systems should be far improved. Finally, the domain transit length is now set largely by the contact separation parallel to epilayers. Such a parameter is controllable during fabrication, whereas with vertical devices it is defined by layer thickness during wafer growth. The planar form thus presents an opportunity for flexible application of a single wafer to devices with different

frequencies. This reduces the need for wafers specialised for a given design and may allow devices of different frequencies to be incorporated on the same chip. All of these factors suggest a substantial reduction in the cost for a given system, compared to implementation using a vertical architecture. This paper presents the results of our continuing investigations into high frequency Gunn oscillator behaviour in HEMT-like diode structures. Section 2 discusses the theoretical and experimental methods, whilst in section 3 our results are presented. Our conclusions are summarised in section 4.

Methodologies

Simulation Methodology

The Monte Carlo (MC) method was selected for the investigation of these structures. While not the most rapid method computationally, its flexibility, accuracy and its ability to extract a wide range of physical parameters concerning the simulated designs are significant advantages over more conventional models. External contact currents are available as a function of time, but in addition internal maps of electron density, electric field and many other properties may also be obtained.

The details of the core of the computational model have been described previously [11]. However the model has since been adapted to include the capability to analyse the effect of degenerate environments, which are increasingly present in the structures now under investigation. The model extension follows previous efforts in the field, whereby the reciprocal-space distribution of electrons is approximated and consulted at potential changes in electronic state to determine if these would breach the Pauli Exclusion principle [12] and the desired fermionic behaviour.

Comparable modelling parameters have been selected, with approximately 20-40,000 electron particles being followed in

each simulation and a field adjusting time-step of 1 fs. Mesh-spacing in active areas was 1-2 nm perpendicular and 2-10 nm parallel to the semiconductor epilayers. The basic layout of a typical simulated structure is shown in figure 1. Further details of the layer structure are given in the next section. Simulation results reported here are for DC biases, since this has been determined to represent the best comparison to experimental conditions.

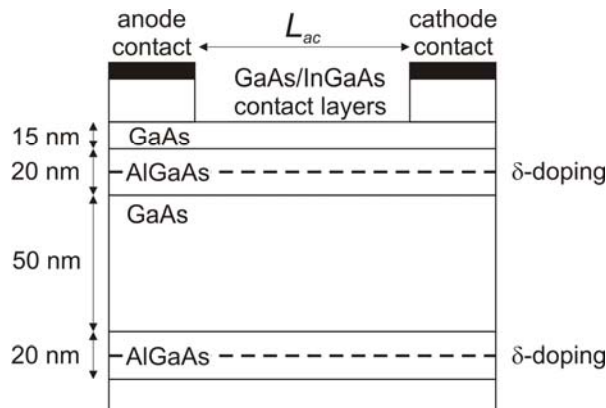


Figure 1: Layer structure of the planar Gunn diodes showing the recess etch between the contacts.

Experimental Methodology

Growth and fabrication followed the same general lines as reported previously [11]. A limited set of details are repeated here for simplicity.

The layer structures agreed after device modelling were grown by molecular beam epitaxy (MBE) and follow the same arrangement as shown in figure 1. The top active (surface) layer is 15 nm of highly doped n-GaAs, below which are two 20 nm undoped $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}$ layers either side of a 50 nm channel layer of GaAs. Charge is supplied by delta-doping in the centre of each AlGaAs layer, at an areal density of $8 \times 10^{11} \text{ cm}^{-2}$. Above these layers are grown multiple graded layers of GaAs/InGaAs; since these are present solely to aid the formation of ohmic contacts they are removed between the contacts as depicted in figure 1.

Device mesas were formed by electron beam (e-beam) direct write into UV-III resist and etching in 1:1:10 of $\text{H}_2\text{O}_2:\text{H}_2\text{O}:\text{H}_2\text{SO}_4$ solution for 90 s, at an etch rate of 60 nm/s. Ohmic contact patterns were made by e-beam direct write into a bilayer of PMMA resist (high molecular weight on top of low molecular weight). The samples were cleaned prior to deposition of contact metal using an oxygen plasma before being de-oxidised, rinsed and dried.

N-type contacts were made by sequential deposition of 20 nm Pd, 50 nm Ge, 10 nm Au, 50 nm Pd and 150 nm Au. After lift-off, annealing at 400 °C for 60 s ensures a reasonable contact resistivity of the order of $5 \times 10^{-6} \Omega\text{cm}^2$.

The aforementioned removal of the GaAs/InGaAs contact layers between the contacts was achieved through use of 3:1 citric acid: H_2O_2 (50% w/w citric acid) for 20 s, with an additional $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ layer inserted during layer growth performing as an effective etch stop [13].

Prior to making RF measurements, each of the diodes is probed at DC to evaluate their current-voltage (IV) characteristics. The data was taken using a combined DC and pulsed IV measurement system (DIVA D210) in order to observe and compare the effect of Joule heating on the device. The measurement system used for radio frequency (RF) measurements is shown schematically in Figure 2.

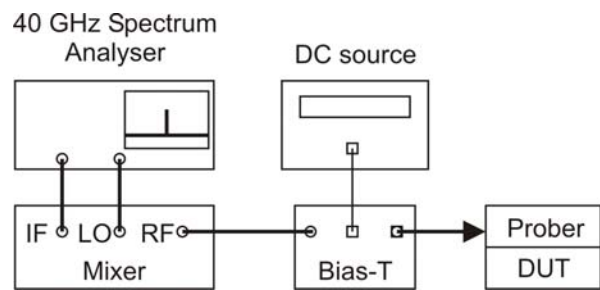


Figure 2: The setup for measuring the RF output from the devices using a W-band GSG probe.

The experimental set-up uses a 40 GHz spectrum analyser, the operating range of which has been extended to the W-band using an external mixer. The intermediate frequency (IF) of the mixer is connected to the RF input of the spectrum analyser. The local oscillator (LO) frequency is in the range 2.9 GHz to 6.6 GHz, and it is from a generator built into the spectrum analyser.

Results & Discussion

The key requirement for operation of these devices has been reported previously, namely the need for a flat potential profile perpendicular to the device layers [11]. This analysis is not repeated here; suffice to say that the device designs pursued satisfy this criterion.

Device Trends

In our previous paper [11] a number of diode results were introduced. In figure 3 a much broader range of simulated and measured results are depicted, expressing clearly the general trend of a significant increase in output frequency as the device length (contact separation) is reduced. This figure shows the expected trend of increased biases depressing the frequency, which is expected to be due to reduced dead-space or mean domain transit speed. These parameters are demonstrated by the trend-lines in this figure, where output frequency is related to the time taken for a domain travelling at a uniform speed v to cover the transit length, the latter being the contact separation less the 'dead space' L_D .

The consistency between simulation, experiment and the trend lines is quite remarkable, confirming the observed behaviour is a transit-time effect and most likely related to Gunn domains. The minor fly in the ointment lies with the contact designs used, the best agreement between theory and experiment having different contact designs (both contacts annealed in experiment, versus solely the anode in simulations). This is under further

investigation, but is not considered a priority due to the good existing match suggesting simulations are promising

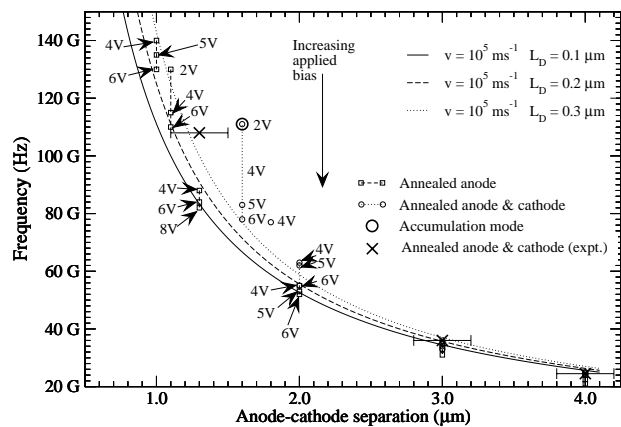


Figure 3: Device Frequency as a function of length for various different contact structures (experimental points indicated by x's).

Effective operation beyond 100 GHz

It may be noted from figure 3 that simulated devices are shown operating beyond the measured 108 GHz, up to 140 GHz. While this is an accurate statement, it does not represent the full story since at these shorter device lengths the oscillations simulated using this layer structure are comparatively weak with a much lower current swing. This weakness results in a tendency to operate in accumulation layer modes, particularly in certain contact configurations and at shorter lengths. A lower efficiency and RF power output would be expected from these devices, if they generated sufficient swing to oscillate successfully at all.

However, based on the experimental reproducibility of the 1.3 μm (108 GHz) diode, it is expected that devices with a comparable current swing should also operate successfully. In order to increase current swing in shorter devices it was natural to investigate scaling the charge (doping) density. This does have the side-effect of increasing the DC power, ie. Joule heating, but as noted earlier it is believed

that these devices are able to cope with such conditions based on the operation of similar existing structures.

Various doping levels and strategies were simulated, ultimately with the aim of restoring the current swing in sub-micron length diodes to that observed in simulations of 1.3 μm length devices. Bulk doping of the channel was investigated, but proved to have little effect at the limited doping levels possible before which it is known that the increased impurity scattering has a distinct negative impact on transport ($\sim 1\text{-}2 \times 10^{23} \text{ m}^{-3}$). Various approaches are now under way to investigate suitable methods for increasing the effective delta-doping density where such doping is already present.

An additional side-effect of scaling up the doping density results from the charge densities approaching the regime where degeneracy effects are potentially an issue. Various tests were performed to elucidate the significance of this, involving the development of degenerate capability in the MC simulator. However it was determined that at the range of higher densities under consideration at this point, such effects were minor. This will require consideration in later stages however, contingent upon the details of future designs.

In addition to scaling of the charge (doping) density in these structures, attention is being given to the use of alternative layer structures, based on the design principles used in existing devices. At this stage one focus lies with construction of devices with layer structures containing a mix of Indium in the active layer structures in addition to in the contact layers. While maintaining a suitable heterostructure arrangement in the transit region of these devices may prove taxing, previous success in vertical Gunn diodes and other types of devices with such 'faster' materials has demonstrated their great potential for performance improvements.

Improvements in Power

Our previous work focused on demonstrating that these structures were feasible as Gunn oscillators. While power measurements were made at this stage, these were not strictly comparable to that from other devices since power was simply sampled from a small solid angle from the device, with no waveguides and without a tuned resonator.

The previous best power achieved from a 108 GHz diode device was -43 dBm. Various investigations into ways in which this power level could be improved have been made.

A matched resonator is a clear option to pursue, however at this stage no equipment was available to directly measure the s-parameters required to achieve an ideal design. As an alternative, a resonator was designed as shown in figure 4. The idea was to systematically trim the metal on either end by keeping a quarter wavelength "open stub" and "short stub" on either side of the diode, based on a design frequency of 90-110 GHz. Whilst not ideal, since the laser trimming was not a clean process (see figure), the desired variation was achieved, the result being a 100-fold increase in power. This figure could be even higher since losses were not calibrated, but resulted in a 104 GHz signal measured with a power of -24 dBm.



Figure 4: Photograph of laser-trimmed resonator.

A second direction involved the optimisation of the ohmic contacts used for the devices. These newer designs, without a resonator of the form discussed in the prior paragraph, have been measured as high as -22 dBm ($\sim 6 \mu\text{W}$) at 108 GHz, another approximately 100-fold improvement. This

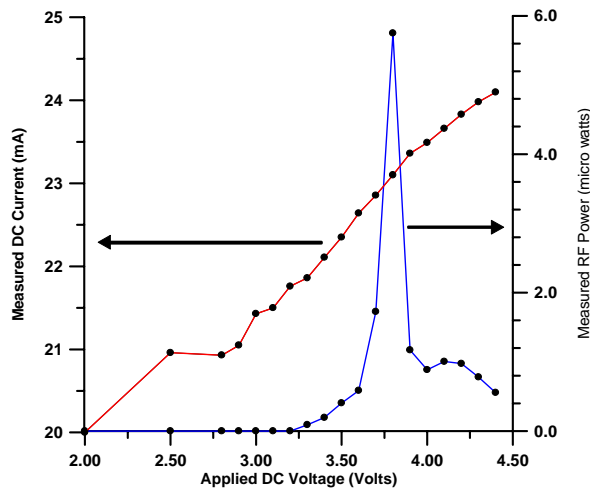


Figure 5: Power and current as a function of voltage (dots: measured; lines: guide to eye)

measurement was made using an RF power meter, which measures integrated power; however the measurements are believed to be of reasonable value for comparison to results measured previously. Characteristics of these devices are shown in figure 5.

Integration Developments

While the planar devices discussed here theoretically allow for simpler integration opportunities, an established base already exists around the circuitry and systems for vertical devices. Since the described oscillators work in the same way outside the diode itself, with help from e2v technologies we are investigating leveraging the existing vertical cavity technology, combining it with the new planar diodes.

Conclusions

In this paper, by means of simulations and experimental fabrication, we have demonstrated our recent developments in the use of HEMT like structures functioning as high frequency Gunn oscillators. A detailed theoretical understanding of device

operation, oscillation mode, frequency and device length relationships has been achieved. In addition, power levels of “bare” devices of -22dBm have been demonstrated and additional power increases of the order of a factor of 100 have been proven for devices placed in simple cavities.

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References

- 1 S Montanari, A Forster, M I Lepsa and H Luth, *Solid State Electronics* (2005) **49** p.245-50
- 2 M. Takeuchi, A. Higashisaka, and K. Sekido, *IEEE Trans. Electron Devices*, (corresp.) **ED-19**, p.125,(1972).
- 3 Chryssafis A. and Harrington J., *IEEE Trans. Electron Devices*, **ED-23**, p.426, (1976).
- 4 Thim H.W., (1973), US Patent No. 3 740 666.
- 5 Rieder G., Thim R., Kuch R. and Lubke K., (1983), *Archiv elektr. Ubertr.*, 37, p.217.
- 6 Scheib H., Lubke K., Grutzmacher D., Diskus C.G., and Thim H.W, *IEEE Trans. On Microwave Theory and Techniques*, 37, (1989), p.2093.
- 7 Yamaguchi K., Asai S. and Kodera H., *IEEE Trans on Elec. Dev.*, **ED-23**, (1976), p.1283.
- 8 Moglestue V., *Eur. Trans. Telecommun. Relat. Technol.*, 1, p.439.
- 9 Dunn G.M., Phillips A. and Topham P.J., *Semicond. Sci. and Tech.*, 16, (2001), p.562.
- 10 Kuang J.B., Tasker P.J., Chen Y.K., Wang G.W., Eastman L.F., Aina O.A., Hier

- H., and Fathimulla A., Elec. Lett., (1988),
24, p.1571
- 11** A Khalid, N Pilgrim et al 2007 Proc. 4th
EMRS DTC Technical Conference A27
- 12** S Bosi and C Jacoboni 1976 J. Phys. C:
Solid State Phys. **9** p.315-319
- 13** X. Hue, B. Boudart and Y. Crosnier, J.
Vac Sci. Technology B **16**(5) (1998) p.296-
299

