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# Concerning the maximum frequency limits of Gunn operators

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**Abstract：** The length of the transit region of a Gunn diode determines the natural frequency at which it operates in fundamental mode—the shorter the device, the higher the frequency of operation. The long-held view on Gunn diode design is that for a functioning device the minimum length of the transit region is about 1.5 μm, limiting the devices to fundamental mode operation at frequencies of roughly 60 GHz. The authors posit that this theoretical restriction is a consequence of limits of the hydrodynamic models by which it was determined. Study of these devices by more advanced Monte Carlo techniques, which simulate the ballistic transport and electron-phonon interactions that govern device behaviour, offers a new lower bound of 0.5 μm, which is already being approached by the experimental evidence shown in planar and vertical devices exhibiting Gunn operation at 0.6 μm and 0.7 μm. It is shown that the limits for Gunn domain operation are determined by the device length required for the transferred electron effect to occur(approximately 0.15 μm, which as demonstrated is largely field independent) and the fundamental size of the domain(approximately 0.3 μm). At this new length, operation in fundamental mode at much higher frequencies becomes possible—the Monte Carlo model used predicts power output at frequencies over 300 GHz.

**Key words：** Gunn diode；Monte Carlo；theoretical limits；GaN

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## 1　Introduction

The Gunn diode is a structurally simple semiconductor device that is commonly used in applications requiring the generation of radiation of a high quality, consistent frequency with a small electronic tuning range. These applications range from garage door openers to collision avoidance systems in automobiles[1-3]. The Gunn effect, for which the diode is named, is quite simply the result of Negative Differential Resistance(NDR) in certain materials, notably Gallium Arsenide(GaAs), Indium Phosphide(InP) and other III-V semiconductors[4-8]. As electrons travelling within these materials gain sufficient energy, they transition into valleys in the material's conduction band where their mass so dramatically increases that the electrons actually slow down: an increase in applied electric field can lead to a decrease in current. This allows the formation of a density instability called a domain in the material. The formation of domains has been explored thoroughly before[9-10], but as it is the central concern of this paper, a brief précis of the theory is perhaps worthwhile.

Near the device's cathode a small density perturbation—perhaps a result of thermal drift of electrons, more likely promoted by the design of the cathode itself—will occur, leading to an accumulation of electrons. By Poisson's equation, this will naturally lead to an increase in the local electric field, which for a material exhibiting NDR will result in a decrease in current. Ahead of this region, the field will be lower, resulting in an electric field that encourages electrons to build at the region of charge accumulation and deplete ahead of it. This gives rise to what is called a dipole domain.

At its simplest, the Gunn diode is a region of n+ doped semiconductor material(called the transit region) sandwiched between two more highly doped n++ regions, though to promote dipole domain formation, many devices incorporate a region of low doping(called a doping notch) appended to the transit region. The fundamental mode of operation of these devices involves the cyclical passage of domains across the transit region; as such their operating frequency is inversely proportional to the length of this region. In most circumstances, the formation of a dipole domain will affect the field

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across the device such that it is impossible for a second domain to form until the first has exited the device. A simple measure of operation frequency in fundamental mode therefore is to divide drift velocity of the domain by the length of the transit region. Therefore devices with shorter transit regions have higher operational frequencies.

The received wisdom about Gunn diodes is that, for GaAs(which is the focus of the bulk of this article) the minimum transit region for which a device can be expected to function is well over a micron in length[11-16]. The standard limit quoted for simple vertical devices is for a transit region of approximately 1.5 μm and correspondingly a maximum fundamental mode frequency of about 60 GHz[15], though this does not consider complications like the effects of doping notch or the introduction of HEMT-like structures. However, there is increasing evidence that this assumed limit is perhaps not as absolute as previously thought. Recent work with planar Gunn diodes has demonstrated that operation frequencies of up to 110 GHz are possible[17] in GaAs and at over 160 GHz in $In_{53}Ga_{47}As$ for 1.3 μm long devices[18]. Experiments with short Gunn diodes at the University of Manchester have also shown operation of vertical Gunn devices with a transit region as short as 0.7 μm[19], and have reported operation of short Gunn diodes at frequencies well in excess of previously theorised limits[20]. Our latest experimental results on submicron planar Gunn diode $In_{53}Ga_{47}As$ for 0.6 μm long devices have yielded 307 GHz[21].

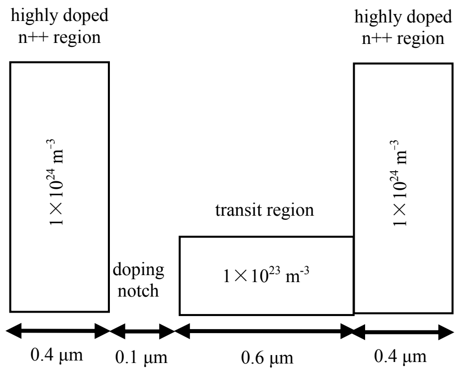


Fig.1 Profile of functioning short Gunn device

Our contention is that previous estimates of the limits of Gunn operation substantially underestimate possible operation frequency because of over simplifications of the assumptions on the rate of formation and transfer of domains. Modern Monte Carlo models are better able to account for the complex dynamics of electron transport in III-V semiconductors including velocity overshoot lengths and time taken for relaxation to equilibrium conditions so that domains may reform, which are complex functions of field strength. In general, Monte Carlo techniques allow for better simulation of ballistic transport properties than hydrodynamic models. Using these techniques we arrive at new theoretical limits that seem to better match recently reported experimental results as well as our own experimental observations in submicron planar Gunn devices, and derive a possible explanation for this new limit of device operation.

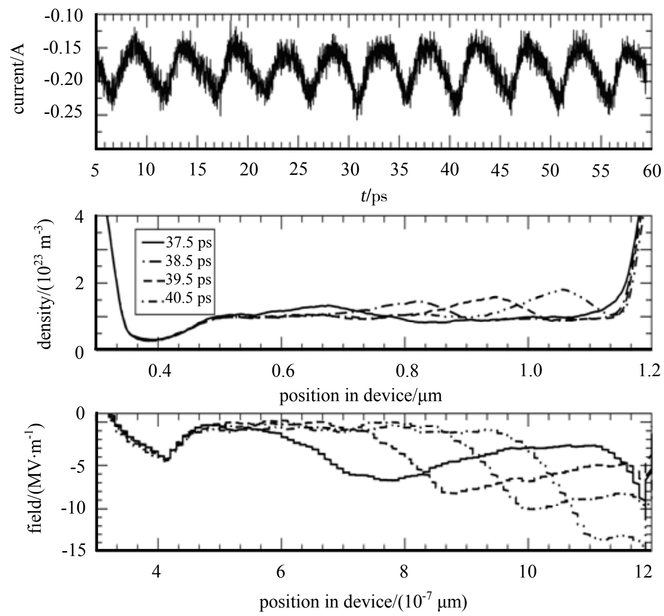


Fig.2 Current versus time, electron density and electric field versus position at time intervals of 1 ps for device specification in fig.1. The current shows steady cyclical operation at roughly 230 GHz. The electron density and the electric field show the formation and transit of a single domain.

## 2 Methodology and Results

The simulations carried out in this paper were performed using the authors' two proprietary Monte Carlo models, details of which can be found in previously published papers, for the one-dimensional model in [22] and for the planar model in [23]. The models incorporate acoustic, polar optic and inter-valley scattering processes, using a Poisson solver to recalculate the electric field at femtosecond time intervals and track the behaviour of approximately 10 000 super-particles. Mesh size is varied depending on the scale of the device under study, naturally, but always lay between 0.5 nm and 1.7 nm.

As stated above, many Gunn diodes incorporate a doping notch to encourage domain formation. This paper explores the limits of Gunn function and so, while numerous simulations were performed without a notch, it is perhaps unsurprising that these simulations did not produce a functioning device. As a result, readers will notice that all the vertical Gunn diodes discussed below feature an ideal doping notch. In case of planar Gunn diodes, the doping notch was not used and still produced functioning devices.

For vertical structures, the device sought was desired to operate under a micron in length, so a range of device designs was simulated with a transit region beginning at this size and ever decreasing as cyclical domain formation was found. The parameter space explored included not just the length of the transit region, of course, but also its doping level, the length(and, as discussed above, presence) of a doping notch and the applied voltage across the device. The length of n++ region simulated by Monte Carlo methods was fixed at 0.4 μm to either side of the transit region.

Operational devices were found down to a transit region length of 0.6 μm, and the working specification for this device can be found in figure 1. As shown in the figure, the featured contacts are doped at $1\times10^{24}$ $m^{-3}$, an idealised doping notch is of length 0.1 μm and a transit region is doped at $1\times0^{23}$ $m^{-3}$. It is perhaps worth mentioning here that the transit region doping is quite high—not unreasonable, by any means[24], but for a device of this length at this doping, thermal output would be worth investigating when the results are more widely accepted.

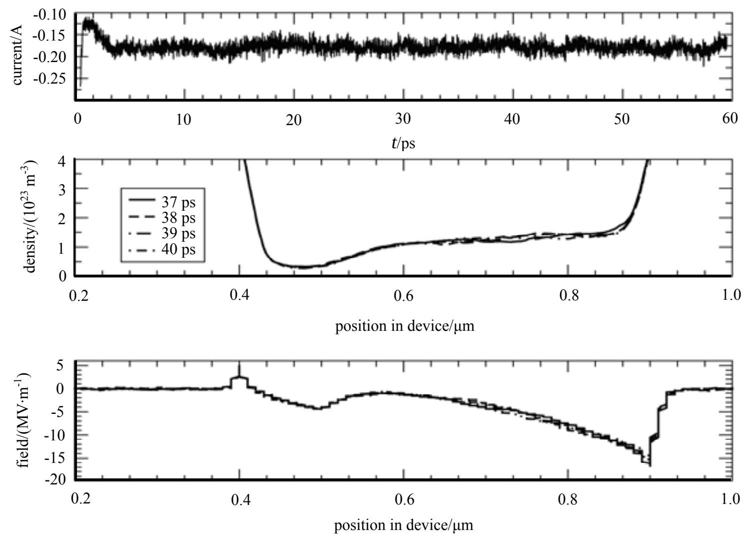


Fig.3 Non-functioning 0.4 μm device. The current shows one initial transit, and then none further. The electron density and the electric field are samples from later in the device's operation, and show the essentially steady state into which the device has settled.

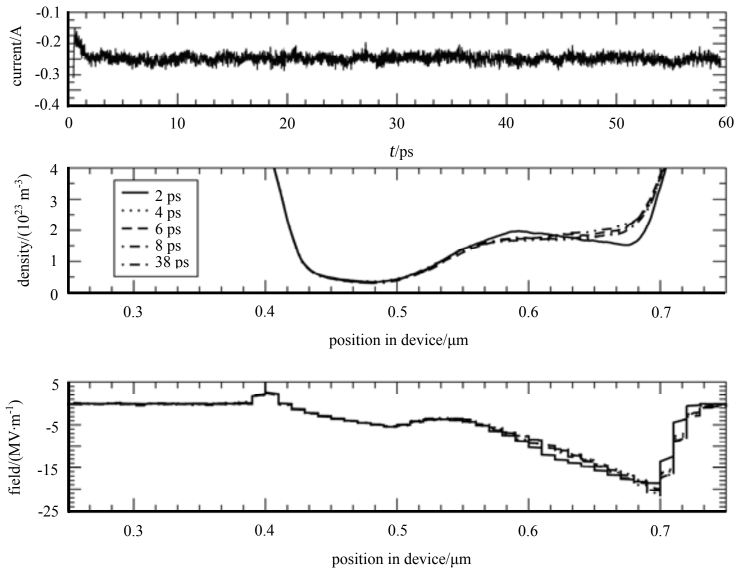


Fig.4 Non-functioning 0.2 μm device. Again, the current shows that this device will not operate continuously. Here, the electron density and the electric field have been selected from the beginning of simulation, to be compared with one result from later on. It can be clearly seen that the device immediately fails to perform.

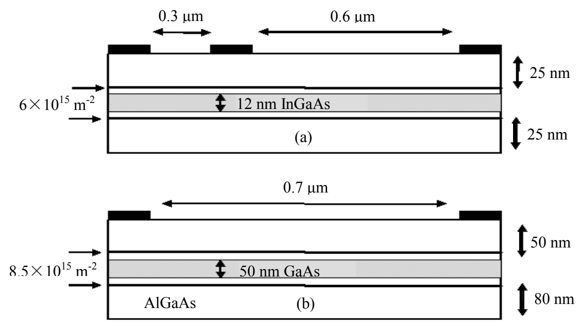


Fig.5 The HEMT like structure of a typical planar Gunn as reported in [18]. Top:An $In_{23}Ga_{77}As$ channel triode structure; bottom: a GaAs channel diode.

The device functions when driven by a potential of 3 V, are shown in figure 2. From the electric field and electron density, it is clear that the device is operating in dipole mode. The normalized current shows the device operating continuously, at a frequency of roughly 230 GHz. This is nearly a four-fold increase from the previous theoretical maximum operation frequency of 60 GHz[15]. While it is impossible to prove a negative, extensive and systematic simulations have failed to show operation for transit regions below this 0.5 μm threshold. Figure 3 shows a device identical to the one previously described, save that the transit region has been reduced to 0.4 μm. Here the device gives a single domain transit, however this is a result of the crude initial conditions of the simulation. Once the device has settled into a more reasonable configuration, it can be seen from the graph of current versus time that the device does not continue to operate. For a still shorter device, with a transit region only 0.2 μm in length, it can be seen that the device fails to function entirely, as demonstrated by figure 4.

Simulations of planar Gunn diodes such as those reported in [25–27] showed a similar natural limit in size with devices shorter than 0.7 μm struggling to operate. Figure 5 shows the typical HEMT like structure of the Planar Gunn diodes and triodes. In the case of the GaAs channel Gunn diode, the length is 0.7 μm, with a 50 nm thick undoped GaAs channel set in delta-doped AlGaAs layers of $8 \times 10^{15}$ $m^{-2}$. This is the smallest GaAs diode observed to produce a reasonable oscillation at about 140 GHz. Better results were obtained from the InGaAs triode structure(the gate in the structure can be used to control and stimulate the nucleation point of the domain). Figure 6 shows a domain in transit in this triode structure. The domain can clearly be seen to be about half of the transit region size(0.6 μm) and this 0.3 μm domain was the smallest observed and is consistent with the predictions of the 1-D model. Again, it is impossible to prove a negative, but no smaller domain or higher frequency operation was observed in this structure. Nevertheless, InGaAs materials have a greater mobility than GaAs and the improved frequency performance is shown in figure 7. It shows the potential of fundamental mode operation at up to 300 GHz. This incredibly high figure has recently been given some credence by the experimental observation of similar InGaAs structures operating at over 160 GHz as mentioned previously.

Having found these new limits for Gunn operators, it is necessary to discuss how they arise.

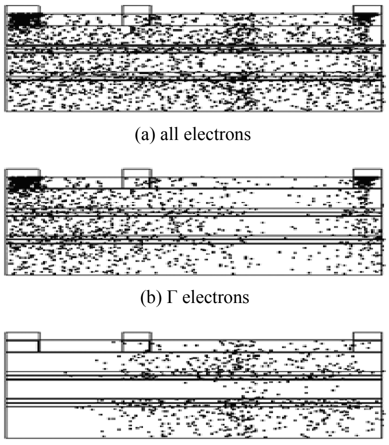


Fig.6 The InGaAs triode structure shows a domain in transit. The points represent a sample of the electron super-particles in the simulations. The domain is about 0.3 μm in width—about half of the transit regions here and is the smallest observed in simulations.

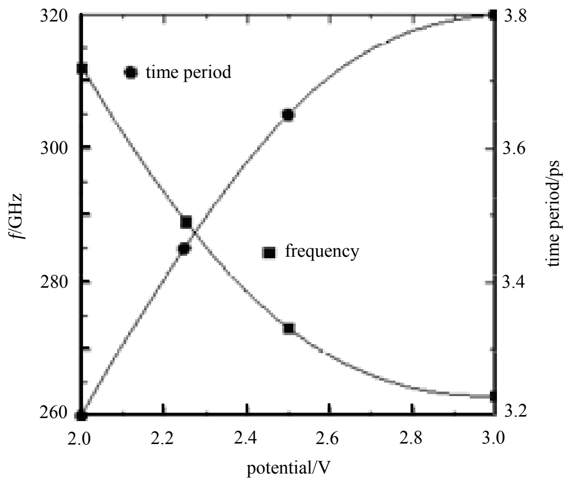


Fig.7 The frequency response of the InGaAs triode as a function of the drain potential shows a considerable electronic tuning range.

## 3 Analysis

In order for a domain to form, not only must there be the requisite charge density over the domain to contain the applied potential—there must also be the ability for valley populations to change over the width of the domain. This allows the electrons to transition to higher valleys in the conduction band, becoming heavy and slowing, and for electrons ahead of the resulting accumulation of electrons and existing in a region of lower field to have lower effective mass and, concordantly, increased velocity. This allows the domain to form.

As shown in figure 8, the time for transfer equilibrium to be reached when considering transitions into higher valleys is dependent on the applied electric field. High fields can promote rapid transfer into higher valleys; however they result in high ballistic transport velocities before equilibrium is reached. Conversely, it takes longer for electron transfer to reach equilibrium in a low electric field but the velocity at which the forming domain travels is much lower. This then effectively limits the minimum feature size over which conduction band valley populations can switch from light to heavy (or vice versa) to the order of 0.15 μm. That is to say, domain formation is governed by the velocity-time product.

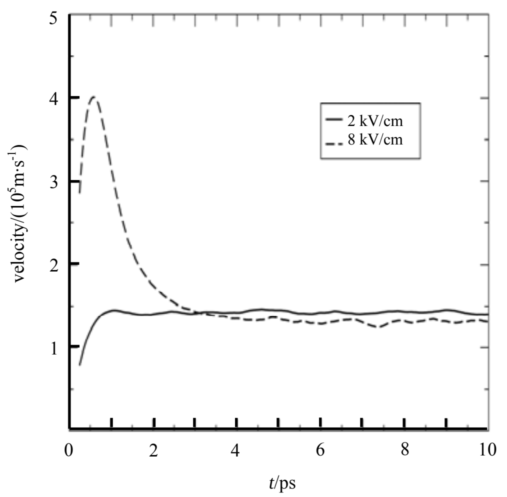


Fig.8 Drift velocity versus time curves at high($8\times10^5$ V·m$^{-1}$) and low ($2\times10^5$ V·m$^{-1}$) electric fields in GaAs.

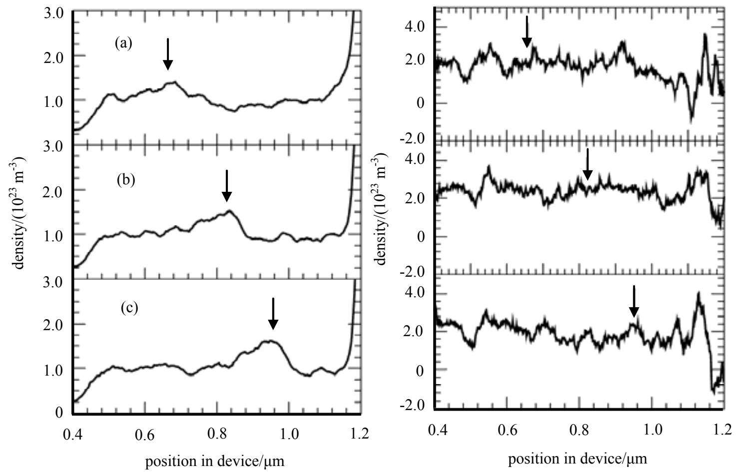


Fig.9 Velocity across device as domain forms and transits. Each figure is set 1 ps after the one preceding it. In the left column is the electron density, with the corresponding device velocity profile on the right. As a guide to the eye, arrows delineate the approximate position of the domain on the graphs.

The change of velocities exhibited in this behaviour is pictured in figure 9, which shows the velocity profile evolving over picosecond intervals as a domain forms and transits. As the velocity across the device is inherently a noisy process and also one that constantly evolves with time(thus limiting the usefulness and applicability of time averaging), discerning the salient points within the figure perhaps requires a little explication. At the position of the notch in all three velocity profiles a high velocity is found, as would be expected given the strong electric field across this region. Moving across the device, the average drift velocity of the system is on the order of $10^5$ m·s$^{-1}$, as would be expected for GaAs. The most interesting feature is of course the incipient domain, which is delineated with an arrow on each of the individual velocity graphs. Within this region the velocity approaches $3\times10^5$ m·s$^{-1}$ then rapidly falls below equilibrium conditions just beyond the dipole, before normalising. This process is illustrated as the density evolves between figures 9(b) and 9(c).

The minimum size of a domain, regardless of electron density, is therefore at least 0.3 μm. Generally speaking, the size of a forming domain will be larger than an established domain. Figures 2 and 10 illustrate how a forming domain can span the entire transit region in a small device. As its peak moves closer to the anode, the field becomes stronger and the domain reduced in extent. It is reasonably to assert then, that whilst the minimum size of an established domain is about 0.3 μm, it needs more room than this to form initially. As a result, the minimum length for the transit region of a functional Gunn operator becomes of the order of 0.5 μm. This new figure is less than one third of the previous limit and, as shown in figure 2, results in an operational frequency that is, at over 230 GHz, substantially higher than previously ascribed limits for GaAs Gunn devices and about twice that which has so far been achieved experimentally, though the experimental figure has recently been increasing at a remarkable rate.

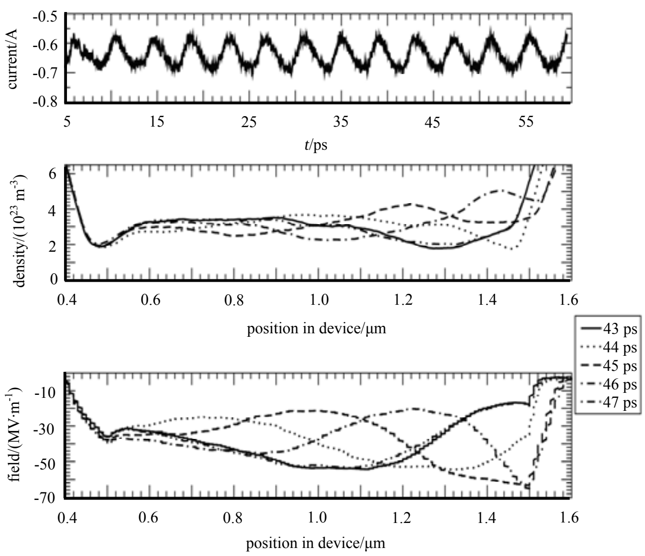


Fig.10 Functioning GaN device. The current shows cyclical operation at a frequency of approximately 265 GHz, for a transit region of one micron in length. The formation, transit and reformation of a domain are shown in both the electron density and the electric field.

## 4 Conclusions

Prompted in part by experimental results, the work described in this paper intended to explore the function of Gunn operators at sub-micron lengths. Simulations using Monte Carlo methods have shown that Gunn diodes may function with transit regions down to 0.5 μm in length. This is substantially smaller than the long-standing rule of thumb that such devices would not work below 1.5 μm. As the transit region length is intrinsically related to the frequency at which these devices operate, this is no mere sciolistic result—new devices of the scale discussed in the paper allow increases in the frequencies which can generate commercial importance.

The historically accepted limit for fundamental mode GaAs Gunn diodes of 60 GHz has already been doubled in realized devices and this work shows that this frequency could be exceeded nearly four-fold. The device described in figure 2 operates at 230 GHz.

As acknowledged earlier in this article, the vertical device discussed features a not unreasonable, but nevertheless quite highly doped transit region. Thermal generation within such a device may be significant, and one area worth further study would be the transport of heat within such a device. Depending on the outcome of this work, the applications of various cooling techniques might also be considered, though arguably further verification of the results reported would be a more pressing matter.

While this article has mainly concerned itself with GaAs, the theory it discusses applies equally well to other NDR materials, including InP and InGaAs, as well as Gallium Nitride(GaN). As relaxation times in these materials are much quicker than in GaAs and higher mobilities as well, it seems possible that devices constructed from these materials might operate with still shorter transit regions and consequently higher frequencies for a given transit region length. Simulations of InGaAs planar diodes have shown the potential for operation at frequencies as high as 300 GHz whilst devices have been realized experimentally that operate at 160 GHz. While exhaustive investigation has not yet been undertaken, a few preliminary simulations of GaN devices(as discussed in [22]) have yielded a functioning device with a transit region of one micron, doped at $3\times10^{23}$ $m^{-3}$. This device includes a notch with the same specifications as above. As can be seen from figure 10, this device operates at a frequency of 265 GHz. Though the device is longer than the GaAs device detailed above, the domain travels faster, so the frequency of operation is higher. A drawback of this device is that, in GaN, thermal effects would be even more pronounced. As previous work by the authors indicates[22], this device would probably need to be operated in a pulsed mode, with periods of operation on the picosecond scale offset by cooling for nanoseconds. However, if devices of similar scale to the above GaAs result prove possible, the operation frequency will be well within the terahertz band.

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**Biography:**

**Dr Macpherson** is currently a teaching fellow in the Department of Physics at the University of Aberdeen. For his PhD he designed and coded a novel Monte Carlo simulation to study thermal effects in semiconductor devices. He has published several widely cited academic papers and one largely unread novel. He has been nominated for several teaching awards and his poetry won the 2014 Nocturne Prize. email:r.f.macpherson@abdn.ac.uk.