Evaluating the microwave performance of a two domain GaN Gunn diode for THz applications

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Abstract: The microwave performance of a two domain GaN Gunn diode is investigated at a fundamental frequency of 0.175 *THz* and its second and third harmonics through Monte Carlo particle simulations. Simulation results show that the two domain diode is feasible and that a significant increase in output power is achieved compared to that of a single domain diode. Furthermore, the microwave performance of the two domain diode can be enhanced by appropriate engineering of the transit region doping profiles. Three doping profiles are considered, namely nominally flat, exponentially increasing and exponentially decreasing, towards the anode contact regions. The exponentially increasing doping profile yields the highest output power, with 5 *W*, 514 *mW* and 87 *mW* generated at 0.175 *THz*, 0.350 *THz* and 0.525 *THz*, respectively. Thermal heating is generally significant in Gunn diode operation, but especially so for GaN diodes. Hence, thermal modeling is incorporated in the simulations consistently with the dynamic evolution of electrons through the device.

This investigation concludes that a narrow pulsed bias voltage is preferred in the simulation of the GaN Gunn diodes to overcome the adverse effect of thermal heating. It is reported that the narrow pulsed bias voltage enhances the performance of the two domain diode. Under these conditions the two domain GaN Gunn diode exhibits a maximum operational frequency limit of 0.525 *THz*.

Keywords: Gunn diode, Graded transit region, Negative differential resistance, Multi domain, Monte Carlo simulation.

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1. Introduction

GaN Gunn diodes are recognized as sources of microwave power at frequencies above W-band. The GaN semiconductor has a wide band-gap and exhibits much shorter energy-relaxation times as compared to traditional III-V materials such as GaAs. This has led to research into the exploitation of the negative differential resistance characteristics of GaN for Gunn operation towards THz frequencies [1-4]. In this paper, the microwave performance of a two domain GaN Gunn diode is investigated at a fundamental frequency of 0.175 *THz* and its second and third harmonics at 0.350 *THz* and 0.525 *THz*, respectively.

Multi-domain GaAs Gunn diodes were investigated by Thim [5] and Tsay *et al* [6]. They predicted that the output power of an N-domain diode will increase by a factor of N^2 as compared to a single domain diode. This increase in output power is possible if its bias voltage and cross-sectional area are scaled appropriately to retain the electric field bias conditions and device conductance of the single domain device. To a first order approximation, this implies that the bias voltage and cross-sectional area of a two domain diode should be twice that of the corresponding single domain diode. This is due to the additional voltage drop and resistance of the second transit region which is effectively connected in series with the first. The transit region doping profiles incorporate a notch on the cathode side, in line with previous research [4]. Further doping profile optimization is studied by simulating graded (exponentially increasing and decreasing) doping concentration levels over the last 25% of the transit regions towards the anode. For the purpose of this paper, the transit region doping profiles are characterized by 'g_f', which is the *grading factor* by which the nominal doping concentration levels in the transit regions vary towards the anode. The device simulations are based on the Ensemble Monte Carlo Particle Simulation Technique (EMCPST). The simulation model incorporates modeling of thermal heating consistently with the dynamic evolution of electrons through the device [7]. The continuous updating of the internal temperature profile renders a realistic performance of the GaN Gunn diode, where thermal heating plays a significant role [3, 8-9]. A three-valley, non-parabolic energy band for GaN (Wz) is implemented with the material parameters referenced from Joshi *et al* [2].

2. Simulation model and method

The approach followed in this paper is to establish a benchmark single and two domain diodes with uniform doping in the transit region(s) (g_f = 1). The simulated microwave performance of these benchmark diodes is compared to determine the improvement expected from multi-domain diodes. In subsequent simulations, the effect of exponentially grading the transit region doping profiles towards the anode contact, on the performance of the two domain benchmark diode is also investigated. Table 1 lists the major design and simulation parameters of the single and two domain benchmark diodes.

Tab. 1 Design and simulation parameters of benchmark single and two domain GaN Gunn diodes

Parameter	Single domain	Two domain
Fundamental frequency	175 *GHz*	175 *GHz*
Transit region length	0.8 *μm*	0.8 *μm* (both transit regions)
Transit region nominal doping concentration	1×10^{23} m^{-3}	1×10^{23} m^{-3}
Notch length	0.2 *μm*	0.2 *μm*
Notch doping concentration	0.25×10^{23} m^{-3}	0.25×10^{23} m^{-3}
Cross-sectional area	2.3×10^{-9} m^2	4.6×10^{-9} m^2
Bias voltage V_{DC}	40 *V*	80 *V*
Duty cycle	1.5 %	0.8 %
Ambient temperature	300 *K*	300 *K*

The doping concentration profile of the two domain diode is illustrated in Figure 1. Regions 1 and 7 are the heavily doped cathode and anode contact regions, respectively. Regions 2 and 5 are doping notches to promote Gunn domain formation close to the cathode side of the transit regions. Regions 3 and 6 are the two transit regions of the Gunn diode. The two domains are separated by a 0.25 *μm* heavily doped buffer, Region 4 [4].

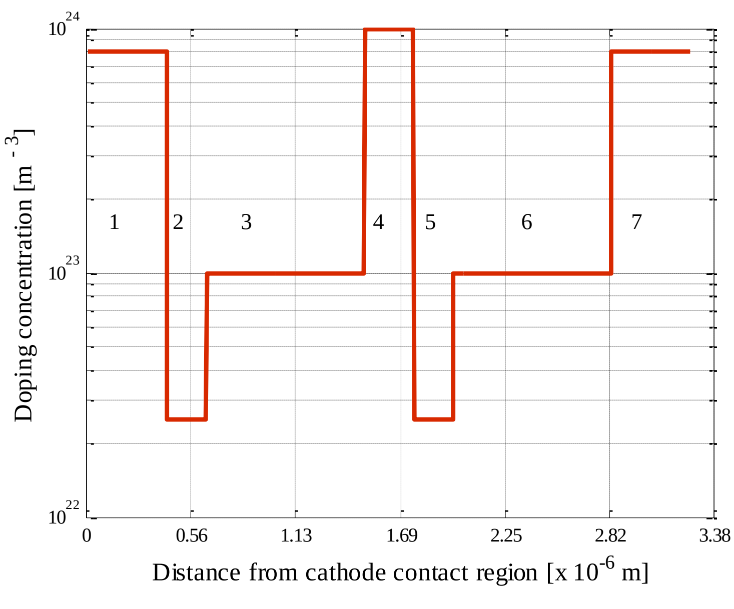

Fig. 1 Doping profile of benchmark two domain diode

For subsequent simulations of the two domain diode, three doping profiles are considered, namely over-doped (g_f = 1.5), flat-doped benchmark (g_f = 1), and under-doped (g_f = 0.5). Figure 2 illustrates these doping profiles.

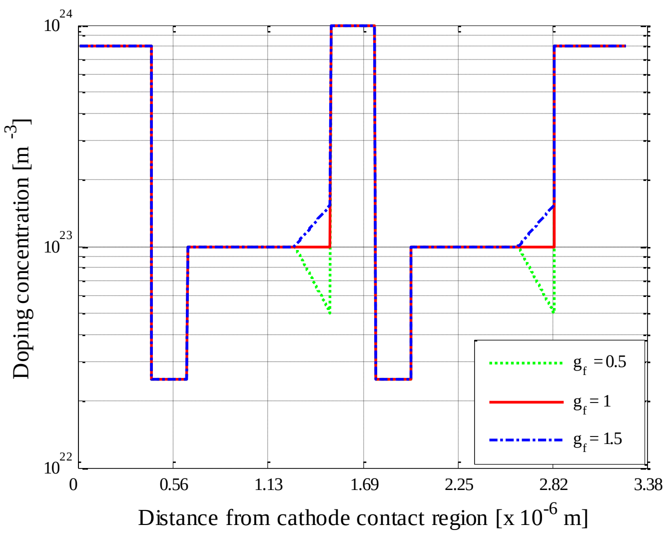

Fig. 2 Graded doping profiles of two domain diode

The microwave performance of the two domain diode is determined by simulating the current response to an applied terminal voltage $v_d(t)$,

$$v_d(t) = V_{DC} + \sum_{n=1}^{3} V_n \sin(2\pi nF + \phi_n) \quad \text{(Equation 1)}$$

where V_{DC} is the bias voltage, F is the fundamental frequency, and V_n and ϕ_n denote the amplitude and phase of the n^{th} harmonic, respectively. The harmonic output power and device admittance are readily derived from frequency transforms of the contact terminal voltage and current waveforms. In this work, external circuit losses, parasitic inductances and capacitances are not modeled; hence, the output power can be expected to be less than the simulated values.

The detrimental effect of heat dissipation on the output power of GaN Gunn diodes is pronounced because of the higher biasing conditions compared to, for example, GaAs diodes [1-4, 8, 10-11]. Consequently, thermal management of GaN diodes proves to be critical. The high operating temperature of a GaN Gunn diode reduces its efficiency significantly [8, 11]. An effective way of countering the increased thermal heating is to apply pulsed bias voltages with very small duty cycles [9]. The on-time of the bias voltage pulses is assumed to be less than 2 *ns* to prevent excessive heating [3]. The effect of the duty cycle is only factored into the effective bias voltage and current, which scales linearly with the duty cycle. For the two domain diode simulations presented here, a duty cycle of 0.8% was required to limit the cathode contact temperature to below 500 *K*. For reference, the single domain diode required a bias voltage duty cycle of 1.5% since the bias voltage is reduced.

3. Results and discussion

3.1 Microwave performance

The simulated microwave performance of the benchmark one and two domain diode, with g_f = 1, is investigated at a fundamental frequency of 0.175 *THz*. Table 2 tabulates the simulated harmonic output power of the single and two domain diodes with g_f = 0.5, 1.0 and 1.5. The corresponding device conductances are also listed.

Tab. 2 Simulated output power of single and two domain diodes with graded transit region doping profiles g_f = 0.5, 1.0, 1.5

Doping profile	Frequency [THz]	Output power | Conductance		Factor increase in output power
		Single domain	Two domain	
g_f = 1.5	0.175	3.4 *W* -0.20 *S*	5 *W* -0.10 *S*	1.5
	0.350	259 *mW* -0.20 *S*	514 *mW* -0.20 *S*	2
	0.525	42 *mW* -0.20 *S*	87 *mW* -0.4 *S*	2
g_f = 1.0 (benchmark)	0.175	3 *W* -0.17 *S*	3.8 *W* -0.15 *S*	1.3
	0.350	229 *mW* -0.18 *S*	460 *mW* -0.20 *S*	2
	0.525	14 *mW* -0.05 *S*	60 *mW* -0.6 *S*	4.3
g_f = 0.5	0.175	2.6 *W* -0.16 *S*	3.1 *W* -0.10 *S*	1.2
	0.350	160 *mW* -0.13 *S*	420 *mW* -0.12 *S*	2.6
	0.525	8 *mW* -0.03 *S*	30 *mW* -0.5 *S*	3.75

The simulated cathode contact temperature of the one and two domain diode was 480 *K* and 500 *K*, respectively. (The temperature profile of the two domain diode is shown in Figure 4.)

An initial observation from Table 2 is that the conductances of the one and two domain diodes are similar. This indicates that the doubling of the cross-sectional area of the two domain diode has the desired effect of retaining the conductance of the single domain diode.

The exponentially increasing transit region doping profile (gf = 1.5) enhances the output power consistently over the full frequency range. This can be attributed to the improved curvature of the time-averaged Gunn domains (see Figure 3) and the marginally lower operating temperature (see Figure 4).

For the two domain diode, the output power generated at the third harmonic was accompanied by a change in the admittance from an inductive at the fundamental and second harmonic to capacitive at the third harmonic. This needs further investigation. This could be due to the device working at its operational frequency limit. Thus implying that the one domain diode has a higher operational frequency limit than the two domain diode. This can be explained by the increased operating temperature of the two domain diode, which has a severe effect on the third harmonic.

It is further evident that two domain operation increases the output power compared to single domain operation. However, the expected four-fold (N^2) increase in output power is generally not achieved. This may, again, be attributed to the higher operating temperature of the two domain diode. A secondary factor is the fact that the Gunn domains in each of the two transit regions of the two domain diode are not identical. This suggests that further optimization of the transit region doping profiles should be possible.

It is therefore instructive to further investigate the behavior of the two domain diode based on the internal electric field, temperature and valley occupation distributions.

3.2 Electric field distribution of two domain diode

The time-averaged electric field distribution is shown in Figure 3. The formation of the characteristic Gunn domains as a result of the transferred electron effect is evident.

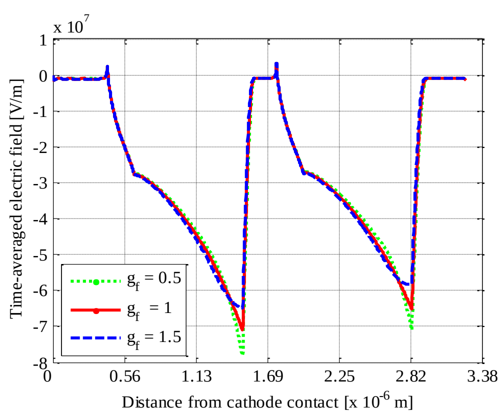

Fig. 3 Time-averaged electric field distributions for the different doping profiles

The electric fields exhibit an improved curvature of the Gunn domains for the exponentially increasing transit region doping profile (g_f = 1.5). The higher electric field peaks associated with the under-doped transit region doping profile (g_f = 0.5) implies that Gunn domains are formed further away from the cathode side than for the over-doped case. This degrades the power efficiency. It is further observed that the domain formation in the two transit regions is not identical as is ideally assumed. This can be attributed to the difference in nominal temperature of the two regions, as is illustrated in Figure 4. This impacts the nominal electron mobility in each region [11]. The non-symmetric nature of the Gunn domains in the two domain diode results in a decrease in output power and efficiency of the diode. Hence, as stated earlier, the fourfold increase in output power compared to a one domain diode is not achieved.

It is clear that the buffer region width of 0.25 μm is adequate for quenching the Gunn domains in-between the transit regions.

3.3 Temperature distribution of two domain diode

The steady state internal temperature distribution is shown in Figure 4.

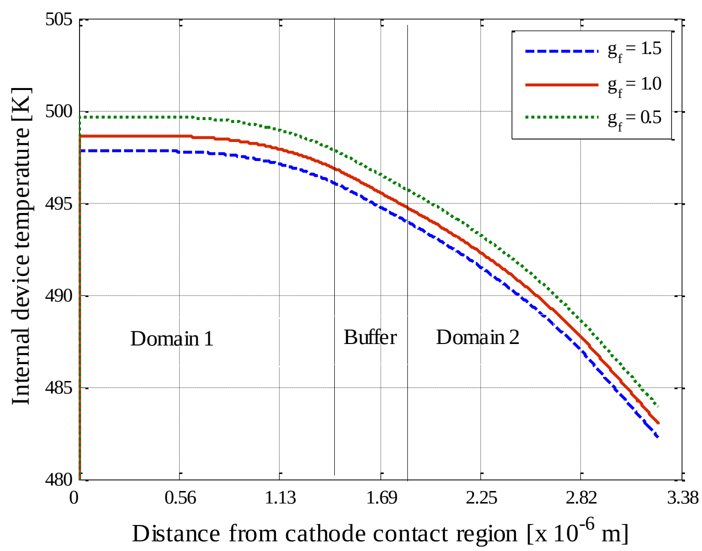

Fig. 4 Internal device temperature distribution of the two domain diode for the different doping profiles

The temperature is highest close to the cathode in the first domain in all three cases. This is attributed to the integral heat sink that is assumed to be on the anode side of the diode. It is noted that the over-doped transit region (g_f = 1.5) exhibits a marginally lower operating temperature. This may be ascribed to the improved curvature of the electric fields in the transit regions, which translates into improved efficiency and lower thermal loss.

3.4 Electron occupation of energy band valleys

The microwave behavior of Gunn diodes is intrinsically linked to the transferred electron effect. Figure 5 illustrates the steady state (time-averaged) electron occupation of the central (C) and satellite (L and X) valleys of the energy band throughout the two domain diode (g_f = 1.5).

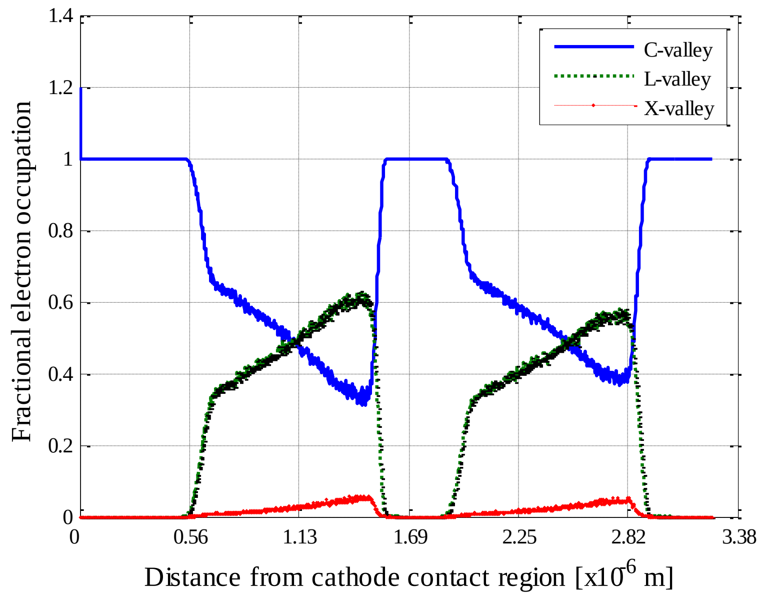

Fig. 5 Steady state electron occupation of the central (C) and satellite (L and X) valleys of the energy band throughout the two domain diode with g_f = 1.5

An immediate observation is that the transfer of electrons from the central to satellite valleys increases towards the anode, but is incomplete due to the short transit region. Only 60% of the central valley electrons transfer to the L-valley. The buffer region serves as a low resistance connector between the two transit regions. The transferred electrons revert to the C-valley upon entry into the buffer region. This is a necessity for two domain operation. A further observation is that the valley occupation in the first transit region is marginally higher than that in the second. This also manifests as the non-identical Gunn domains evident in Figure 3. From a modeling perspective, the negligible occupation of the X-valley suggests that a two valley energy band model could be implemented to reduce the computational load associated with the MCPST.

3.5 Operational frequency limit

From Table 2 the operational harmonic frequency limit of the two domain diode is between 0.35 *THz* and 0.525 *THz*.

The over-doped (g_f = 1.5) two domain diode was subsequently simulated at a higher fundamental frequency of 0.200 *THz*. Simulations show negligible output power at the fundamental frequency of 0.200 *THz* and its second and third harmonics. It is, therefore, asserted that 0.175 *THz* approaches the operational fundamental frequency limit of the two domain diode

The sharp reduction in output power from 0.175 *THz* to 0.2 *THz* in the fundamental mode suggests that the diode should be highly frequency selective, which can be attributed to the very short transit regions of 0.8 μm.

4. Conclusions

The research shows that it is feasible to increase the output power of GaN Gunn diode by using a two domain diode. The simulation of two domain over-doped transit region predicts an output power of 5 *W*, 514 *mW* and 87 *mW* at fundamental frequency of 0.175 *THz*, at the second and third harmonic respectively. The output power of the two domain diode is higher as compared to that of a single domain at 3.4 *W*, 259 *mW* and 42 *mW* at the fundamental frequency of 0.175 *THz* and its second and third harmonics respectively.

The output power of GaN Gunn diodes is improved through appropriate profiling of the transit region doping concentration. Previous research has shown the benefit of incorporating a doping notch for Gunn domain nucleation. This paper predicts that further optimization of the Gunn diode is possible through increasing the doping concentration exponentially over the last 25% of the transit region towards the anode region. Compared to a nominally flat transit region doping concentration profile, the simulations predict a minimum increase in the output power of 30 % at the fundamental frequency of 0.175 *THz* and its second and third harmonics.

Heating of the GaN Gunn diode is a major concern which can be overcome by proper heat sinking of the device and by decreasing the average bias current. This investigation concludes that a narrow pulsed bias voltage with a duty cycle below 1% should be used for two domain GaN Gunn diode to avoid excessive heating. This needs further investigation.

The highest operating frequency for a single domain and two domain diode is projected to be of the order 0.175 *THz* in fundamental mode and 0.525 *THz* in harmonic mode. This is a more conservative estimate than that reported in literature, which can be attributed to the appropriate incorporation of thermal effects in the Monte Carlo simulation model used in this paper.

From the simulation results the authors are of the view that although a two domain diode yields substantially higher output power than the single domain diode, the use of three domains or more will not be feasible due to the severe thermal heating of the diodes.

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