Evaluating graded doping profiles of single domain GaN gunn diodes for THz applications

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(Received March 02, 2013)

Abstract: The microwave performance of a single domain GaN Gunn diode is investigated using the Monte Carlo particle simulation technique. The simulations show that the performance of the diode is enhanced by appropriate engineering of the transit region doping profile. Three doping profiles are considered, namely flat, exponentially increasing and exponentially decreasing towards the anode. Improved microwave performance is obtained with the increasing doping profile, yielding 728 *mW* at a fundamental frequency of 0.175 *THz*, and 36 *mW* at the third harmonic of 0.525 *THz*. The simulations suggest this to be approaching the operational frequency limit of the device. Thermal effects are incorporated consistently with charge evolution through the device.

Keywords: Gunn diode, Negative differential resistance, Monte Carlo Simulation, Graded transit region

doi: 10.11906/TST.177-182.2013.09.11

1. Introduction

At frequencies above W-band, GaN Gunn diodes are recognized as sources of microwave power. Compared to traditional III-V semiconductor-based generators such as GaAs, GaN exhibits much shorter energy-relaxation times, which has lead to research interest into exploiting the negative differential resistance characteristics of GaN for Gunn operation towards THz frequencies [1-4]. Some reported findings are optimistic, as thermal effects are not generally taken into account. In this paper, the performance of a single domain GaN Gunn diode is investigated at frequencies exceeding 0.175 *THz*. 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 region towards the anode. The device simulation is based on a Monte Carlo Particle simulation technique (MCPST) that incorporates thermal effects consistently with the dynamic evolution of electrons through the device [5]. The continuous updating of the temperature renders a realistic performance of the GaN Gunn diode, where thermal heating plays a significant role [3].

2. Simulation model and method

A single domain GaN Gunn diode with a flat transit region doping profile is simulated as a benchmark for investigation. The doping notch is placed next to the cathode [4]. The diode has a diameter of 55 *μm*. A three-valley, non-parabolic energy band is implemented. The GaN (Wz) material parameters used are referenced from Joshi *et al* [2]. The doping concentration profile for 0.175 *THz* fundamental mode operation is presented in Figure 1**.** The doping levels are in close agreement with those reported in literature [2, 3].

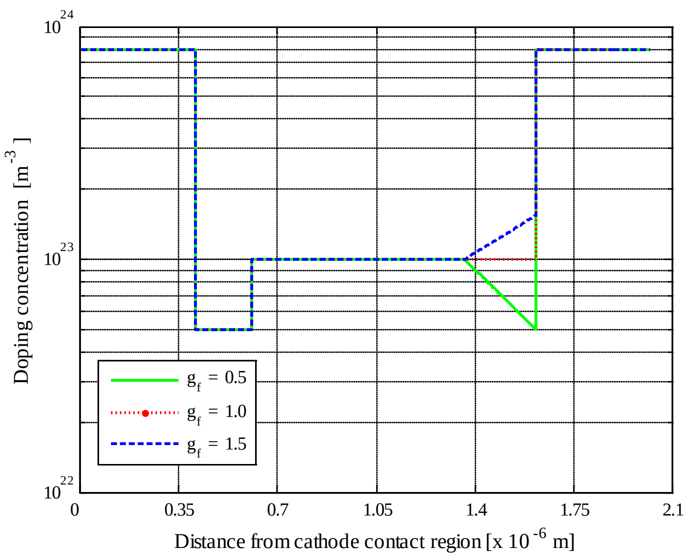

Fig. 1 Exponentially graded doping profiles of the benchmark, single domain 0.175 *THz* Gunn diode with doping notch at the cathode. The active region is sandwiched between two highly doped ohmic contact regions.

The microwave performance of the diode is determined by simulating the current response to an applied terminal voltage $v_d(t)$ described by Equation 1,

$$v_d(t) = V_{DC} + \sum_{n=1}^{3} V_n \sin(2\pi nF + \phi) \qquad (1)$$

where V_{DC} is the bias voltage, F is the fundamental frequency, V_n denotes the amplitude of the n^{th} harmonic and ϕ is the phase difference. The high operating temperature of a GaN Gunn diode reduces its efficiency significantly [4, 6]. To limit the thermal heating of the diode, a pulsed bias voltage with a 1.5% duty cycle is applied, with an on-time assumed to be less than 2 *ns* [3]. In this work external circuit losses are not modeled. Three doping concentration profiles are considered, namely a benchmark flat profile (g_f = 1.0), an exponentially increasing profile (g_f = 1.5) and an exponentially decreasing profile (g_f = 0.5), where g_f is the *grading factor* by which the nominal doping concentration level in the transit region is varied towards the anode.

3. Results and discussion

3.1 Benchmark simulations

The simulated output power of the benchmark, flat doping profile diode, at fundamental frequencies varying from 0.15 *THz* to 0.2 *THz*, is presented in Table 1, together with reported simulation results of a similar ‘referenced diode’ by Joshi *et al* [2]. The adjusted values for output power are scaled to compensate for the smaller device cross-section of the referenced diode. The expected roll off in output power with increased frequency is evident in both the benchmark and referenced diode simulation results. The far more rapid decline in output power of the reference diode is a result of the fixed external LCR resonator circuit model employed by Joshi *et al*. The resonator circuit further reduces the output power away from its centre frequency. In contrast, the microwave performance of the benchmark device is simulated by applying a terminal voltage with optimised harmonics. This in effect matches the diode at every frequency simulated to the resonator circuit, and will therefore not lead to an external circuit-driven roll off in output power. The discrepancy in output power at 0.15 *THz* of the benchmark and referenced diode can be attributed to different bias conditions; 50 *V* for the referenced diode compared to 40 *V* implemented here.

Tab. 1Comparison of output power of the benchmark and referenced diodes at various fundamental operating frequencies

Frequency [*THz*]	Output power of Gunn diode		
	Benchmark diode	Referenced diode	Referenced diode adjusted
0.150	500 *mW*	265 *mW*	629 *mW*
0.175	430 *mW*	100 *mW*	238 *mW*
0.200	260 *mW*	20 *mW*	48 *mW*

3.2. Simulations for graded doping profiles (g_f = 0.5, 1.0, 1.5) at THz harmonic frequencies

Table 2 lists the output power predicted at a fundamental frequency of 0.175 T*Hz* and its *THz* harmonics for the flat and graded doping profiles.

Tab. 2 Simulated output power for graded transit region doping profiles gf = 0.5, 1.0, 1.5 at THz harmonics

Doping profile	Frequency (*THz*)		
	0.175	0.350	0.525
g_f = 1.5	728 *mW*	110 *mW*	36 *mW*
g_f = 1.0	430 *mW*	86 *mW*	30 *mW*
g_f = 0.5	355 *mW*	44 *mW*	5 *mW*

The associated time-averaged electric field distributions and the temperature profiles are presented in Figures 2 and 3.

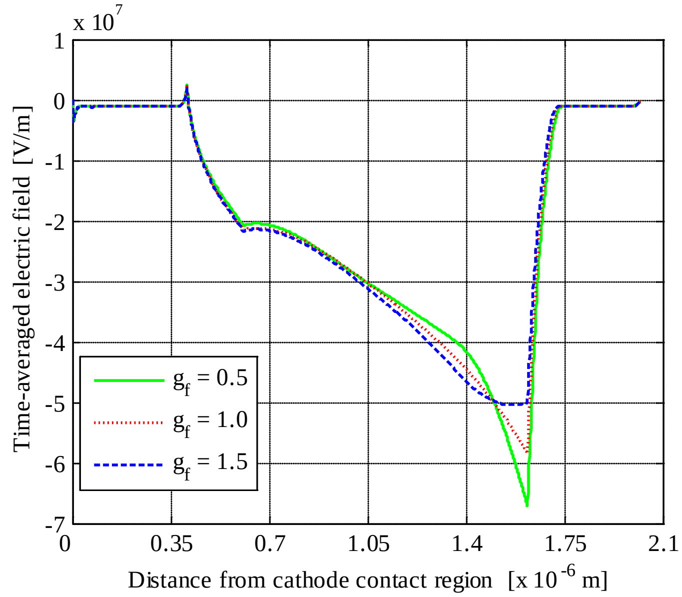

Fig. 2 Time-averaged electric field distribution for transit region doping concentration profiles (g_f = 0.5, 1.0, 1.5)

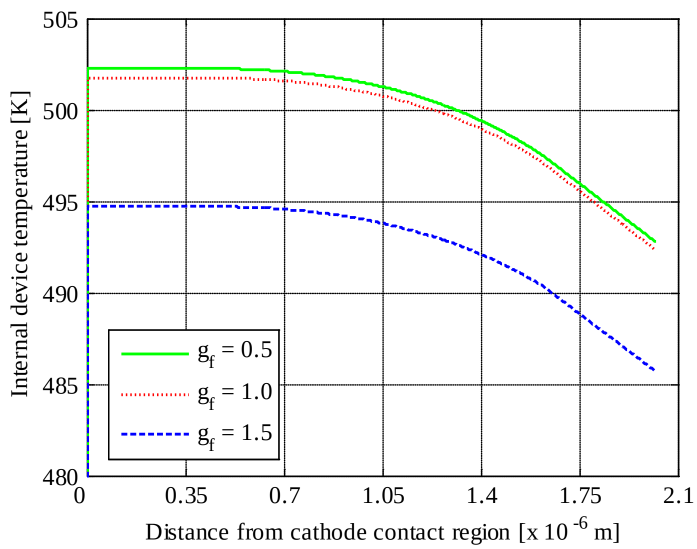

Fig. 3 Temperature profiles for different transit region doping concentration profiles with an ambient temperature of 300 *K*

The doping profile with a transit region graded profile of g_f = 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 domain, and the marginally lower operating temperature.

3.3 Investigating the upper operational frequency limit of the optimized diode ($g_f = 1.5$)

To investigate the upper operating frequency limit of the single domain GaN Gunn diode with a $g_f = 1.5$ graded transit region doping profile, the fundamental frequency is increased from 0.175 *THz* to 0.250 *THz* in incremental steps of 0.025 *THz*. The simulated output power at each frequency is listed in Table 3. The length and nominal doping concentration of the transit region are adjusted appropriately to maintain a sufficient '*nL*' product [2, 7].

Tab. 3 Output power as a function of frequency of the optimized GaN Gunn diode with $g_f = 1.5$ graded transit region doping profile

Fundamental frequency [*THz*]	Output power at the fundamental (P_1), second (P_2) and third (P_3) harmonics		
	P_1	P_2	P_3
0.175	728 *mW*	110 *mW*	36 *mW*
0.200	590 *mW*	67 *mW*	0
0.225	482 *mW*	60 *mW*	0
0.250	126 *mW*	6 *mW*	0

The highest fundamental frequency is predicted to be in the region of 0.250 *THz*. The 0.5 *THz* second harmonic associated with this fundamental frequency yields 6 *mW*, which is less than that of the 0.525 *THz* third harmonic of the 0.175 *THz* fundamental harmonic previously simulated. This is attributed to the higher 0.175 *THz* (fundamental) harmonic amplitude.

4. Conclusions

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% towards the anode region. Compared to a nominally flat transit region doping concentration profile, the simulations predict an increase of output power of 70 %, 27 % and 20 % at 0.175 *THz*, 0.35 *THz* and 0.525 *THz*, respectively.

The highest operating frequency for the optimized diode is projected to be of the order 0.25 *THz* in fundamental mode and 0.525 *THz* in harmonic mode. This is a more conservative estimate than reported in literature, which can be attributed to the appropriate incorporation of thermal effects in the Monte Carlo simulation model used in this paper.

Thermal heating of GaN Gunn diodes are significant. This can be countered through appropriate heat sinking of the device, and the reduction of the bias current. The latter is achieved through applying a pulsed bias voltage with a 1.5% duty cycle and with an on-time of less than 2 *ns*.

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