GaN GUNN DIODES FOR THz SIGNAL GENERATION

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ABSTRACT

The frequency and power capability of GaN-based Gunn diodes is evaluated using transient hydrodynamic simulations. GaN Gunn oscillators with *2μm*-thick GaN Gunn diodes are predicted to have fundamental frequency of *148-162GHz* and power density of $>10^5 W/cm^2$. Due to their high frequency and power characteristics, applications of these devices are envisaged for THz signal generation.

INTRODUCTION

GaAs- and InP-based Gunn diodes, based on the transferred-electron effect, have been successfully employed for microwave and millimeter-wave signal generation [1,2]. Studies of the fundamental properties of GaN indicate that it also exhibits transferred-electron effect [3]. The use of wide-bandgap semiconductors, such as GaN, with increased electrical strength offers the possibility to increase frequency and power capability of semiconductor devices. Thus, GaN-based MODFETs with a record power density of *7W/mm* have been recently demonstrated [4].

Although further confirmation is needed regarding the presence of the transferred-electron effect in GaN-based materials, it is worthwhile to evaluate the frequency and power capability of GaN Gunn devices in order to estimate the advantages of using this material for microwave power generation. The authors previously reported first results along these lines [5]. Increased electrical strength, a higher threshold field, and a possibility of higher frequency of operation due to larger electron velocity and reduced energy-relaxation time are expected to be key features of GaN Gunn diodes. These can be exploited in order to generate signals in the THz regime where renewed interest has recently been shown for various civil and defense applications.

MODELING OF GaN MATERIAL PARAMETERS

Studies of GaN Gunn diodes were conducted by employing a commercial device simulator *Medici*. GaN material parameters used for this purpose were carefully selected and verified by comparing simulated and experimental characteristics of GaN FETs and PIN diodes, as was discussed in a prior publication [6].

Models for field dependence of electron mobility in GaN were based on the *v-F* characteristics calculated by Monte-Carlo simulations [3]. The threshold field for intervalley transfer F_{TH} is much larger in GaN (*150KV/cm*) than in GaAs (*3.5KV/cm*). The increased value of F_{TH} is caused by a larger separation between the high- and low-mobility valleys in GaN $\Delta E \approx 2.1eV$ compared to $\approx 0.3eV$ for GaAs. GaN also manifests a higher peak velocity v_{PEAK} (3×10^7 vs. $1.5\times10^7 cm/sec$) and increased saturation velocity v_{SAT} (2×10^7 vs. $0.6\times10^7 cm/sec$). At the same time, the GaN low-field mobility of $280cm^2/Vs$ and peak negative differential mobility $\mu_{NDR} \equiv \max(-dv/dF)$ of $50cm^2/Vs$ are lower than the GaAs values of $8000cm^2/Vs$ and $2500cm^2/Vs$, respectively.

Frequency-independent *v-F* characteristics can be used to describe electron transport in the presence of time-varying electric field as long as the frequency of operation is much lower than the Negative Differential Resistance (NDR) relaxation frequency $f_{NDR} = 1/(\tau_{ER} + \tau_{ET})$, where τ_{ER} is the energy-relaxation time and τ_{ET} is the intervalley-transfer relaxation time. τ_{ER} was calculated as the electron acceleration time

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$\tau_{ER} = \sqrt{2m_{eff}\Delta E}/qF_{TH}$ [1], and was *0.15ps* and *1.5ps* for GaN and GaAs, respectively. τ_{ET} was evaluated from the results of Monte Carlo studies of ballistic transport in these materials [7]. By extrapolating reconstructed $\tau_{ET}(F)$ curves to the point of threshold field $F=F_{TH}$, τ_{ET} values of *7.7ps* and *1.2ps* were found for GaAs and GaN, respectively.

Based on the results of this analysis, the NDR relaxation frequency of GaAs was found to be *109GHz* in excellent agreement with previously published results [1]. The frequency capability of GaN Gunn devices was found superior to that of GaAs as indicated by the higher GaN NDR relaxation frequency of *740GHz*. This suggests the THz potential of nitride NDR devices through multiplication of signals generated in the fundamental mode or through harmonics that exceed, in both cases, the power level of two terminal devices made from traditional III-V compounds.

DESIGN OF GaN GUNN DIODES

When a high electric field $F > F_{TH}$ is applied to bulk GaN, electrons experience a negative differential mobility μ_{NDR}. Under these conditions, a non-uniformity of electron concentration grows at a rate $1/\tau_{DDR}$ where τ_{DDR} is the differential dielectric relaxation time calculated using expression $\tau_{DDR} = \varepsilon/q\mu_{NDR}N$ where N is the electron concentration and μ_{NDR} is the peak negative differential mobility. It is expected that domain growth last for at least $3\times\tau_{DDR}$ [8]. Thus, Gunn domain instability in an electronic device with doping N and thickness L is possible if $N\times L > 3\times\varepsilon\times v_{PEAK}/q\times\mu_{NDR}$ [8]. The critical values of $N\times L$ product for GaN and GaAs were calculated using their material parameters and the results are summarized in Table 1. The results show that, due to a higher peak velocity and a smaller negative mobility, $N\times L$ for GaN is about *80* times larger than for GaAs.

Table 1. $N\times L$ Product and Critical Doping Level

Material	GaAs	GaN
$N\times L$, $[cm^{-2}]$	1×10^{10}	8.2×10^{12}
N_{CRIT} $[cm^{-3}]$	3.4×10^{15}	4.3×10^{18}

To avoid formation of static domains at the anode, N should not exceed the critical doping concentration $N_{CRIT} = \varepsilon\times F_{TH}^{\ 2}/q$ [8], also shown in Table 1. N_{CRIT} in GaN is also much higher than in GaAs and, thus, GaN devices can be doped significantly higher ($\sim10^{17}cm^{-3}$) than GaAs devices ($\sim10^{15}cm^{-3}$). The latter is a very important result in terms of feasibility of GaN-based Gunn devices since the growth of high-quality low-doped GaN is still challenging.

The possibility of increased doping in GaN Gunn diodes also leads to reduction of the differential dielectric relaxation time and, as a result, enhanced growth rate of Gunn domains. Thus, the differential dielectric relaxation frequency of GaN Gunn diodes with N of $5\times10^{17}cm^{-3}$ exceeds *530GHz*.

Several designs of GaN Gunn diodes were investigated. A W-band design had an *n*-type active layer with doping N of $1\times10^{17}cm^{-3}$ and thickness L of $3\mu m$. The D-band active layer was $2\mu m$ thick and its doping varied between $8\times10^{16}cm^{-3}$ and $5\times10^{17}cm^{-3}$. Cathode and anode layers in all designs were $0.1\mu m$-thick and doped at $1\times10^{19}cm^{-3}$. All diodes had 50-μm diameter.

RESULTS AND DISCUSSION

To allow large-signal power analysis of Gunn diode oscillators, an *LCR* cavity was implemented using special boundary conditions based on Kirchhoff equations. The regions of voltage $V(t)$ and current $I(t)$ waveforms corresponding to sustained oscillations were subjected to harmonic analysis and the resulting power spectrum was used to determine the frequency and power of the Gunn diode oscillators. The build-up of Gunn-effect oscillations in the W-band GaN diode biased with $V_D=2\times V_{CR}$ (*90V*) and terminated with an

LCR cavity ($L=17.5pH$, $C=0.1pF$, $R=50\Omega$) is shown in Figure 1. Initial build-up of oscillations is shown by the current waveform while the emergence of sustained large-signal oscillations is indicated by the dynamic load line.

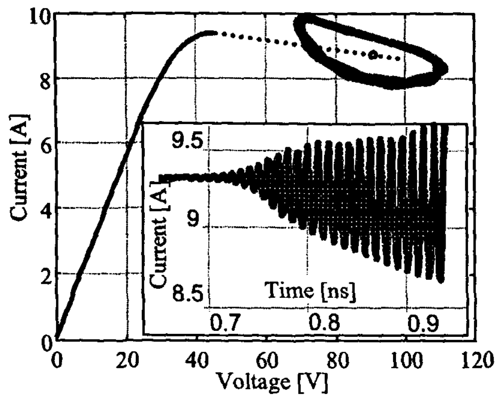

Figure 1. Dynamic load line and current waveform

Profiles of electron concentration as a function of time were also extracted from these simulations and demonstrated formation and propagation of Gunn domains in GaN devices as shown in Figure 2. The oscillation frequency was *87GHz,* corresponding to a period of *11ps,* while the output power was *37.6dBm*, resulting in a power density of $2\times10^5 W/cm^2$.

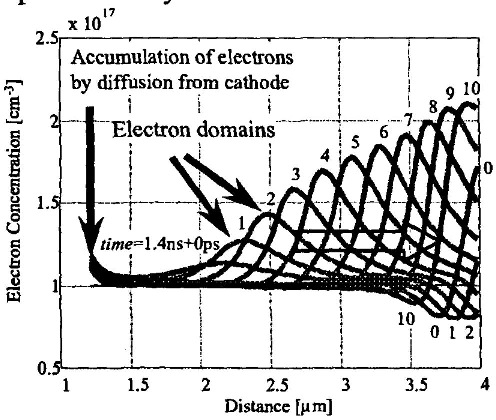

Figure 2. Time-dependent concentration profiles.

The modeling approach adopted in this study was verified by simulating the performance of Ka-band GaAs Gunn diode oscillators. The simulated GaAs Gunn diode also had a *3μm*-thick active layer, but its doping was reduced to 3×10^{15}cm^{-3} in order to satisfy the design condition $N < N_{CRIT}$. The bias was selected using the same criteria as for GaN diodes: $V_D=2\times V_{CR}$ (*2.1V*) and the *LCR* termination was re-optimized for maximum power at the GaAs frequency. The simulations showed that the operation frequency of GaAs Gunn diodes was approximately *40GHz*, while the output power was about *10dBm* in good agreement with the expectations for this design [9]. GaN devices showed significant improvements over GaAs devices in terms of output power density and frequency. These results are also supported by the high value of GaN signal-generator figure-of-merit $Pf^2Z=F_B^2V_{SAT}^2/4$ [1], which is *100* times higher than for GaAs.

A D-band Gunn diode design having a thinner active layer (*2μm*) and, thus, expected to operate at a higher frequency was used to further investigate the potential of GaN-based Gunn diodes for millimeter-wave power generation. The power spectrum of the D-band GaN Gunn oscillator was obtained by harmonic analysis of the current and voltage waveforms corresponding to sustained oscillations and showed a fundamental of *162.6GHz* and a second harmonic frequency of *325.2GHz* as shown in Figure 3.

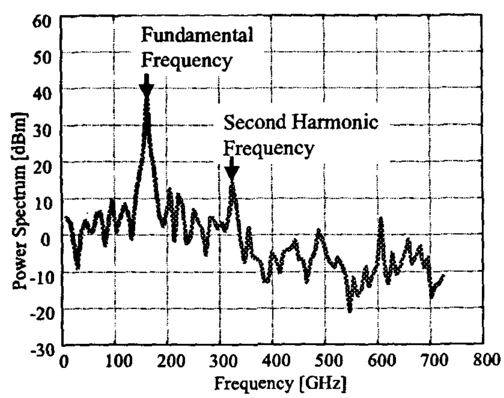

Figure 3. Simulated output power spectrum.

This high frequency capability of GaN is due to high carrier velocity, short relaxation times and large threshold field in this material.

The power and frequency capabilities of GaN NDR diodes were evaluated by simulating the performance of D-band GaN Gunn oscillators while modifying the doping N of the active layer in these devices. The results of this study are shown in Figure 4 and demonstrate the high power ($4\times10^5 W/cm^2$) and frequency ($325GHz$) capabilities of GaN Gunn diodes.

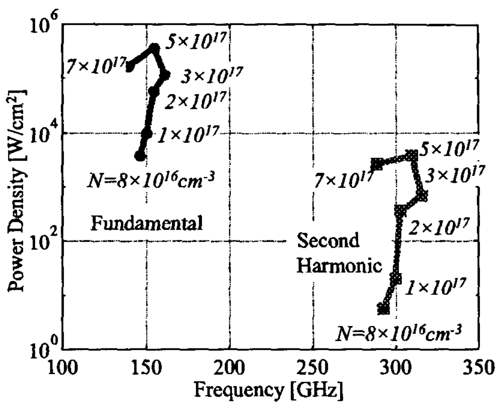

Figure 4. Frequency and power density of Gunn diode oscillators vs. doping of the GaN active layer

Expected trends of increasing the oscillation frequency and output power were observed when the doping of the active layers was increased from $8\times10^{16}cm^{-3}$ to $3\times10^{17}cm^{-3}$. This improvement was due to reduction of differential dielectric relaxation time in higher-doped devices. This decrease of the oscillation frequency and output power for GaN NDR diodes with $N>5\times10^{17}cm^{-3}$ was attributed to an increasing mismatch between the device and the resonant cavity.

CONCLUSIONS

The high frequency capability offered by GaN Gunn diodes is due to higher electron velocity and reduced relaxation times in this material. Increased electrical strength which allows operation with higher doping levels and at a higher bias contributes to the high power capability ($>10^5 W/cm^2$) of the devices. Overall, GaN Gunn devices are expected to have twice the frequency and a hundred-times the power capability of GaAs Gunn diodes. This makes them suitable for THz signal generation by means of multiplication of signal generated in nitride semiconductor diodes or harmonic generation at much higher levels than any other currently available semiconductor device.

ACKNOWLEDGEMENTS

Work supported by ONR (No. N00014-92-J-1552) and DARPA/ONR (No. N00014-99-1-0513). We also would like to thank Dr. Heribert Eisele for many helpful discussions.

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