

GaN-based Gunn Diodes: Their Frequency and Power Performance and Experimental Considerations

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Recent advances in the area of nitride-based wide-bandgap semiconductor technology allowed demonstration of new generation devices with high power capability. Discrete GaN-based HFETs with $10W$ of output power at X-band have been recently demonstrated [1]. At the same time, electron transport in III-V nitrides is expected to have some common features with GaAs- and InP-based materials. Thus, studies of fundamental properties in GaN indicate that this material also exhibits Negative Differential Resistance (NDR) and as a result, electrons exposed to high electric field experience negative differential mobility. However, the threshold field for NDR in GaN appears to be as much as 40 times higher than in GaAs ($F_{TH}=150KV/cm$ vs. $3.5KV/cm$) [2].

Gunn diodes made of conventional III-V compound semiconductors have been successfully applied for generation of high-power millimeter-wave signals using oscillators based on the NDR effect [3, 4]. The frequency capability of such Gunn-diode oscillators is limited by the energy-relaxation time in the semiconductor material since the NDR effect disappears when the period of oscillations is shorter than the intervalley electron transfer time. Monte-Carlo studies of high-field electron transport in GaAs and GaN [5], estimated the energy-relaxation times (τ) in these materials and a much shorter time ($\tau_{GaN} \sim 1.2ps$) was found in GaN than in GaAs ($\tau_{GaAs}=7.7ps$) [6]. Based on the above considerations, it appears therefore that use of GaN with increased electrical strength and reduced electron-transfer time constants offers the possibility to increase the operation frequency, as well as, the power-capability of NDR diode oscillators and extend the range covered by more traditional III-V semiconductor-based generators to THz frequencies.

Large-signal power analysis of Gunn diode oscillators was performed by introducing boundary conditions to represent the LCR oscillator cavity in which the diode was inserted. 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 approach of this study was verified by simulating the performance of Ka-band GaAs Gunn diode oscillators. 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 [7]. GaN Gunn diodes with the same thickness and diameter showed significant improvement over GaAs devices in terms of output power density and frequency in agreement with the signal-generator figure-of-merit Pf^2Z [3], which is 100 times higher for GaN.

A THz diode design having a thinner active layer ($0.3\mu m$) and, thus, expected to operate at a higher frequency was used to further investigate potential of GaN-based Gunn diodes for THz power generation. The power spectrum of the THz GaN Gunn oscillator showed operation frequency of $774GHz$ and conversion efficiency of 0.7% . This high frequency capability of GaN is due to high carrier velocity, short relaxation times and large threshold field in this material.

GaN Gunn diode layers were grown by in-house MOCVD. The active layer doping varied between $1 \times 10^{17} \text{ cm}^{-3}$ and $5 \times 10^{17} \text{ cm}^{-3}$ while the thickness was $2.5 \mu m$ to $3.0 \mu m$. Cl-based

RIE was used for etching while ohmic contacts were made of Ti/Al/Ti/Au. GaN diodes were tested using a pulsed setup and their characteristics were compared with those of GaAs diodes. The GaN-based diodes showed larger voltage and current capability and their operation was limited by heating. Overall, we present the frequency and power characteristics of GaN-based Gunn diodes and discuss their process and first experimental evaluation.

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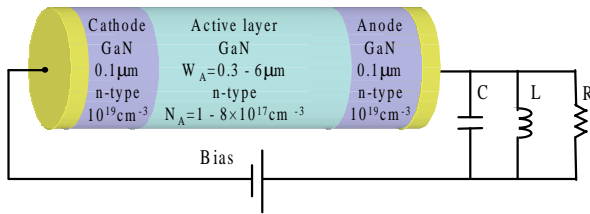


Fig.1. Schematic of GaN NDR diode oscillator showing the cross-sectional design of GaN NDR layers, bias supply, and an equivalent-circuit representation of the resonant cavity

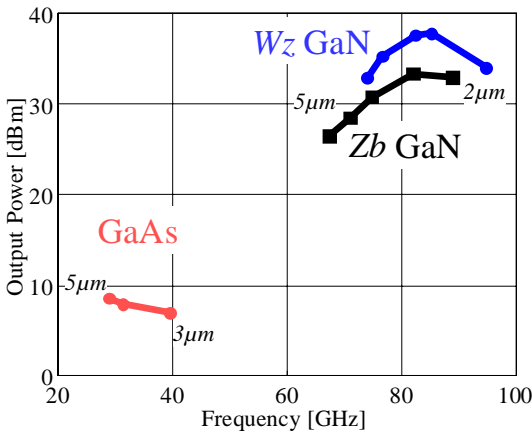


Fig.2. Concentration-frequency diagram illustrating frequency capabilities of NDR diodes made of GaAs and GaN

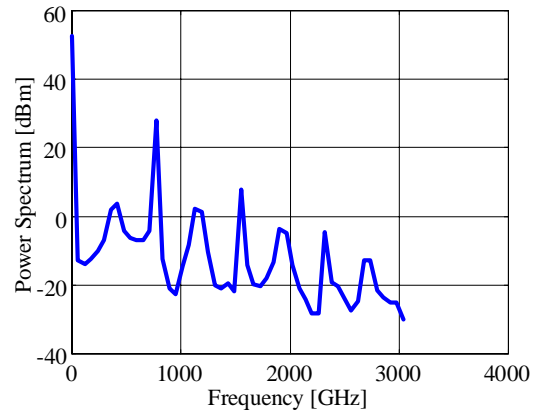


Fig.3. Simulated output power spectrum of 0.3 μm-thick GaN-based NDR diode oscillator designed for operation at THz frequencies.

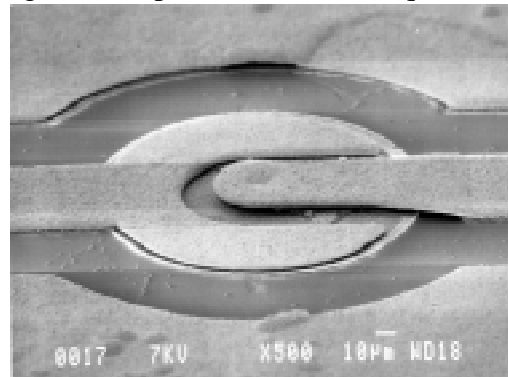


Fig.4. Fabricated GaN NDR Diode with air-bridge interconnects

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