

High-Power Monolithic AlGaIn/GaN HEMT Oscillator

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Abstract—A monolithic X-band oscillator based on an AlGaIn/GaN high electron mobility transistor (HEMT) has been designed, fabricated, and characterized. A common-gate HEMT with 1.5 mm of gate width in conjunction with inductive feedback is used to generate negative resistance. A high Q resonator is implemented with a short-circuit low-loss coplanar waveguide transmission line. The oscillator delivers 1.7 W at 9.556 GHz into 50- Ω load when biased at $V_{ds} = 30$ V and $V_{gs} = -5$ V, with dc-to-RF efficiency of 16%. Phase noise was estimated to be -87 dBc/Hz at 100-kHz offset. Low-frequency noise, pushing and pulling figures, and time-domain characterization have been performed. Experimental results show great promise for AlGaIn/GaN HEMT MMIC technology to be used in future high-power microwave source applications.

Index Terms—AlGaIn/GaN HEMT, microwave FET oscillator, MMIC oscillator.

I. INTRODUCTION

RAPIDLY developing AlGaIn/GaN high electron mobility transistor (HEMT) monolithic microwave integrated circuit (MMIC) technology has already demonstrated great potential for use in microwave power amplifier applications [1], [2]. Owing largely to high electrical breakdown field and high electron sheet charge density, AlGaIn/GaN HEMTs are capable of amplifying and delivering significantly larger power density signals than the currently used MMIC technologies. The wide bandgap and absence of ionized impurities in the undoped heterostructure are expected to have a positive effect on the oscillator noise properties. These fundamental physical factors should make AlGaIn/GaN HEMTs an attractive option for microwave sources.

Due to the relatively low output power of GaAs oscillators, most current systems need to employ a power amplifier at the oscillator's output to generate a high-power signal. Potentially, a single AlGaIn/GaN HEMT oscillator with reasonable pulling figure could replace a low-power oscillator and amplifier, thus reducing the size and cost of the system. A hybrid high-power

AlGaIn/GaN oscillator with low phase-noise performance has already been demonstrated [3].

This paper is organized as follows. In Section II, we will describe the epitaxial growth of an AlGaIn/GaN heterostructure and device and circuit fabrication sequences. In Section III, the oscillator design procedure is explained. Section IV deals with experimental results.

II. EPITAXIAL GROWTH AND DEVICE FABRICATION

Epitaxial layers for the AlGaIn/GaN HEMT structure are grown by organo-metallic vapor phase epitaxy (OMVPE). First, an AlGaIn nucleation layer is grown on the (0001) surface of a semi-insulating SiC substrate followed by an AlN (2000 Å) layer [4]. Then, a 1- μ m-thick GaN buffer layer is deposited. Finally, an approximately 250-Å-thick layer of undoped Al_{0.35}Ga_{0.65}N is grown. Discontinuity of spontaneous and piezoelectric polarization vectors across the hetero-interface induces two-dimensional electron gas (2-DEG) at the interface [5]. C - V and Hall measurements show the existence of a sheet charge with concentration of 1.2×10^{13} cm⁻² and typical room temperature mobility of 1200 cm²/(V*s).

Device fabrication on grown epitaxial layers starts with the deposition of Ti-Pt alignment marks for electron beam (e-beam) and photolithographies. Mesa isolation is then photolithographically patterned and etched with chlorine-based electron cyclotron resonance (ECR) plasma.

Ti(20 nm)-Al(100 nm)-Ti(45 nm)/Au(55 nm) ohmic contacts are patterned with e-beam lithography, deposited with e-gun evaporation, and annealed at 800°C for 60 s. Ohmic contact resistance and sheet resistance, measured using the transmission line matrix (TLM) method, were equal to 0.5 Ω -mm and 500 $\Omega/\square$, respectively. Ni(25 nm)-Au(375 nm) mushroom gates were written with an e-beam, developed using the triple-resist stack of PMMA/copolymer/PMMA and deposited with e-gun evaporation. The first interconnect level is defined by photolithography and uses deposition of 3500 Å of Au to form the contact pads. Preliminary device characterization is then performed. Following that, an 1800-Å-thick plasma enhanced chemical vapor deposition (PECVD) Si₃N₄ film is deposited in order to passivate the surface as well as to form the insulator layer for MIM capacitors. The second interconnect level processing, which consists of via hole etching, airbridge post definitions and deposition, seed layer evaporation, and electrochemical plating of 3- μ m-thick Au, concludes the device fabrication sequence. Typical dc device parameters are as follows: open-channel current density = 1000 mA/mm,

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peak transconductance = 200 mS/mm, and pinchoff voltage = -6 V. A more detailed description of the epitaxial growth and device fabrication can be found in [4] and [6].

III. DESIGN PROCEDURE

The common-gate oscillator with inductive feedback architecture was used as a basis for the design because it maximizes device instability in comparison with the common-source architecture. It is also considered the more suitable design option for high-power oscillators.

Following typical procedure for the design of a two-port negative-resistance oscillator, the measured common-source small-signal S-parameters of a 10-channel HEMT with 1.5-mm total gate periphery and $0.25\text{-}\mu\text{m}$ gate length and measured $f_t = 27$ GHz and $f_{\max} = 36$ GHz were converted to common-gate S-parameters. In order to minimize sensitivity of the oscillation frequency on power-supply variation, i.e., improve pushing figure, S-parameters for gate voltage of -4.5 V were used. Gate-source capacitance for this bias is nearly constant for small voltage changes, and is equal to 1 pF/mm.

An output matching network, placed across the HEMT's drain-gate junction, was designed to maximize the input reflection coefficient at 10 GHz. The resonator circuit, placed across the HEMT's source-gate junction, is designed so that inductive reactance of the resonator compensates capacitive reactance of an unstabilized common-gate HEMT, while resonator resistance stays less than third of the HEMT's negative resistance in order to ensure oscillation startup. In other words, resonator impedance was designed to be equal to

$$Z_{\text{resonator}} = \frac{R_{\text{in}}}{3} - jX_{\text{in}}$$

where R_{in} and X_{in} are real and imaginary parts of the common-gate HEMT's input impedance, respectively.

Inductive feedback, output, and resonator networks are implemented with coplanar waveguide transmission lines of various characteristic impedances based on known small-signal models. Inductive feedback uses a high impedance ($Z = 80\ \Omega$, width = $20\ \mu\text{m}$, gap = $50\ \mu\text{m}$) line. An open-circuit stub in the output matching network is implemented with a $50\text{-}\Omega$ line (width = $60\ \mu\text{m}$, gap = $30\ \mu\text{m}$). The dc current path, which contains the resonator and a line connecting HEMT's drain electrode with the RF output and drain bias pad, is laid out with an airbridge transmission lines ($Z = 68\ \Omega$, width = $40\ \mu\text{m}$, gap = $30\ \mu\text{m}$). In comparison with a regular coplanar waveguide, this transmission line type has a lower effective dielectric constant because a significant portion of the electromagnetic wave propagates in the air as opposed to semiconductor. The lower effective dielectric constant allows creating a higher impedance transmission line without reducing line width, and, thus, helps to prevent possible dc current handling problems.

The gate bias network uses MIM capacitors and a bulk resistor. Due to the asymmetric connection of the resonator to the HEMT's source electrode, the measured value of source inductance (10 pH) is added in series with the source electrode during the simulation. The oscillator schematic is shown in Fig. 1.

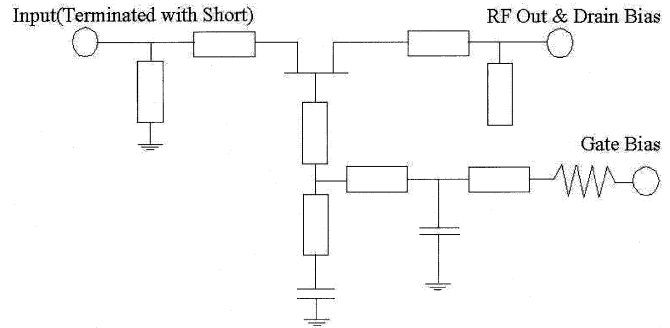


Fig. 1. Oscillator schematic.

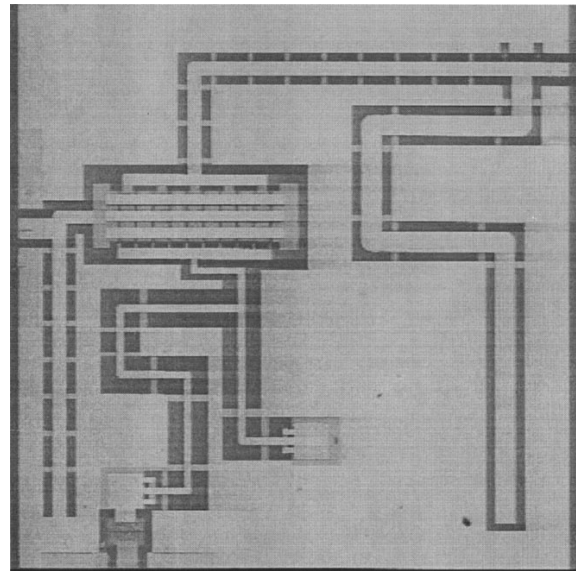


Fig. 2. SEM image of the fabricated AlGaN/GaN HEMT oscillator.

IV. EXPERIMENTAL RESULTS

A scanning electron microscope (SEM) image of the fabricated monolithic oscillator is shown in Fig. 2. The oscillator occupies 1.6 mm^2 . Circuits were characterized on wafer with air-coplanar probes.

A. Power Performance

The output power spectrum of the oscillator was measured with an Agilent 8562A Spectrum Analyzer at different drain bias voltages. The oscillator delivers 1.7 W at 9.556 GHz into a $50\text{-}\Omega$ load when biased at $V_{\text{ds}} = 30$ V and $V_{\text{gs}} = -5$ V, with dc-to-RF efficiency of 16%. The oscillator's power spectrum measured under these conditions is shown in Fig. 3. Output power and dc-to-RF efficiency as functions of drain voltage are shown in Fig. 4. The efficiency maximum (18%) occurs at $V_{\text{ds}} = 25$ V. Output power and efficiency can be considerably improved if the circuit is packaged, because in the proper thermal environment the oscillator can be operated at larger drain bias voltages. The second harmonic was measured to be 20 dB below the fundamental signal for all measured drain bias voltages. Loaded Q , calculated as a ratio of oscillation frequency to 3-dB bandwidth, is equal to 75 000.

Fig. 5 shows a power comparison of the AlGaN/GaN HEMT oscillator with various reported oscillator results, collected by

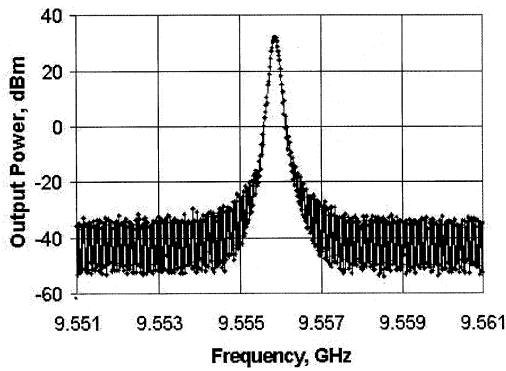


Fig. 3. Measured power spectrum of the AlGaIn/GaN HEMT oscillator, biased at $V_{ds} = 30$ V, $V_{gs} = -5$ V. Frequency span of the spectrum analyzer is 10 MHz; resolution bandwidth is 100 kHz.

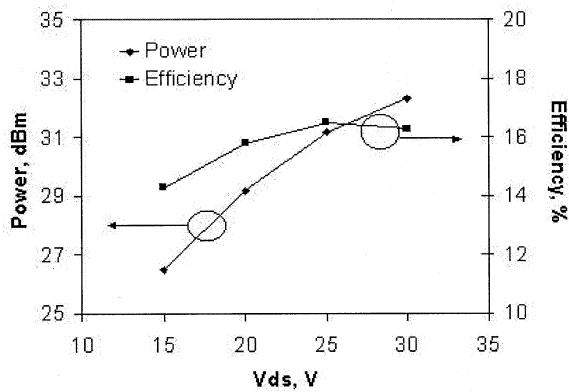


Fig. 4. Output power and dc-to-RF efficiency as functions of drain voltage ($V_{gs} = -5$ V).

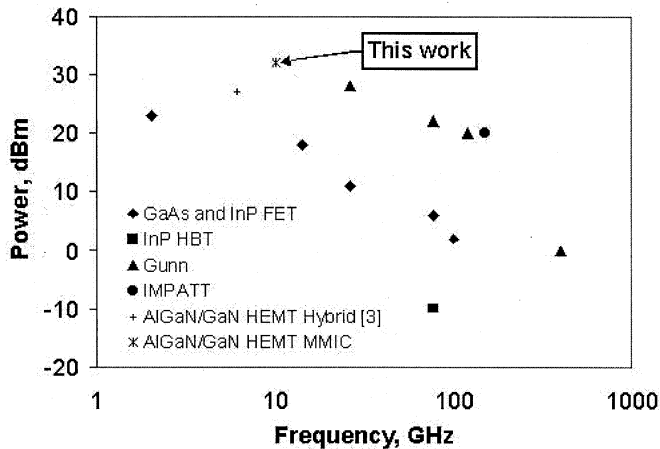


Fig. 5. Comparison of AlGaIn/GaN HEMT oscillator power with reported semiconductor oscillator results [3], [7].

Riddle [7]. The presented circuit clearly has an advantage in output power as compared with other transistor-based oscillators.

B. Oscillator Noise

The power spectrum measured with a spectrum analyzer was used to estimate oscillator noise, which exhibits itself as a frequency broadening near the carrier. Since amplitude noise has

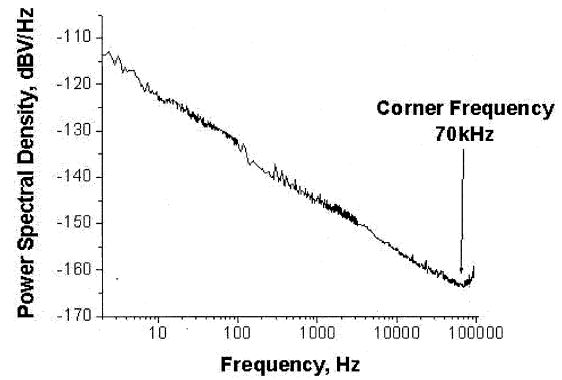


Fig. 6. Low-frequency noise power spectral density.

little gain while phase noise has nearly infinite gain for an active device with positive feedback [7], the oscillator noise in the vicinity of the oscillation frequency is dominated by phase noise, which is equivalent to jitter in the time domain. Phase noise was estimated to be -87 dBc/Hz and -115 dBc/Hz at 100-kHz and 1-MHz offsets, respectively. No significant dependence of the phase noise on drain bias voltage was observed.

Typically, oscillator noise exhibits approximately $1/f$ dependence, which is attributed to upconversion of low-frequency drain current variations due to internal noise sources related to electron trapping on semiconductor surface. Fig. 6 shows the results of a low-frequency noise power spectral density measurement performed on a discrete HEMT with the same gate periphery as the one in the oscillator. The apparent rise in power spectral density indicates that the corner frequency is equal to 70 kHz, which is somewhat lower than what is reported for GaAs field-effect transistors [7]. The Hooke parameter of 3×10^{-3} was extracted from the measured data. The measured value of the Hooke parameter was in the range of the values measured for the GaAs-based devices (3 – 6×10^{-3}) [9]. Lower values of the Hooke parameter for GaN heterostructures reported in the literature [10] indicate that further improvement of the material quality may result in reduction of flicker noise and corner frequency and have a positive impact on the phase-noise performance of AlGaIn/GaN HEMT-based oscillators.

C. Bias and Load Sensitivity

Dependence of the oscillation frequency on gate bias voltage was characterized for a range of voltages around $V_{gs} = -4.5$ V, which was the bias condition used in the initial design. Frequency shift as a function of the gate bias voltage for $V_{ds} = 30$ V is shown in Fig. 7. The observed change in oscillation frequency is attributed to a change in gate–source capacitance, which modifies the HEMT’s input reactance. Since resonator impedance is constant, the frequency at which resonance occurs is shifting. The pushing figure, which describes oscillation frequency sensitivity on power-supply variation, is equal to -18 MHz/V.

One reason for using a buffer amplifier along with an oscillator, besides obvious amplification, is to provide a constant load impedance to the oscillator, and thus ensure that the oscillation frequency is not being affected by the rest of the system. A high-power oscillator can be considered a viable alternative to a low-power oscillator/buffer amplifier combo only if it is capable of

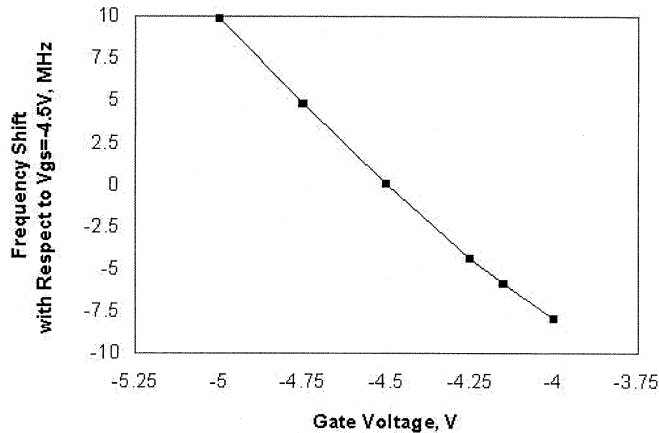


Fig. 7. Pushing figure measurement for $V_{ds} = 30$ V.

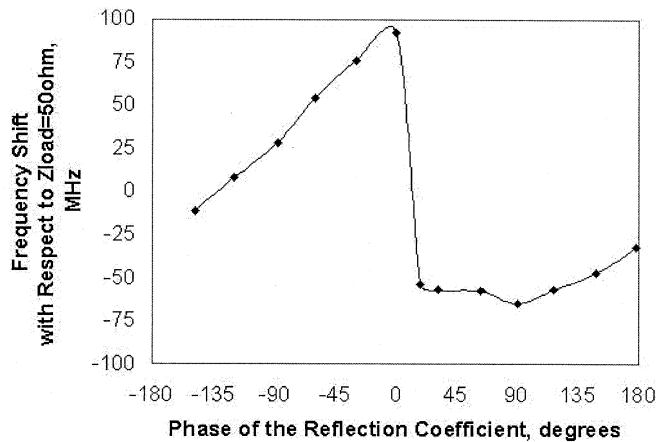


Fig. 8. Pulling figure measurement for $V_{ds} = 30$ V. Return loss = -12 dB, corresponding to $|T| = 0.25$.

having very low sensitivity to changes in the load impedance. This sensitivity is typically characterized by a pulling figure measurement, where the shift in the oscillation frequency is measured as a function of the output reflection coefficient phase for a constant return loss of -12 dB, corresponding to reflection coefficient magnitude of 0.25. This measurement has been performed with a load-pull system, and the results are shown in Fig. 8. The pulling figure, i.e., maximum frequency shift with respect to the “no reflection” condition, is equal to 90 MHz. If system requirements allow, the pulling figure can be considerably improved at the expense of output power by inserting an on-chip passive attenuator.

D. Time-Domain Characterization

The time-domain output wave has been measured with an HP 70820A Microwave Transition Analyzer. Microwave voltage and current waveforms at the device’s output have been de-embedded using a method proposed by Wei *et al.* [11]. The extracted waveforms for the bias condition of $V_{ds} = 25$ V and $V_{gs} = -5$ V are depicted in Fig. 9. As expected from measured power spectrum, both output voltage and current signals have nearly ideal sinusoidal shape with peak-to-peak voltage swing of 20 V.

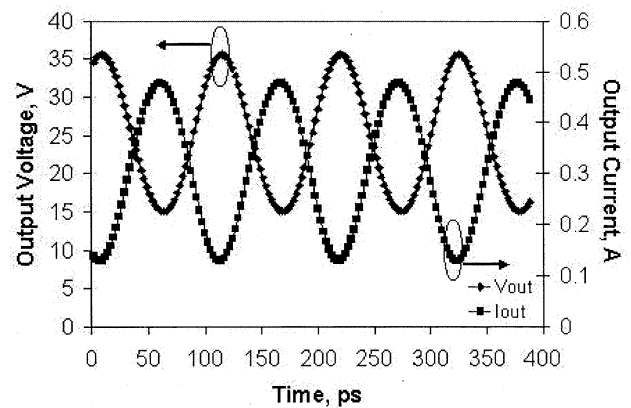


Fig. 9. Microwave voltage and current waveforms extracted at the oscillator’s output at $V_{ds} = 25$ V, $V_{gs} = -5$ V.

V. CONCLUSION

A monolithic AlGaIn/GaN HEMT oscillator has been demonstrated. The oscillator generates a 9.556-GHz signal with 1.7 W of power and delivers it to a 50- Ω load with 16% of dc-to-RF efficiency. Phase noise is estimated to be -87 dBc/Hz at 100-kHz offset. The oscillator exhibits a pushing figure of -18 MHz/V, a pulling figure of 90 MHz for -12 -dB return loss, and more than 20-V peak-to-peak output voltage.

While the phase-noise performance of the AlGaIn/GaN oscillator is on par with a comparable GaAs circuit [8], much higher attainable output power makes an AlGaIn/GaN HEMT a good candidate for future use in microwave source applications.

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