High Power GaN Oscillators using Field-Plated HEMT Structure

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***Abstract* — 5 GHz MMIC GaN oscillators based on AlGaN/GaN HEMTs are presented. By using field-plated HEMT structures, both the output power and dc-to-RF efficiency were improved from the oscillator with non-field-plated GaN HEMT. An oscillator using AlGaN/GaN HEMT with 0.5 mm of gate width and 1.1 µm field-plate extension, delivers 1.9 W output power with dc-to-RF efficiency of 21.5%, when biased at V_{ds} = 40 V and V_{gs} = -4.5 V. Phase noise was measured to be -132 dBc/Hz at 1 MHz offset frequency range. The oscillator output power density was found to be 3.8 W/mm and is the highest yet reported. The study of the output power, dc-to-RF efficiency and phase noise with different field-plate extension is also presented.**

***Index Terms* — GaN, high electron-mobility transistor (HEMT), Field plate, monolithic-microwave integrated-circuit (MMIC), oscillator, phase noise.**

I. INTRODUCTION

AlGaN/GaN HEMTs have attracted considerable interest as power devices in microwave applications, promising greater than a tenfold increase in power-density as compared with GaAs devices. Limited by the low power capacity of GaAs oscillator, most of current microwave systems require a power amplifier following oscillators to deliver a high-power signal. Study on low-frequency noise shows that GaN HEMTs will offer comparable noise levels to conventional GaAs devices [1]. It indicates the possibility of the use of GaN HEMTs to simultaneously achieve both high power and low phase noise performance in a single oscillator circuit [2-4]. How ever, GaN HEMT device performance is limited by RF dispersion phenomena. Recently, the power capacity of AlGaN/GaN HEMT was dramatically improved by applying field-plated structures. It not only increases device breakdown voltage, but also reduces the high-field trapping effect. Using field-plate, AlGaN/GaN HEMTs with a CW power density of 32.2 W/mm at 4 GHz was reported [5]. This paper presents a study of the effect of field-plate dimensions on the output power, dc-to-RF efficiency and phase noise. By field-plate optimization, dramatic improvement was achieved over previous state-of-the-art.

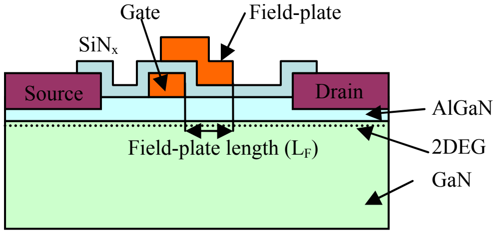

Fig. 1. Cross-section of the GaN HEMT with a field-plate.

II. DEVICE AND CIRCUIT DESIGN

The structure of the devices in this paper is shown in Fig. 1 with a gate structure first used by Chini *et al.* [6]. After gate contact was formed, a 200-nm SiN$_x$ passivation layer was deposited. The field-plate was then evaporated as a second gate on top of the passivation layer. Field-plate length (L_F) is defined as the distance of gate-drain edges between two gate metal layers. The field-plate was connected to the gate through the common path of the gate feeder and pad in the extrinsic device region. To further reduce the resistance and improve uniformity of ac current density on gate fingers, the field-plate was also connect to the gate at the ends of gate fingers [7]. The field-plate will change the distribution of electric field at the edge of the gate on the drain side and reduce its peak value, which will help to increase the breakdown voltage. Also it will help to reduce the high frequency dispersion effect in high power applications. To study and optimize the effect of field-plate, the field-plate length of GaN HEMTs using in oscillator circuits of this paper was varied from 0 to 1.1 µm, while keeping the circuit structure and other components fixed.

The oscillator circuit used a single end Colpitts topology with a common-gate structure (Fig. 2). The resonator was formed by lumped LC components. This simple structure can help us to control parasitics from both active and passive components, reduce the variation from fabrication process and therefore accurately analyze the impact of field-plate on the performance of circuits.

The design procedure was similar to [3]. The small-signal properties of devices were characterized in the frequency range from 50 MHz to 25 GHz. The small-signal model parameters were extracted by using ADS-based parameter extraction routines. The model incorporated dominant parasitics and losses. The circuit was optimized to achieve maximum available output power, while keeping reasonable phase noise and linearity performance. An ADS EEHMT1 scalable non-linear large-signal model was used to simulate transient and harmonic performance. The output power and frequency were also verified.

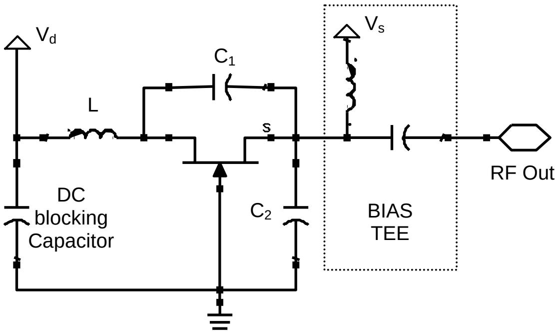

Fig. 2. Circuit schematic of the oscillator.

Instead of using spiral inductors, a metal stripline was used to make a high quality factor inductor. Compared to spiral inductors, striplines can avoid ac current coupling between sections. Therefore it exhibits better Q factor and higher self-resonate frequency. The EM simulated Q factor of 1.1 nH inductor used in the circuit is 39 at 5 GHz. Also special attention was paid to make compact circuit layout and avoid the paracitics between components.

III. DEVICE AND CIRCUIT FABRICATION

The AlGaN/GaN HEMT devices were grown by metal organic chemical vapor deposition (MOCVD) on SiC substrates. The epitaxial structure consisted of a semi-insulating Fe-doped GaN base layer, followed by a 290 Å thick $Al_{0.27}Ga_{0.73}N$ barrier layer. The room temperature sheet electron concentration and Hall mobility were ~$9.96\text{x}10^{12}$ cm^{-2} and ~1450 cm^2/Vs, respectively. They were fabricated using our standard process described elsewhere [8]. The GaN HEMT device has a gate length of L_g = 0.7 µm and width of W_g = 4x125 µm. The channel pinched off at a gate-source bias of -5.3 V and the saturated drain current density is 1 A/mm with a zero gate bias. With a bias of drain voltage 20 V and drain current density 200 mA/mm, the measured unit current gain cutoff frequencies (f_t) decreases from 21 to 15 GHz for devices with field-plate length from 0 to1.1 µm. A detailed discussion on small-signal performance of field-plated HEMT devices can be found in [5].

The GaN HEMT MMIC fabrication started with source and drain ohmic. After that, HEMT devices were completed with mesa isolation and gate metallization. The GaN HEMT is passivated by PECVD SiN_x layer, which is also used as dielectric material in MIM capacitors. Field-plate of HEMTs were then deposited on top of the SiN_x. SiN_x capacitors, stripline inductors and bridges used for multi-finger HEMT structure were fabricated in the last steps. The chip size is 0.72 mm x 0.7 mm. As shown in Fig. 3, The LC resonator tank is at the drain terminal of the HEMT device. The feed-back path between the source and drain is made by SiN_x MIM capacitors.

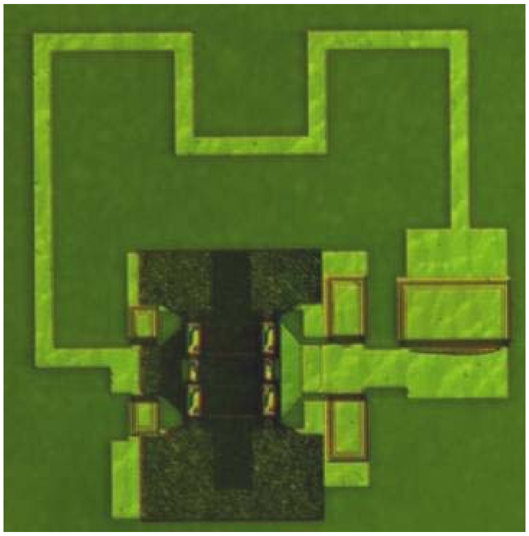

Fig. 3. Chip photomicrograph of the developed oscillator.

IV. EXPERIMENTAL RESULTS

Circuits were characterized on-wafer with air-coplanar probes by an Agilent Spectrum Analyzer E4440 with phase noise option. Bias feeds for gate and drain were provided through off-wafer bias tees for convenience in testing.

A. Power, efficiency and linearity measurements

From comparison, all oscillators were characterized at bias of 40 V drain-to-source voltage and -4.5 V gate-to-source voltage. Output power and dc-to-RF efficiencies of oscillators with HEMT devices using different field-plate lengths were shown in Fig. 4. The output power increases from 28.4 to 32.8 dBm from L_F = 0 to L_F = 1.1 µm. dc-to-RF efficiency exhibited a similar trend. It increases from 11 to 21.5%. As discussed in [5], [6], the field-plated structure helps to reduce the knee-voltage and RF drain current dispersion effect of devices. With 40 V drain voltage, the enhancement by the field-plate becomes more significant, as the L_F steps up to 1.1 µm. But as the output power approaches maximum saturated power level, the signal is compressed more. The 2nd harmonic distortion drops from 26.6 to 22.4 dBc as the field-plate length increases to 1.1 µm.

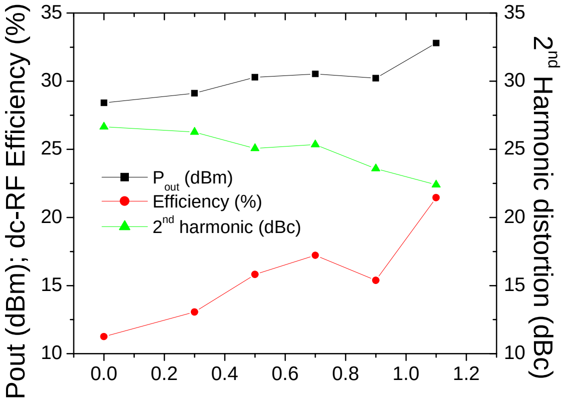

Fig. 4. Output power, dc-to-RF efficiency and second harmonic vs. L_F.

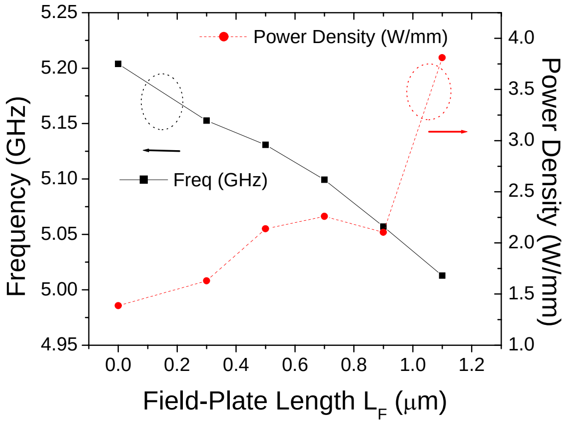

Fig. 5. Carrier frequency and power density vs. L_F.

From small-signal analysis, the gate-drain capacitance of field-plated devices increases, as the field-plate length increases, because of stronger gate to drain coupling. In oscillator circuits it will lower the carrier frequency, since the effective capacitance in the LC tank increases. Fig. 5 shows carrier frequency shifts about 4% with 1.1 µm change of field-plate length. This effect can be reduced by using LC tank with a larger capacitance. Fig. 5 also demonstrates that the oscillator power density improved dramatically by using field-plate structure. With 1.1 µm field-plate length, the output power density reached 3.8 W/mm. Output power and dc-to-RF efficiency of this oscillator are shown as functions of drain voltage in Fig. 6. The oscillator delivers a maximum of 30 dBm at 5 GHz into a 50-Ω load with peak dc-to-RF efficiency of 24%.

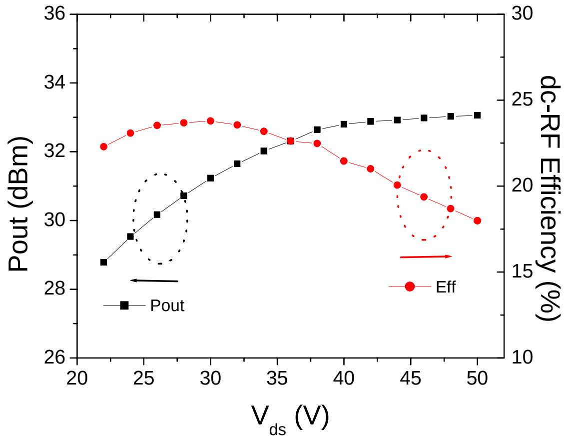

Fig. 6. Output power and dc-to-RF efficiency of oscillator with a 1.1-µm-long field-plate.

B. Phase noise measurement

The phase noise of the oscillator was measured across the offset frequency range from 10 kHz to 10 MHz. Fig. 7 summarizes the measurement results at V_{ds} = 40 V and V_{gs} = -4.5 V. According to the Leeson formula:

$$L(f_m) = 10log\left\{\frac{1}{2}\left[1+\frac{1}{f_m^{\ 2}}\left(\frac{f_0}{2Q_l}\right)^2\right]\bullet\frac{FkT}{P_s}\left(1+\frac{f_c}{f_m}\right)\right\}$$

where Q_l is the loaded quality factor, f_0 is the resonation frequency, f_c is the flicker corner frequency of the device , f_m is the offset frequency, P_s is the amplifier's input signal power, F is its noise figure, k is the Boltzman constant, and T is the temperature. It can be seen that phase noise is inversely proportional to output power, the loaded qualify factor and noise figure. Since we kept passive components same for all oscillators, Q_l has a fixed impact on the phase noise with different field-plate lengths. It is known that with an identical peripheral dimension, the noise figure of field-plated devices is generally better than devices without field-plate (L_F = 0). But among all field-plated devices, noise figure becomes worst with a 0.7-µm-long field-plate [7], [9]. Phase noises in Fig 7 showed a similar shape that phase noise is bumped for L_F = 0.7 µm. Phase noise drops fast for devices with larger L_F because of higher output power. The enhancement in the output power helps to reduce the phase noise of oscillators. The 1/f baseband noise also plays important role in phase noise. Further low frequency noise measurement on field-plated devices is required to understand the impact of field-plate on 1/f noise.

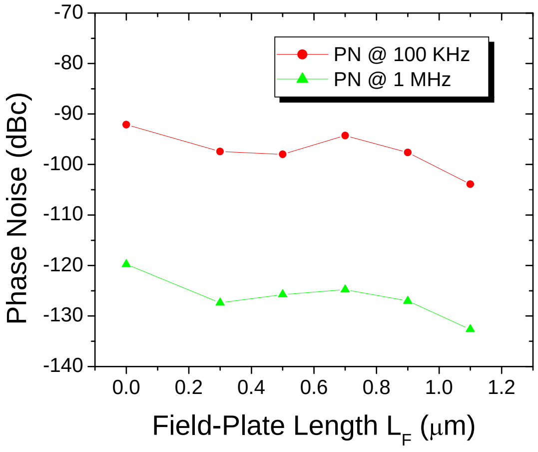

Fig. 7. Phase noise at 100 kHz and 1 MHz offsets vs. L_F.

A measured phase noise performance for the device with 1.1 μm field-plate length is given in Fig. 8. The phase noise are -103 and -132 dBc/Hz at offset frequencies of 100 kHz and 1 MHz respectively from 5 GHz carrier.

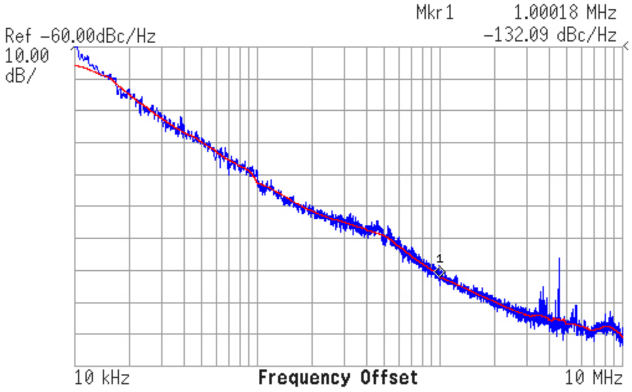

Fig. 8. Measured phase noise of oscillator with a 1.1-μm-long field-plate.

V. CONCLUSION

The power and noise performance of oscillators based on field-plated GaN HEMTs were investigated. It has been shown that at 5 GHz the field-plate offered enhancement on both power and noise properities. With a 1.1-μm-long field-plate, the oscillator delivered 32.8 dBm output power with 21% dc-to RF efficiency, corresponding to an output power density of 3.8 W/mm. Such high power density gives a possibility to make ultra compact high power oscillators. Meanwhile, the high dc-to-RF efficiency will ease the requirement of thermal management. The field-plate devices also exhibited the better phase noise than devices without field-plate. With a 1.1-μm-long field-plate, the measured phase noise is -132 dBc/Hz at 1 MHz offset from 5 GHz carrier. It has been demonstrated that with these further improvements of power and noise performance, as next-generation microwave power devices, GaN HEMTs will be an ideal candidate in microwave source application.

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