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Advances In High Power Density GaN Transistors

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Abstract—**Progress in GaN HEMTs achieving high power densities is reviewed. The development of material technologies produced high quality GaN epi-layers on SiC substrates with superior thermal conductivity. Straight-gate GaN HEMT structures with high-current designs generated greater than 9 W/mm CW power at microwave frequencies. Electric field engineering with a field-plate boosted the power density to 30 W/mm. Double field plates with the right terminations extended the power density to >40 W/mm at 4 GHz.**

1. INTRODUCTION

GaN as a wide band gap semiconductor promises higher current densities and higher operation voltages over traditional III-V and Si devices. The progress in GaN high-electron-mobility-transistors (HEMTs) has gone through a few stages including selection of substrates, improvement in material growth, epi-layer designs and advanced device designs. As a result, power performance has steadily improved. Power densities have reached 10-30x of what achievable in GaAs-based field effect transistors (FETs).

2. STRAIGHT-GATE GAN HEMTS

Because of the lack of lattice-matched substrates, it has been difficult to grow high-quality GaN. In the early development stage, research work was focused on material improvement. The first GaN based HEMT with microwave power capability was reported in 1996, which was grown on a sapphire substrate and produced a power density of 1.1 W/mm at 2 GHz [I]. These devices used an AlGaN donor/barrier on top of an insulating GaN buffer. A two-dimensional electron gas (2-DEG) was induced at the AlGaN-GaN interface due to piezo and spontaneous polarization charges. Ohmic contacts were Ti-Al based and the gate was a simple Schottky metal stripe. The poor thermal conductivity of the sapphire (0.3 W/^{o}C-cm) was considered as a limiting factor for power performance.

At the end of 1998, the first GaN HEMT on a SiC was successfully fabricated to take advantage of the high thermal conductivity of SiC (4 W/^{o}C-cm) [II]. These devices used a 14%-Al AlGaN layer, resulting in a current density of 680 mA/mm. When biased at 30 V, a power density up to 6.9 W/mm was measured at 10 GHz along with 35.4% power-added-efficiency (PAE).

Further improvement using a higher Al-content AlGaN barrier-donor layer boosted the current density to greater than 1 A/mm, leading to an enhanced power density of 9.1 W/mm at 8.2 GHz with 47% PAE [III]. This is an increase by an order of magnitude in power density compared with the 0.5-1W/mm values generally obtained with GaAs and Si based FETs.

To overcome the notorious trapping effect manifested as dispersions of current or knee voltage between DC and RF operations, surface control by SiN passivation or a thick epi layer [IV] was typically employed. To clarify the misconception that the lower efficiency at higher bias voltages often observed with immature GaN HEMTs (even on SiC) was thermally related as a result of the 10x higher power density over FETs of conventional semiconductors, an experiment backed by theoretical derivation showed that a well-engineered AlGaN/GaN HEMT actually had constant efficiency at increasing drain biases under a constant load line within the I-V plane of the device [V].

This type of device also exhibited good linearity performance [VI]. When biased at 35V, 40 mA/mm quiescent current and tuned for linearity under a two-tone input, a linearity and PAE combination of -30 dBc and 40% was obtained at 4 GHz, with only –5.5 dB back off from the 3 dB compression point, along with 2 W/mm output power density.

3. GAN HEMTS WITH GATE CONNECTED FIELD PLATE

A field plate on top of a dielectric layer extending from the gate to the drain side was used by Zhang et al in an AlGaN/GaN HEMT intended for high-voltage switching applications [VII]. Ando et al adapted such a structure into a microwave AlGaN/GaN HEMT, obtaining excellent performance [VIII]. An in-depth study was then carried out to investigate the effect of the field plate and to optimize its dimensions for microwave power amplifications at various voltages and frequencies [IX].

After a HEMT with conventional gate was fabricated, a layer of SiN_x was then deposited on the wafer surface. The formation of the field plate was by placing a metal layer over the gate and extending to the access region on the drain side. The field plate was electrically connected to the gate on the gate pad outside of the active channel region. There are a few important dimensions in this structure. Gate length ($\mathbf{L_G}$) determines the transit time under the gate. The SiN_x thickness ($\mathbf{t}$) controls the onset voltage for additional channel depletion under the field plate while the field-plate length ($\mathbf{L_F}$) dictates the size of the field-reshaping region. With an $\mathbf{L_G}$ of 0.5-0.6 μm and an AlGaN thickness of about 250 Å, $\mathbf{t}$ was chosen as 2000 Å and $\mathbf{L_F}$ was varied from 0 to 1.1 μm. The separation between the field plate and the drain ($\mathbf{L_{FD}}$) was set to >2 μm to avoid premature breakdown.

The load-pull measurement results at 4 GHz for devices with different field plate dimensions at increasing bias voltages were analyzed, revealing that the field plate not only modified the electric field distribution and increased breakdown voltages, but also reduced the trapping effect as a result of the decreased peak electric field. Within a certain limit, a GaN HEMT with a longer field plate could operate at a higher voltage and produce a higher output power. A power sweep was taken at 4 GHz for a device with $\mathbf{L_F}$=1.1 μm. The device was biased at 120 V in a deep class-AB mode to minimize self-heating. The linear gain was 16.8 dB at low input levels. At 2.9 dB compression, the output power reached 39.0 dBm, or 32.2 W/mm, with associated gain and PAE of 14 dB and 54.8 %, respectively. This was a 3x enhancement over straight gate GaN HEMTs and is 30x higher than the power density from traditional GaAs and Si FETs.

Linearity performance of such field-plated devices was also improved from straight-gate GaN HEMTs [X]. A power sweep was performed for a field-plated GaN HEMT with $\mathbf{L_F}$=0.7 μm when biased at 48V and driven by a two-tone input at around 4 GHz. At an IM_3 of -30dBc, the PAE and output power density were 57% and 3.7 W/mm, much better than the 40% and 2 W/mm values obtained from previous straight-gate devices [VI].

4. GAN HEMTS WITH DOUBLE FIELD PLATES

As an effort to further extend performance of the GaN HEMTs, multiple field plate structures were pursued [XI], [XII]. The double field plate configuration allows better optimization of the electric field profile at the gate-drain region. Also, connecting the 2nd field plate to the source of the device could reduce the gate-drain capacitance, enhancing power gain. As an ultimate demonstration of the potential of such a device, a double field-plated GaN HEMT with $\mathbf{L_{F1}}$=0.5 μm and $\mathbf{L_{F2}}$=1.2 μm was able to operate up to 135 V, generating an CW output power of 41.4 W/mm at 4 GHz, with associated gain and PAE of 16 dB and 60% respectively. This is a significant improvement over the single field plate devices and represents the highest power density of any microwave transistor to date. Although such an ultra-high power density places extreme requirements for thermal management, it shows the tremendous promise of the wide-gap FET.

5. SUMMARY

Over the last decade, there has been remarkable progress in advancing the power density of GaN based HEMTs. Maturity in material growth and selection of the high thermal conductivity SiC substrate allowed the straight gate (non-field-plated) devices to produce greater than 9 W/mm at microwave frequencies. Adoption and optimization of single field-plated GaN HEMTs boosted the power density to greater than 30 W/mm. A well-engineered double-field-plate design further extended the power density to greater than 40 W/mm. Such ultra-high power densities attested to the tremendous potential of the wide-gap GaN HEMTs for microwave power generation.

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[I] Y.-F. Wu, B.P. Keller, S. Keller, D. Kapolnek, P. Kozodoy, S.P. Denbaars, and U.K. Mishra, "Measured power performance of AlGaN/GaN MODFETs", *IEEE Electron Device Lett.*, vol. 17, pp. 455-457, Sept. 1996

[II] S.T. Sheppard, K. Doverspike, W.L. Pribble, S.T. Allen and J.W. Palmour, "High Power Microwave GaN/AlGaN HEMTs on Silicon Carbide", *IEEE Electron Device Lett.*, Vol. 20, No. 4, pp. 161-163, April 1999

[III] Wu et al., "High Al-content AlGaN/GaN HEMTs on SiC substrates with very highpower performance", *IEDM Technical Digest*, pp. 925-927, Dec.1999

[IV] Shen et al, "High-power polarization-engineered GaN/AlGaN/GaN HEMTs without surface passivation", *IEEE Electron Device Lett*, pp.7-9, Vol. 25, Jan, 2004

[V] Wu et al, "Bias-dependent performance of high-power AlGaN/GaN HEMTs", *IEDM Technical Digest*, pp. 17.2.1-17.2.3, Dec. 2001.

[VI] Wu et al, "Linearity and gain characteristics of AlGaN/GaN HEMTs", *IEDM Technical Digest*, pp. 697- 699, Dec. 2002.

[VII] N.-Q. Zhang, S. Keller, G. Parish, S. Heikman, S.P. DenBaars and U.K. Mishra, "High breakdown GaN HEMTs with overlapping gate structure," *IEEE Electron Device Lett.* Vol. 21, pp. 421-423, Sept. 2000

[VIII] Y. Ando, Y. Okamoto, H. Miyamoto, T. Nakayama, T. Inoue, and M. Kuzuhara, "10-W/mm AlGaN-GaN HFET with a field modulation plate", *IEEE Electron Device Lett.*, Vol.24, No.5, Mar 2003

[IX] Y.-F. Wu, A. Saxler, M. Moore, R.P. Smith, S. Sheppard, P.M. Chavarkar, T. Wisleder, U.K. Mishra, and P. Parikh, "30-W/mm GaN HEMTs by field plate optimization*", IEEE Electron Device Lett.*, vol.25, pp. 117-119, 2004.

[X] Wu et al, "Linearity performance of GaN HEMTs with field plates", *IEEE 62th DRC*, *Conference Digest*, pp. 35-36, June 2004.

[XI] Wu et al, "Wide bandgap transistors with multiple field plates", *United States Patent Application, 20050253168*, Published on Nov. 17, 2005, Filed on October 29, 2004.

[XII] Y. Ando, A. Wakejima, Y. Okamoto, T. Nakayama, K. Ota, K. Yamanoguchi, Y. Murase, K. Kasahara, K. Matsunaga, T. Inoue, H. Miyamoto, and H. Miyamoto, "Novel AlGaN/GaN dual-field-plated FET with high gain, increased linearity and stability", *IEDM 2005 Technical Digest*, pp. 585-588, Washington, DC, Dec. 5-7, 2005.