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References

1 WILK, G.D., WALLANCE, R.M., and ANTHONY, J.M.: 'High-k gate dielectrics: current status and materials properties considerations', *J. Appl. Phys.*, 2001, **89**, pp. 5243–5275

2 HOBBS, C., TSENG, H., REID, K., TAYLOR, B., DIP, L., HEBERT, L., GARCIA, R., HEGDE, R., GRANT, J., GILMER, D., FRANKE, A., DHANDAPANI, V., AZRAK, M., PRABHU, L., RAI, R., BAGCHI, S., CONNER, J., BACKER, S., DUMBUYA, F., NGUYEN, B., and TOBIN, P.: '80 nm poly-Si gate CMOS with HfO_2 gate dielectric', *IEDM Tech. Dig.*, 2001, pp. 663–666

3 WILK, G.D., and WALLANCE, R.M.: 'Electrical properties of hafnium silicate gate dielectrics deposited directly on silicon', *Appl. Phys. Lett.*, 1999, **74**, pp. 2854–2856

4 YAMAGUCHI, T., SATAKE, H., and FUKUSHIMA, N.: 'Degradation of current drivability by the increase of Zr concentrations in Zr-silicate MISFET', *IEDM Tech. Dig.*, 2001, pp. 663–666

5 FISCHETTI, M.V., NEUMAYER, D.A., and CARTIER, E.A.: 'Effective electron mobility in Si inversion layers in metal-oxide-semiconductor systems with a high-k insulator: the role of remote phonon scattering', *J. Appl. Phys.*, 2001, **90**, pp. 4587–4608

6 SZE, S.M. (Ed.): 'Physics of semiconductor devices' (John Wiley & Sons, New York, 1985, 2nd edn.), p. 447

Unpassivated AlGaN/GaN HEMTs with CW power density of 3.2 W/mm at 25 GHz grown by plasma-assisted MBE

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The Ka-band power performance of unpassivated AlGaN/GaN HEMTs grown by plasma-assisted molecular beam epitaxy on 6H-SiC substrates is reported. Transistors with a gate length of 0.2 μm, source-drain spacing of 2 μm, and 100 μm periphery displayed maximum drain currents greater than 1.6 A/mm. Small signal S-parameter measurements yielded an f_T of 53 GHz and f_{MAX} of 109 GHz. Passive load pull measurements at 25 GHz of 0.2 × 100 μm transistors yielded a power density of 3.2 W/mm with 30% PAE and 44% drain efficiency at 1.8 dB gain compression. To the knowledge of the authors, this is the first report of RF output power above 20 GHz from MBE-grown AlGaN/GaN HEMTs.

Introduction: Recent advances in the development of AlGaN/GaN high electron mobility transistors (HEMTs) has led to the demonstration of power densities exceeding 10 W/mm at 8 GHz for small periphery devices grown by MOCVD [1, 2]. In addition, Micovic *et al.* have reported excellent performance with MBE-grown layers [3]. Our group has recently demonstrated AlGaN/GaN HEMTs grown by plasma-assisted MBE on 6H-SiC with power densities exceeding 8 W/mm at 2 GHz [4] and 6 W/mm at 7 GHz. Presently there is great interest in exploring the use of AlGaN/GaN transistors for power amplification beyond X-band. To date there are only a few reports in the literature of AlGaN/GaN HEMTs operating above 20 GHz [5–7]. Recently, a CW power density of 5.1 W/mm at 26 GHz for a 200 μm-wide device grown by MOCVD has been reported [5]. In this Letter, we report on the MBE growth and power performance of AlGaN/GaN HEMTs operating at 25 GHz. At 25 GHz, a CW power density of 3.2 W/mm was achieved with a PAE of 30% and drain efficiency of 44% at 1.8 dB gain compression.

Growth and fabrication: AlGaN/GaN heterostructures were grown by plasma-assisted MBE on semi-insulating 6H-SiC substrates. Prior to growth, the SiC substrates receive an additional chemical–mechanical polish treatment from NovaSiC Inc. to remove polishing scratches on the as-received wafers. In our experience, this step has proven necessary for the reproducible growth of high quality epilayers. The growth is initiated with the deposition of an approximately 60 nm AlN nucleation layer at a substrate temperature of 800°C. The utility of the AlN nucleation layer is governed by the aluminium to nitrogen ratio and substrate temperature. We have found that growth under Al-rich growth conditions such that a streaky 1 × 1 rheed pattern is observed during the entire 60 nm layer is crucial to epilayer quality. The AlN nucleation layer is followed by 2 μm undoped GaN buffer grown at 745°C under Ga-rich conditions near the border to Ga droplet formation. The structure is completed with a 30 nm $Al_{0.34}Ga_{0.66}N$ barrier and a 5 nm GaN capping layer. The top half of the AlGaN barrier and the GaN capping layer are doped with Si. This MBE growth recipe consistently produces two-dimensional electron gases with a room temperature mobility of 1400 cm^2/Vs at a sheet density of $1.2 \times 10^{13}\ cm^{-2}$. Typical sheet resistances are between 350 and 380 Ω/sq.

Source and drain contacts are defined using electron beam lithography. The ohmic metal stack of Ti 20 nm/Al 100 nm/Ni 55 nm/Au 45 nm is annealed at 850°C in a nitrogen atmosphere. The ohmic contact resistance has been determined by TLM measurements to be 0.9 Ω mm. Mesas are then defined with optical lithography and a shallow chlorine-based ICP etch. The etch depth is 150 nm. A 0.2 μm-long Ni/Au T-gate is fabricated by electron beam lithography and lift-off using a bi-layer resist [8]. The HEMT process is completed with a coplanar test frame that is defined with optical lithography and the deposition of 500 nm of Au. The devices are not passivated with SiN prior to DC and RF testing.

Fig. 1 shows the DC I–V characteristics of a typical $0.2 \times 50\ \mu m^2$ transistor. The saturated current density is over 1.6 A/mm at a gate-source bias of +2 V. The device pinches off near −9 V. As shown in Fig. 2, the extrinsic transconductance peaks at 180 mS/mm at a gate-source bias of −7.5 V. The drain-source voltage for this measurement was 15 V. Small-signal S-parameter measurements are performed up to 110 GHz using a Hewlett-Packard HP8510X network analyser. At a drain bias of 10 V and a gate bias of −7.5 V, the measured unity current gain cutoff frequency (f_T) was 53 GHz. The maximum frequency of oscillation (f_{MAX}) of 109 GHz was determined by fitting the −20 dB/decade decay to Mason's unilateral power gain.

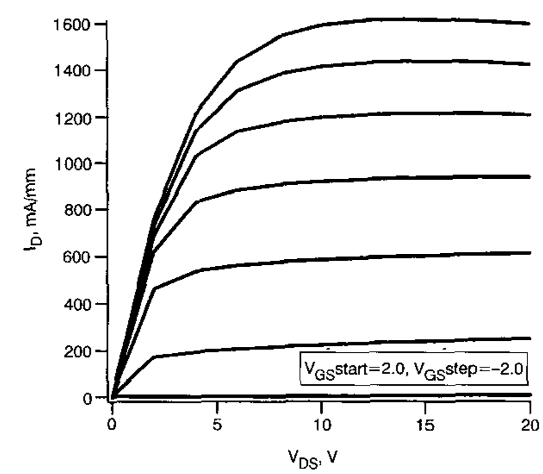

Fig. 1 *DC I–V characteristics of 0.2 × 25 μm HEMT*
Source-drain spacing 2 μm

On-wafer CW load-pull measurements were performed without substrate cooling at 25 GHz. Fig. 3 shows the measurement of a 100 μm device under class AB bias conditions. The drain-source bias is 20 V and the quiescent current is 36 mA. The device exhibited a linear gain of 6.4 dB. At an input power of 20.5 dBm, an output power of 25.1 dBm is recorded, corresponding to a power density of 3.2 W/mm. The power added efficiency is 30% and the drain efficiency is 44% with 1.8 dB gain compression. We note that the device was not driven far into gain compression and the output power has not yet saturated. The PAE is still rising at the highest input drive used in this measurement.

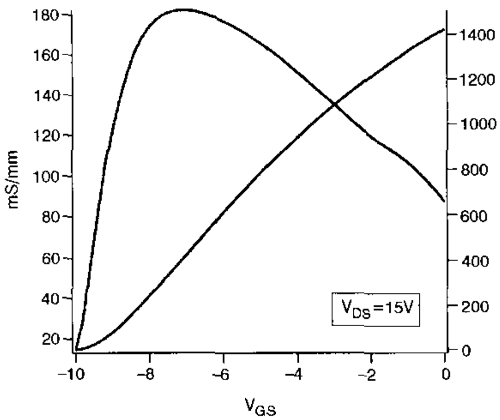

Fig. 2 *Transconductance and drain current of device shown in Fig. 1 at drain-source voltage of 15 V*

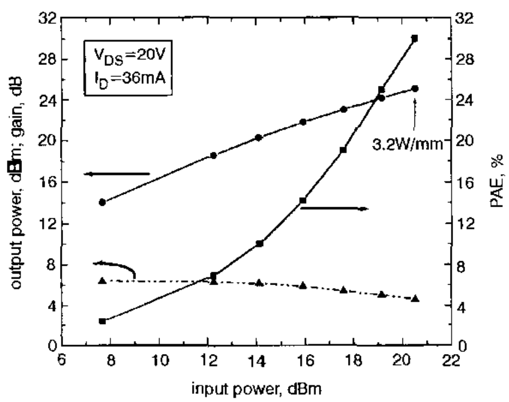

Fig. 3 *Load-pull data at 25 GHz*

Device is bias at $V_{DS}=20$ V and $V_{GS}=-7.5$ V. Quiescent drain current 36 mA. Device geometry 0.2 × 100 μm

Conclusions: We have detailed the MBE growth conditions and the fabrication of 0.2 μm gate length unpassivated AlGaN/GaN HEMTs operating at 25 GHz. The measured power density of 3.2 W/mm at 25 GHz demonstrates the potential for MBE-grown AlGaN/GaN HEMTs operating at 25 GHz and higher.

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References

1 MISHRA, U., PARIKH, P., and WU, Y.-F.: 'AlGaN/GaN HEMTs—an overview of device operation and applications', *Proc. IEEE*, 2002, **90**, p. 1022

2 TILAK, V., GREEN, B., KAPER, V., KIM, H., PRUNTY, T., SMART, J., SHEALY, J., and EASTMAN, L.: 'Influence of barrier thickness on the high-power performance of AlGaN/GaN HEMTs', *IEEE Electron Device Lett.*, 2001, **22**, p. 504

3 MICOVIC, M., KURDOGHLIN, A., HASHIMOTO, P., WONG, D., MOON, J., MCCRAY, L., and NGUYEN, C.: 'AlGaN/GaN heterojunction field effect transistors grown by nitrogen plasma assisted molecular beam epitaxy', *IEEE Trans. Electron Devices*, 2001, **48**, p. 591

4 WEIMANN, N., MANFRA, M., CHAKRABORTY, S., and TENNANT, D.: 'Unpassivated AlGaN–GaN HEMTs with minimal dispersion grown by plasma-assisted MBE on semi-insulating 6H-SiC substrates', *IEEE Electron Device Lett.*, 2003 (accepted for publication)

5 LEE, C., WANG, H., YANG, J., WITKOWSKI, L., MUIR, M., KHAN, M.A., and SAUNIER, P.: 'State-of-art CW power density achieved at 26 GHz by AlGaN/GaN HEMTs', *Electron. Lett.*, 2002, **38**, p. 924

6 KASAHARA, K., MIYAMOTO, H., ANDO, Y., OKAMOTO, Y., NAKAYAMA, T., and KUZUHARA, M.: 'Ka-band 2.3 W power AlGaN/GaN heterojunction FET', *IEDM Tech. Dig.*, 2002, p. 677

7 EASTMAN, L.F.: 'Experimental power-frequency limits of AlGaN/GaN HEMTs', *IEEE MTT-S Int. Microw. Symp. Dig.*, 2002, p. 2273

8 OCOLA, L.E., TENNANT, D.M., and YE, P.D.: 'Bilayer process for T-gates and Γ-gates using 100 KV e-beam lithography', *Microelectron. Eng.*, 2003 (accepted for publication)

Digital all-pass filter design method based on complex cepstrum

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One method for the design of all-pass filters approximating a given all band group delay function with small approximation error is presented. The design procedure is based on the calculation of the complex cepstrum coefficients of the denominator of the all-pass filter which approximate the desired group delay in a weighted least square sense.

Introduction: All-pass filters have applications in several signal processing areas, such as notch filtering, complementary filter banks, and equalisation of undesired group delay in communication systems [1].

Several all-pass design methods have been proposed where the design goal is to approximate a desired phase [2–4] or a group delay [5, 6]. This Letter is focused on the group delay approximation. The proposals in [5] and [6] are based on the relationship between the group delay of the minimum-phase denominator of a stable all-pass filter, and the complex cepstral coefficients arising from its discrete Hilbert Transform. The method in [5] requires the use of four FFTs and in [6] it is reduced to only one FFT. Both methods approximate the cepstral coefficients in the denominator of the all pass filter in a least square sense.

In this Letter an all-pass design method which requires no FFT operations is presented. To reduce the group delay approximation error we compute the cepstral coefficients in the denominator using a weighted least square approximation. In this way a smoother and a smaller group delay error is obtained.

Complex cepstrum for minimum-phase filter: The complex cepstrum of an FIR minimum-phase filter with an impulse response $d(n)$ is the complex sequence $\hat{d}(n)$ the frequency response of which is given as:

$$\hat{D}(e^{j\omega}) = \log[D(e^{j\omega})] = \hat{d}(0) + \sum_{k=1}^{\infty} \hat{d}(n)e^{-jn\omega} \tag{1}$$

where $D(e^{j\omega})$ is the frequency response of the sequence $d(n)$, and the logarithm base is e. When $D(e^{j\omega})$ is written in the polar form, the frequency response of the complex cepstrum can be expressed as

$$\hat{D}(e^{j\omega}) = \log|D(e^{j\omega})| + j\angle D(e^{j\omega}) \tag{2}$$

The minimum-phase filter group delay $\tau_{\min}(\omega)$ can be derived by equating the imaginary parts of (1) and (2), [6], yielding

$$\tau_{\min}(\omega) = \sum_{n=1}^{\infty} n\hat{d}(n)\cos(n\omega) \tag{3}$$

Using the fact that the complex cepstrum of a minimum-phase filter is causal, the minimum-phase impulse response $d(n)$ can be expressed as a function of its complex cepstrum coefficients by the following recursive nonlinear equation [7]

$$d(n) = \sum_{k=1}^{\infty} \left(\frac{k}{n}\right)\hat{d}(n)d(n-k) \tag{4}$$

where $\hat{d}(0) = 0$ and $d(0) = 1$.