Effects of Surface Passivation and Deposition Methods on the 1/f Noise Performance of AlInN/AlN/GaN High Electron Mobility Transistors

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***Abstract*— This letter reports on effects of Si_3N_4 and Al_2O_3 surface passivation as well as different deposition methods on the low-frequency noise (LFN) characteristics for AlInN/AlN/GaN high electron mobility transistors (HEMTs). Two samples are passivated with Al_2O_3, deposited by two different methods: 1) thermal atomic layer deposition (ALD) and 2) plasma-assisted ALD. The third sample is passivated with Si_3N_4 using plasma-enhanced chemical vapor deposition. The LFN of the three samples is measured under a bias condition relevant for amplifier and oscillator applications. It is found that the surface passivation has a major impact on the noise level. The best surface passivation, with respect to LFN, is the thermal ALD Al_2O_3 for which the noise current spectral density measured at 10 kHz is 1×10^{-14} Hz^{-1} for a bias of $V_{dd}/I_{dd} = 10$ V/80 mA. To the best of our knowledge, this result sets a standard as the best reported LFN of AlInN/GaN HEMTs. It is also in the same order as good commercial AlGaN/GaN HEMTs reported in literature and thus demonstrates that AlInN/GaN HEMTs, passivated with thermal ALD Al_2O_3, is a good candidate for millimeter-wave power generation.**

***Index Terms*— AlInN/AlN/GaN, high electron mobility transistor (HEMT), low frequency noise (LFN) measurement, passivation, deposition methods.**

I. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) have been established as a commercial technology for high-power and relatively high-frequency MMIC design. To further stretch the frequency limit, other III-nitride (III-N) materials are considered, e.g., AlInN/GaN HEMTs that is a promising candidate for high power millimeter-wave applications [1].

To make useful AlInN/AlN/GaN devices, a good surface passivation method must be established. A high quality passivation significantly reduces the impact of surface traps while maintaining a low gate leakage. This will reduce current collapse, improve the transconductance, and lead to better pinch-off characteristics [2], [3]. The passivation also improves microwave output power density as well as efficiency, reduces memory effects and has a positive effect on the low-frequency-noise (LFN) performance. Reduced LFN will have a direct positive effect on oscillator phase noise and performance of mixers and IF amplifiers. A factor of 10 reduction in flicker noise would result in a 10 dB improvement in phase noise if flicker noise is the dominant noise source in the device [4]. Further, as LFN is related to traps and gate leakage current, a reduction in LFN can be correlated to improved reliability. For these reasons, methods to improve LFN of AlInN/GaN HEMTs, e.g., different passivation methods, are important to investigate.

Two different dielectrics are widely used as surface passivation for III-N HEMTs: Si_3N_4 and Al_2O_3. LFN reduction in AlGaN/GaN HEMTs after passivation was reported in [5], but a comparison between Si_3N_4 and Al_2O_3 is still missing. Focusing particularly on AlInN/GaN HEMTs, a few reports of flicker noise measurements have been published [6], [7]. However, there is no report on the effectiveness of different passivation techniques.

This letter investigates LFN of AlInN/AlN/GaN HEMTs passivated with Si_3N_4 and Al_2O_3, deposited with three different methods: Si_3N_4 deposited with Plasma-Enhanced Chemical Vapor Deposition (PECVD), Al_2O_3 deposited with plasma-assisted Atomic Layer Deposition (ALD) and Al_2O_3 deposited with thermal ALD. The LFN is measured under high drain voltage condition, which is relevant for oscillator and amplifier applications.

II. Material Growth and Device Fabrication

The heterostructure is grown by MOCVD on SiC substrate. The layer structure consists of a nucleation layer (100 nm), a GaN buffer (1.6 μm), an intermediate AlN layer (2nm) and an $Al_{0.81}In_{0.19}N$ layer (6 nm). Details about the growth can be found in [8]. Devices of size 2×50 μm are processed starting with mesa formation in a Cl_2 plasma. Ohmic contacts

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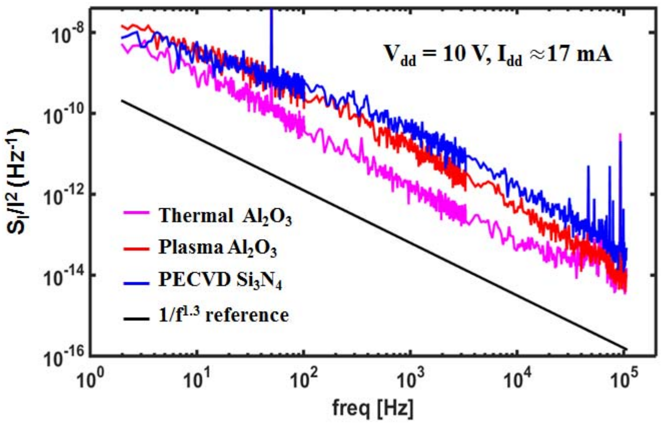

Fig. 1. Drain noise current spectra of the three AlInN/AlN/GaN HEMTs versus frequency at $V_{dd} = 10$ V, $I_{dd} \approx 17$ mA.

are fabricated using a Ta-based metallization that is annealed at 550 °C, with a resulting contact resistance of 0.64 Ωmm. The source-drain distance L_{SD} is 1 μm. 100 nm long Ni/Au gates, centered in the source-drain opening are defined by e-beam lithography. After the deposition of Ti/Au contact pads, the sample is split in three pieces which are passivated separately. Two pieces are passivated with Al_2O_3 dielectric, one using thermal ALD (Thermal ALD HEMT), and the other using plasma-assisted ALD (Plasma ALD HEMT). The chamber temperature is 300 °C in both cases. The third sample is passivated with Si_3N_4 by PECVD (PECVD HEMT) at 340 °C. The gates are subjected to a post deposition anneal (PDA) in nitrogen ambient at 300 °C for 5 min. More details about the device processing can be found in [1]. The room-temperature sheet carrier densities (n_s) and mobilities (μ) are extracted from Hall measurements. The results are $n_s = 1.53\times10^{13}$, 1.60×10^{13} and 1.66×10^{13} cm^{-2}, and μ = 1575, 1540, 1555 cm^2/Vs, for the thermal ALD, plasma ALD and PECVD HEMTs, respectively. The corresponding pinch voltages (V_{po}), measured at $V_{dd} = 10$ V, are -4.0 V, -5.0 V and -5.1 V, for the three samples.

III. Results and Discussion

The LFN measurements are carried out with a set up based on a voltage-voltage preamplifier from Stanford Research (SR560), which is suitable for LFN measurement of high power devices such as GaN HEMTs [9]. In most previous works, LFN measurements have been performed in the ohmic region (at low drain bias) which is relevant for device characterization but less applicable to oscillators and amplifiers which often operate in the saturation region. With a focus on circuit applications, this letter presents LFN measured under high drain voltage condition. The drain voltage is kept constant at 10V while the gate bias is swept. The measured drain noise current spectral density S_I(A^2/Hz) normalized to the drain current squared (I^2) is used as LFN figure of merit.

Fig. 1 shows the normalized drain current noise spectra (S_I/I^2) of the three HEMTs presented in Section II at a bias of $V_{dd} = 10$ V and $I_{dd} \approx 17$ mA. This is a reasonable operating point of an oscillator circuit. The noise spectrum level of the thermal ALD HEMT is significantly

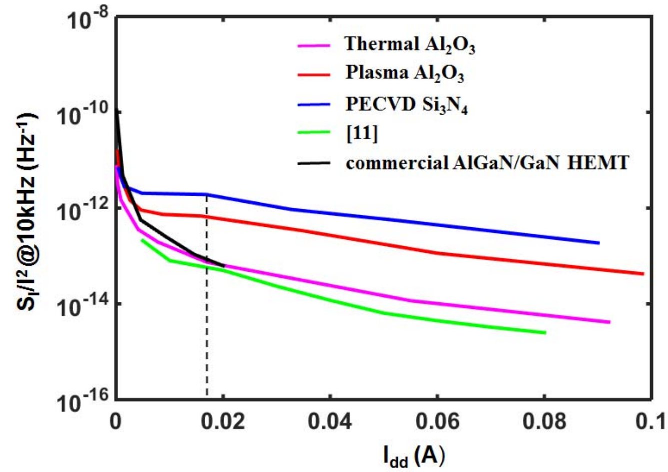

Fig. 2. Drain noise current spectra at 10 kHz versus the DC drain current of the three AlInN/AlN/GaN HEMTs at $V_{dd} = 10$ V, a 2×50 μm commercial AlGaN/GaN HEMT measured in [9] at $V_{dd} = 10$ V and an AlGaN/GaN device reported in [11] at $V_{dd} = 5$ V. The dashed line indicates $I_{dd} \approx 17$ mA.

lower than for the two other samples. It is also seen that the noise spectrum of the thermal ALD HEMT has a nearly constant slope $1/f^{\gamma}$ with $\gamma = 1.3$ up to 50 kHz where a plateau, possibly due to generation-recombination (GR-type) noise is observed. On the other hand, the noise spectra of the plasma ALD and PECVD HEMTs are more Lorentzian type, which indicates the existence of deep level traps [10].

Fig. 2 shows the LFN spectral densities at 10 kHz versus DC drain current measured at $V_{dd} = 10$ V of the three HEMTs in this letter. For low drain currents, there is no significant difference in noise performance. For larger drain currents, the thermal ALD HEMT presents an order of magnitude lower noise compared to the plasma ALD HEMT and about 50 times better noise compared to the PECVD HEMT. The noise levels are also compared to a commercial AlGaN/GaN HEMT measured in [9] and a state-of-the-art AlGaN/GaN HEMT reported in [11]. It is found that the thermal ALD HEMT performs well in comparison, even though the technology is less mature.

It has been suggested that LFN may be modelled as the sum of the noise from the channel and series resistance in the ungated region [12]. To further investigate the LFN source of HEMT devices at high drain voltage biasing, noise current spectra at 10 kHz of the three AlInN/AlN/GaN HEMTs ($V_{dd} = 10$ V) are plotted versus the effective gate voltage $V_{gn} = V_{gs} - V_{po}$ (Fig. 3). Two main regions may be identified: 1) close to pinch-off, where $S_I/I^2 \propto V_{gn}^{-1}$ and 2) at full channel bias, where $S_I/I^2 \propto V_{gn}^{-3}$. Based on this, it can be concluded that close to pinch-off the main contribution to LFN originates from the channel, where the different passivations have no direct effect. In contrast, at full channel which is most relevant for circuit applications, the noise current spectra of the three HEMTs differ significantly. This is attributed to the extent of trap passivation achieved for the different dielectrics, which directly affects the LFN.

Further, the gate leakage current is found to be lower for the thermal ALD HEMT compared to the plasma ALD and PECVD HEMTs. Devices with higher gate leakage

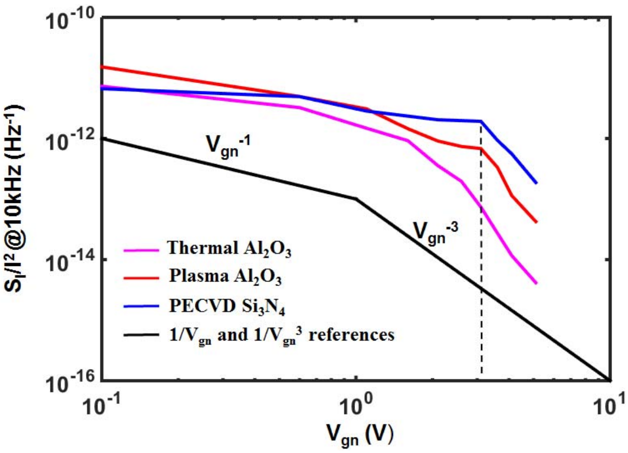

Fig. 3. Drain noise current spectra at 10 kHz of the three AlInN/AlN/GaN HEMTs versus the effective gate bias V_{gn} (V_{dd} = 10V). The dashed line corresponds to $I_{dd} \approx 17$ mA.

current generally display higher LFN, due to larger number of defects in the device [5]. All results show that the thermal ALD HEMT results in a better LFN characteristic, compared to the plasma ALD and PECVD HEMTs.

The large signal microwave properties of the three different passivations have previously been characterized with 3GHz load-pull measurements [13]. The output power densities of the thermal ALD, plasma ALD, and PECVD HEMTs are 1.9, 3.3, and 2.4 W/mm, respectively. Interestingly, the maximum power density is not obtained for the same passivation as the lowest flicker noise. Nevertheless, for oscillator applications, the thermal ALD HEMT is much more suitable due to its significantly lower flicker noise level. Assuming flicker noise as the dominant noise source, the 10-50 times improvement in noise spectral density would result in more than 10 dB improvement in oscillator phase noise while the difference in power density between the three samples would affect phase noise by less than 3 dB [4].

IV. Conclusion

LFN characteristics are presented for AlInN/AlN/GaN HEMTs with different passivations: Si_3N_4 deposited by PECVD, Al_2O_3 deposited by plasma-assisted ALD, and Al_2O_3 deposited by thermal ALD. The LFN is measured under high drain voltage condition, which is relevant for oscillator and amplifier applications. It is found that thermally deposited Al_2O_3 HEMT results in the lowest noise, which is comparable to good commercial AlGaN/GaN HEMTs reported in literature. This demonstrates that AlInN/GaN HEMTs, passivated with thermal ALD Al_2O_3, is a good candidate for millimetre-wave power generation.

References

[1] A. Malmros *et al.*, "Evaluation of an InAlN/AlN/GaN HEMT with Ta-based ohmic contacts and PECVD SiN passivation," *Phys. Status Solidi C*, vol. 11, nos. 3–4, pp. 924–927, Apr. 2014.

[2] W. Lu *et al.*, "A comparative study of surface passivation on AlGaN/GaN HEMTs," *Solid-State Electron.*, vol. 46, no. 9, pp. 1441–1444, Sep. 2002.

[3] H. Wang *et al.*, "Al_2O_3 passivated InAlN/GaN HEMTs on SiC substrate with record current density and transconductance," *Phys. Status Solidi C*, vol. 7, no. 10, pp. 2440–2444, Oct. 2010.

[4] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE*, vol. 54, no. 2, pp. 329–330, Feb. 1996.

[5] A. V. Vertiatchikh and L. F. Eastman, "Effect of the surface and barrier defects on the AlGaN/GaN HEMT low-frequency noise performance," *IEEE Electron Device Lett.*, vol. 24, no. 9, pp. 535–537, Sep. 2003.

[6] P. Sakalas *et al.*, "Compact modelling of InAlN/GaN HEMT for low noise applications," *Semicond. Sci. Technol.*, vol. 29, no. 9, p. 095014, Aug. 2014.

[7] C. Kayis *et al.*, "Low-frequency noise measurements of electrical stress in InAlN/GaN and AlGaN/GaN heterostructure field-effect transistors," *Proc. SPIE*, vol. 7939, p. 79392G, Mar. 2011.

[8] M.-A. di Forte Poisson *et al.*, "LP MOCVD growth of InAlN/GaN HEMT heterostructure: Comparison of sapphire, bulk SiC and composite SiCopSiC substrates for HEMT device applications," *Phys. Status Solidi C*, vol. 7, no. 5, pp. 1317–1324, Mar. 2010.

[9] T. N. T. Do *et al.*, "Low frequency noise measurements—A technology benchmark with target on oscillator applications," in *Proc. 44th Eur. Microw. Conf. (EuMC)*, Rome, Italy, Oct. 2014, pp. 1412–1415.

[10] S. H. Hsu *et al.*, "Characterization and analysis of gate and drain low-frequency noise in AlGaN/GaN HEMTs," in *Proc. IEEE Lester Eastman Conf. High Perform. Devices*, Aug. 2002, pp. 453–460.

[11] C. Sanabria, "Noise of AlGaN/GaN HEMTs and oscillators," Ph.D. dissertation, Dept. Elect. Comput. Eng., Univ. California, Santa Barbara, CA, USA, Jun. 2006.

[12] J.-M. Peransin *et al.*, "1/f noise in MODFETs at low drain bias," *IEEE Trans. Electron Devices*, vol. 37, no. 10, pp. 2250–2253, Oct. 1990.

[13] A. Malmros *et al.*, "Evaluation of thermal versus plasma-assisted ALD Al_2O_3 as passivation for InAlN/AlN/GaN HEMTs," *IEEE Electron Device Lett.*, to be published.