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**Temperature Dependent Characteristics of InAlN/GaN HEMTs for
mm-Wave Applications**Weichuan Xing^{a,b}, Zhihong Liu^a, Geok Ing Ng^b, Tomas Palacios^c^a*Singapore-MIT Alliance for Research and Technology, Singapore*^b*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore*^c*Massachusetts Institute of Technology, USA***Abstract**

This work presents a 100 nm-gate InAlN/GaN HEMT with current-gain cutoff frequency (f_T) up to 120 GHz at room temperature (25 °C). Temperature dependent DC and RF characteristics are measured from 25 °C to 200 °C. The maximum drain current (I_{d-max}) decreases from 1247 mA/mm to 927 mA/mm as the temperature increases from 25 °C to 200 °C. For maximum f_T , it drops to 87 GHz and 64 GHz at 100°C and 200°C respectively. These results show that although both DC and RF performances decrease with the increase in temperature, the device still exhibits high mm-wave performance at high temperatures. Thus, InAlN/GaN based HEMTs are very promising for high temperature mm-wave applications.

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Keywords: InAlN/GaN HEMTs; RF performance; temperature dependent.

1. Introduction

Due to the unique properties of GaN based materials, including wide bandgap, high critical breakdown field, high electron saturation velocity and high polarization-induced two dimensional-electron-gas (2DEG) density [1]-[3], GaN based high electron mobility transistors (HEMTs) [4] are emerging as one of the hottest topics for high frequency and high power applications. Great progress has been made on improving the performance of GaN HEMTs in the last decade. K. Shinohara et al. reported record cut-off frequency (f_T) of 450 GHz and maximum oscillation frequency (f_{max}) of 600 GHz [5]. Output power density of 10.5 W/mm at 40 GHz has been measured by T. Palacios et al. [6]. Minimum noise figure (NF_{min}) of 1.2 dB can be achieved up to 50 GHz by Margomenos, A. et al. [7]. Compared with the devices with an AlGaN barrier, the GaN HEMTs using lattice-matched InAlN as a barrier

can have a larger band-gap difference and a larger polarization charge difference between the barrier and channel, thus higher 2DEG sheet carrier density ($\sim 2x$) can be achieved as compared to AlGaIn/GaN HEMTs. In addition, the barrier can also be designed to be thinner to realize a high 2DEG electron density which can help to reduce the distance between the gate and channel and thereby improve the gate modulation efficiency. Also, there is less strain induced reliability issues because of the lower lattice mismatch between InAlN and GaN. Thus, InAlN/GaN HEMTs are very promising for mm-wave applications.

As GaN based RF HEMTs are expected to be able to work at extreme environments, both DC and RF performance at elevated temperatures need to be studied. Till now, there are a few reports available on the high temperature characterization of GaN HEMTs [8]-[13]. Temperature dependent device performance including DC drain current, transconductance, gate leakage current, and cut-off frequency etc, have been well studied. However, most of these reports are on AlGaIn/GaN HEMTs and very limited results of temperature dependent characteristics for InAlN/GaN HEMTs have been published. In this work, InAlN/GaN HEMTs on a sapphire substrate with 100 nm gate length have been fabricated, and DC and RF small-signal performance including maximum drain current I_{dmax} , f_T and f_{max} have been characterized from room temperature to 200 $^{\circ}$ C.

2. Experimental details

The wafer used for this work was grown on a sapphire substrate by metal-organic chemical vapor deposition (MOCVD). The InAlN/GaN heterostructure consists of a 10 nm un-doped $In_{0.17}Al_{0.83}N$ top barrier, a 1 nm AlN spacer and a 1 μ m GaN buffer layer, as shown in Fig. 1. The device fabrication started with mesa isolation by Cl_2 based plasma dry etch. The measured mesa height is 120 nm. Metals of Ti/Al/Ni/Au with thickness of 20/120/40/50 nm were deposited followed by rapid thermal annealing (RTA) at 775 $^{\circ}$ C for 30 seconds at N_2 atmosphere to form the ohmic contact. Contact resistance (R_C) of $\sim 0.3 \Omega \cdot mm$ has been measured using transmission line model (TLM) patterns and the sheet resistance (R_{sh}) is $270 \pm 20 \Omega/\square$. A 100nm length rectangular gate was defined by electron beam lithography (EBL) and Ni/Au (30/70 nm) metallization. At the end, interconnect and pad were formed by Ti/Au metallization to land the RF probes. The surface of the device used in this work is not passivated. The devices have a source-to-drain distance (L_{sd}) of 1 μ m, and gate width (W_g) of $2 \times 20 \mu$ m. The DC performance was measured using an Agilent B1500A semiconductor device analyzer, and the RF performance was measured using an Agilent N5244A PNA network analyzer. The temperature-dependent characterization was carried out using a cascade probe station with its chuck temperature varied from room temperature to 200 $^{\circ}$ C at a step of 25 $^{\circ}$ C.

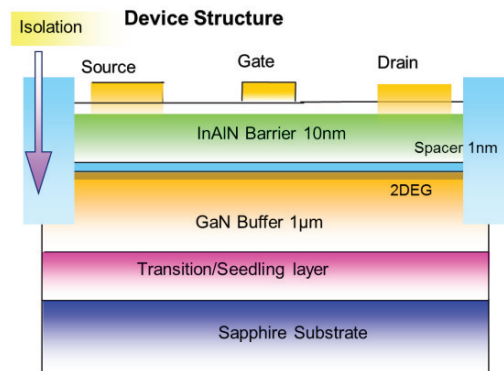


Fig. 1 Fabricated device structure

3. Result and discussion

Fig. 2 (a) and (b) show the DC output and transfer characteristics of the device at room temperature separately. Maximum drain current (I_{dmax}) of 1.25 A/mm has been achieved at $V_g = 0$ V. And maximum transconductance (g_m) of 270 mS/mm has been achieved at $V_g = -4.8$ V, $V_d = 4$ V.

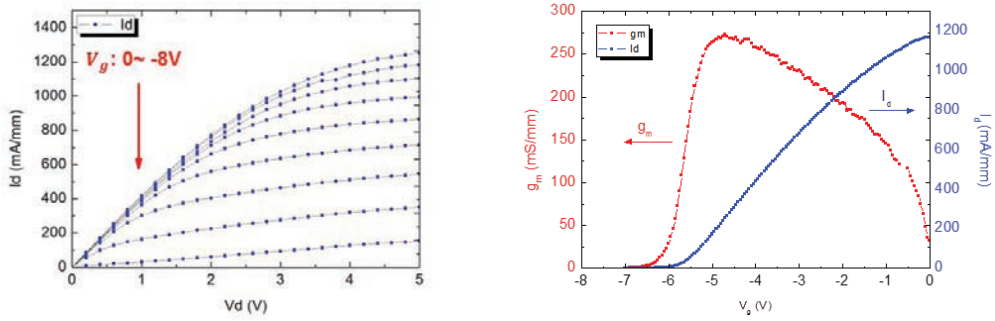


Fig. 2 (a) DC output characteristic of the fabricated device; (b) DC transfer characteristic at $V_d = 4$ V.

Fig. 3 shows the small signal characteristics of the device at $V_g = -5$ V and $V_d = 4$ V. An extrinsic f_T of 72 GHz and an extrinsic f_{max} of 40 GHz have been obtained for the device measured at 25°C.

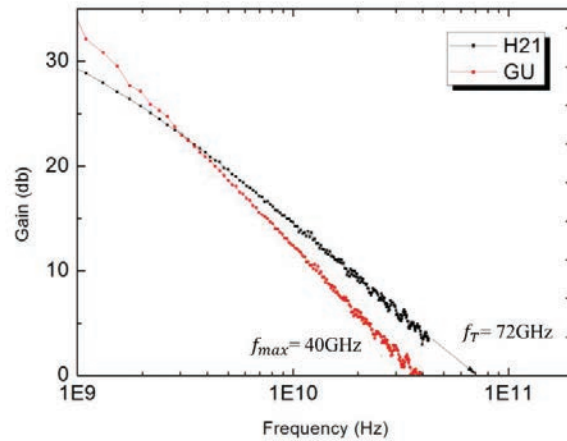


Fig. 3 Extrinsic f_T and f_{max} at $V_g = -5$ V and $V_d = 4$ V measured at 25°C

Cold/hot FET de-embedding method was used to eliminate the effect of interconnect pad [14]. After de-embedding, a high intrinsic $f_T = 120$ GHz has been achieved. The intrinsic f_{max} remains almost the same as the measured extrinsic value because it is mainly limited by the large gate resistance. Higher f_{max} can be achieved with a mushroom gate rather than the existing rectangular gate.

I_{d-max} and f_T measured at different temperatures are shown in Fig. 4 (a) and (b). It can be seen that, as the temperature increases from 25°C to 200°C, the maximum drain current drops from 1247 mA/mm to 927 mA/mm ($\Delta = 26\%$) and the maximum intrinsic f_T drops from 120 GHz to 64 GHz ($\Delta = 47\%$). The results show that even the DC and RF performance has decreased with the increased temperature; the InAlN/GaN HEMT still demonstrates excellent performance at a high base temperature up to 200 °C.

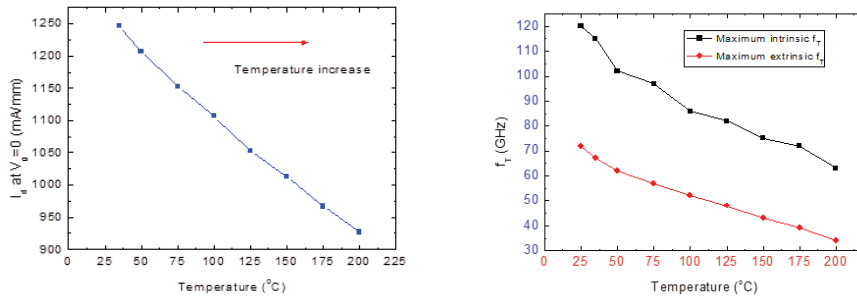


Fig. 4 (a) I_{d-max} (b) intrinsic and extrinsic f_{T-max} measured from 25°C to 200°C

As shown in Fig. 4, the I_{d-max} and f_{T-max} decrease approximately in a linear trend as the temperature increases. Their temperature dependency can be modeled by [15]:

$$P(T) = P(T_0) [1 + B(T - T_0)] \quad (1)$$

Where $P(T)$ is the value of the I_{d-max} or f_{T-max} at temperature T , $P(T_0)$ is the value at a reference temperature T_0 and B is the temperature coefficient (TC) in units of ($^{\circ}\text{C}$). By fitting the curves, the temperature coefficients of the measured parameters are obtained and listed in Table 1.

Table 1. Temperature coefficients of I_{d-max} and f_{T-max} .

Temperature coefficients	$B_{f_T} (10^{-3}/^{\circ}\text{C})$	$B_{I_d} (10^{-3}/^{\circ}\text{C})$
Values	-2.67	-1.47

4. Conclusion

In this work, we report the InAlN/GaN HEMT grown on a sapphire substrate ($L_g=100\text{nm}$) with maximum drain current of 1247 mA/mm and maximum cut-off frequency of 120 GHz. Device DC and RF performance was measured from 25°C to 200°C and still shows good performance at 200°C. The results show that the InAlN/GaN HEMT is a promising candidate in mm-wave application over a wide range of temperature.

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Reference

- [1] O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger, and J. Hilsenbeck, "Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N-doped Ga-face AlGaIn/GaN heterostructures," *J. Appl. Phys.*, vol. 85, no. 6, pp. 3222–3233, Mar. 1999.
- [2] M. A. Khan, Q. Chen, C. J. Sun, M. Shur, and B. Gelmont, "Two-dimensional electron gas in GaN-AlGaIn heterostructures deposited using trimethylamine-alane as the aluminum source in low pressure metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 67, no. 10, pp. 1429–1431, 1995.
- [3] M. A. Khan, J. N. Kuznia, J. M. Van Hove, N. Pan, and J. Carter, "Observation of a two dimensional electron gas in low pressure metalorganic chemical vapor deposited GaN-AlxGa1-xN heterojunctions," *Appl. Phys. Lett.*, vol. 60, no. 24, pp. 3027–3029, 1992.
- [4] M. Asif Khan, A. Bhattacharai, J. N. Kuznia, and D. T. Olson, "High electron mobility transistor based on a GaN-AlxGa1-xN heterojunction," *Appl. Phys. Lett.*, vol. 63, no. 9, p. 1214, Aug. 1993.
- [5] Shinohara, Keisuke, Regan, Dean C., Tang, Yan, Corrion, Andrea L., Brown, David F., Wong, Joel C., Robinson, John F., Fung, Helen H., Schmitz, Adele, Oh, Thomas C., Kim, Samuel Jungjin, Chen, Peter S., Alexandros, D., Margomenos, Alexandros D., Micovic, Miroslav, "Scaling of GaN HEMTs and Schottky diodes for submillimeter-wave MMIC applications," *IEEE Trans. Electron Devices* 60, 2982, 2013.

- [6] Nidhi , T. Palacios , A. Chakraborty , S. Keller and U. Mishra “Study of impact of access resistance on high-frequency performance of AlGaIn/GaN HEMTs by measurements at low temperatures,” *IEEE Electron Device Lett.*, vol. 27, no. 11, pp.877 -880, 2006
- [7] Margomenos, A., HRL Labs., LLC, Malibu, CA, USA ; Kurdoghlian, A. ; Micovic, M. ; Shinohara, K. “W-Band GaN Receiver Components Utilizing Highly Scaled, Next Generation GaN Device Technology,” *IEEE Compound Semiconductor Integrated Circuit Symposium (CSICs)*, 2014.
- [8] S. Arulkumar, Z. H. Liu, G. I. Ng, W. C. Cheong, R. Zeng, J. Bu, H. Wang, K. Radhakrishnan, and C. L. Tan, “Temperature dependent microwave performance of AlGaIn/GaN high-electron-mobility transistors on high-resistivity silicon substrate,” *Thin Solid Films*, vol. 515, no. 10, pp. 4517-4521, Mar. 2007.
- [9] Darwish, et al., “Dependence of GaN HEMT Millimeter-Wave Performance on Temperature,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 12, 2009.
- [10] M. Akita, et al., “High-Frequency Measurements of AlGaIn/GaN HEMTs at High Temperatures,” *IEEE Electron Device Letters*, vol. 22, no. 8, pp. 376-377, 2001.
- [11] HUSNA et al., “High-Temperature Performance of AlGaIn/GaN MOSHEMT with SiO₂ Gate Insulator Fabricated on Si (111) Substrate,” *IEEE Trans. Electron Devices*, vol. 59, no. 9, 2012.
- [12] Ali M. Darwish, Amr A. Ibrahim, and H. Alfred Hung, “Temperature Dependence of GaN HEMT Small Signal Parameters,” *International Journal of Microwave Science and Technology*, volume 2011.
- [13] Z. H. Liu, G. I. Ng, S. Arulkumar, Y. K. T. Maung, K. L. Teo, S. C. Foo, and S. Vicknesh, “Temperature dependent microwave noise characteristics in ALD Al₂O₃/AlGaIn/GaN MISHEMTs on silicon substrate,” *IEEE Electron Device Letters*, vol. 32, no. 3, pp. 318-320, Mar. 2011.
- [14] G. Dambrine, A. Cappy, F. Heliodore, and E. Playez, “A new method for determining the FET small-signal equivalent circuit,” *IEEE Trans. Microw. Theory Tech.*, vol. 36, no. 7, pp. 1151–1159, 1988.
- [15] Jimmy P. H. Tan, et al., “Temperature Dependent Small-Signal Model Parameters Analysis of AlGaAs/InGaAs pHEMTs in Multilayer 3D MMIC Technology,” *European Microwave Conference*, Paris, 2010.