

**TH01G-1**

# A 25.5-31GHz Power Amplifier Using Enhancement-Mode High-K Dielectric GaN MOS-HEMTs in 300mm GaN-on-Si Technology

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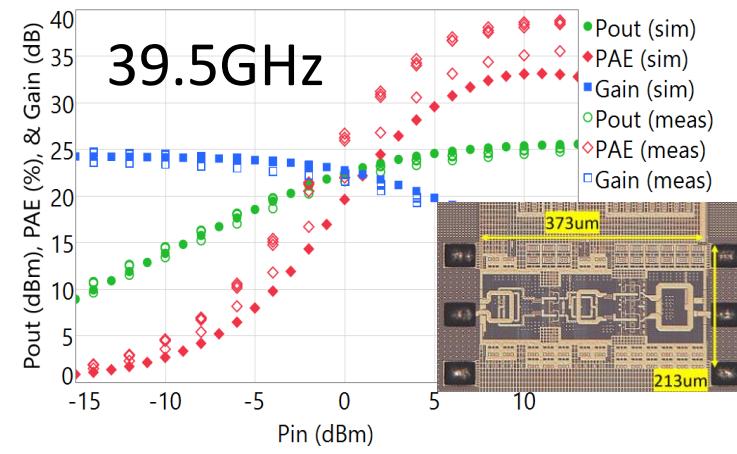


# Outline

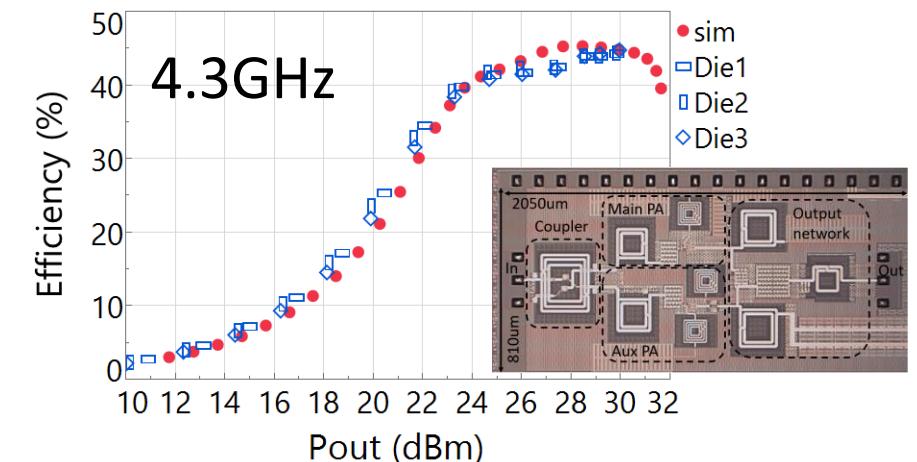
- **Introduction**
- **300mm E-mode GaN MOS-HEMT technology**
- **mmWave power amplifier implementation**
- **Measurement results**
- **Conclusion**

# Introduction

- **GaN technology for RF/mmWave front-ends**
  - High power and efficiency vs. other technologies
  - Problems - smaller wafer and mostly D-mode
- **D-mode Schottky gate HEMTs -> E-mode High-k metal gate GaN MOS-HEMT**
  - Previous D-mode demo
  - This work - first E-mode demo



Q. Yu, VLSI 2022

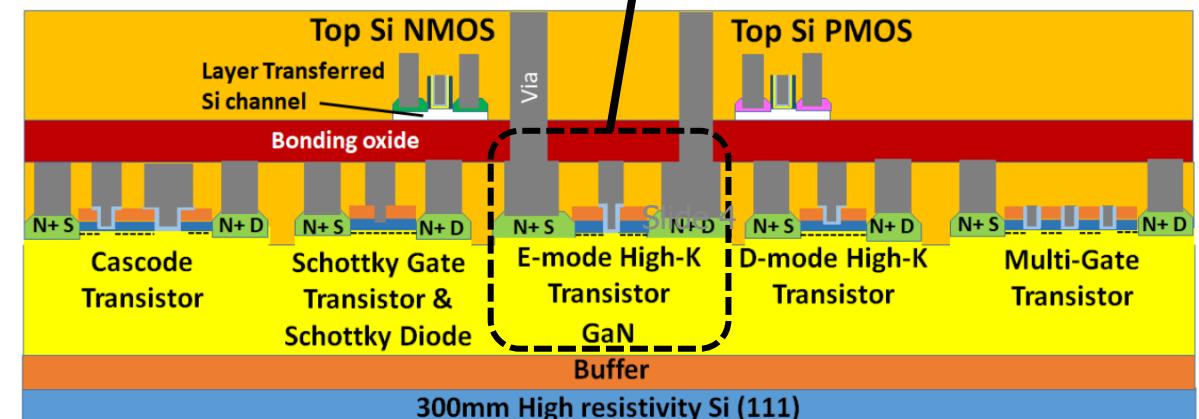
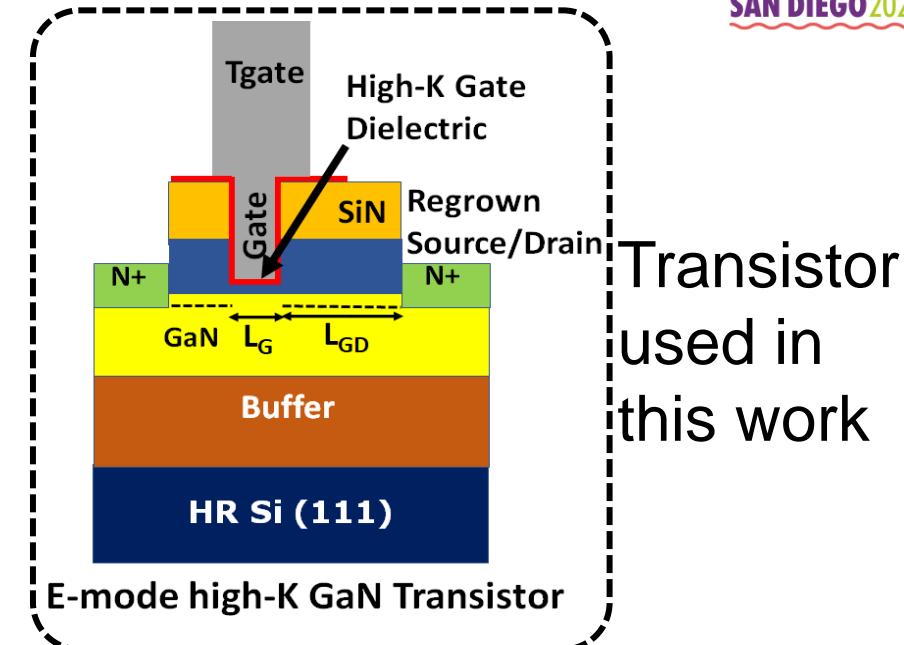
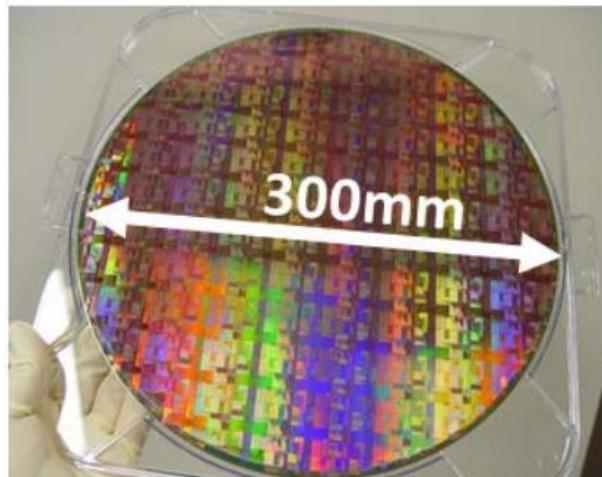


Sub-6GHz wideband Doherty PA  
Q. Yu, BCICTS 2022

# 300mm GaN-on-Si Technology I

- 300mm GaN-on-Si process

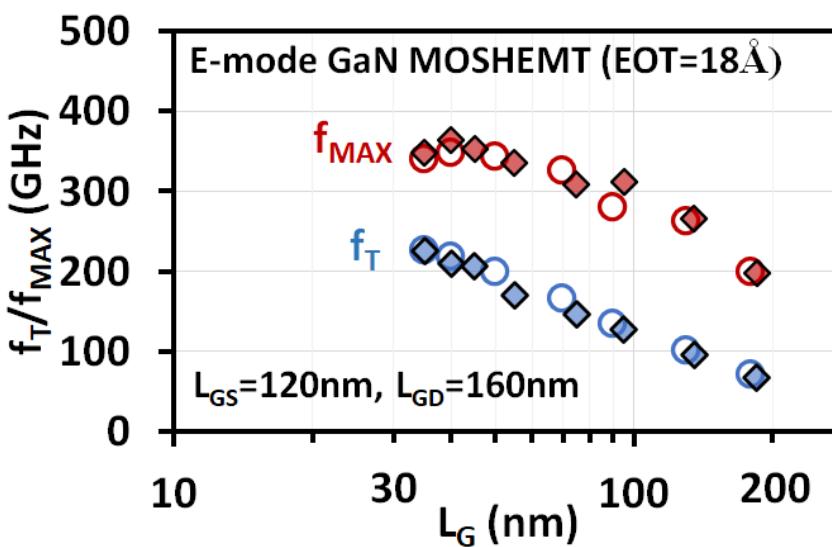
- Cost-effective manufacturing solution
- Monolithic integration of GaN and Si transistors
  - Better performance
  - More functionalities
  - Smaller formfactor



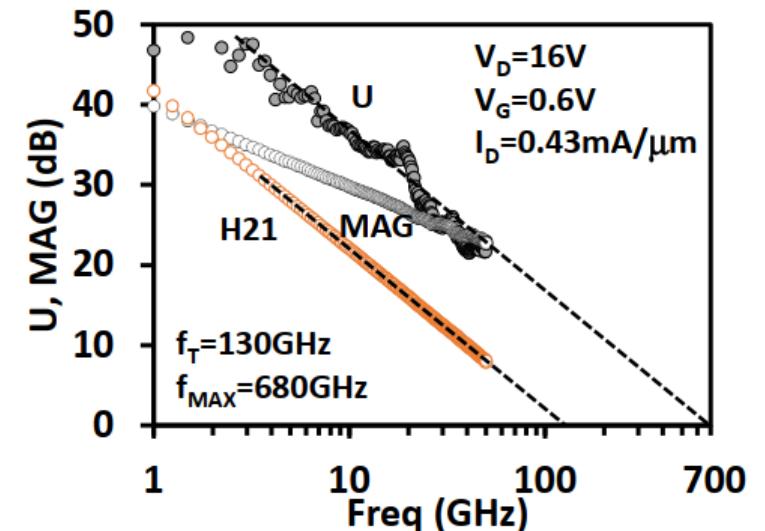
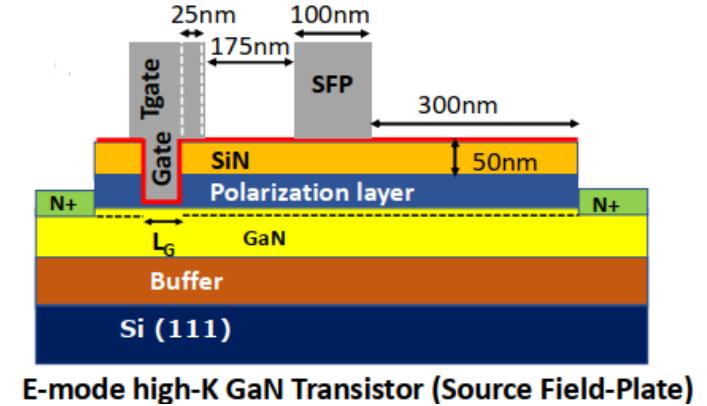
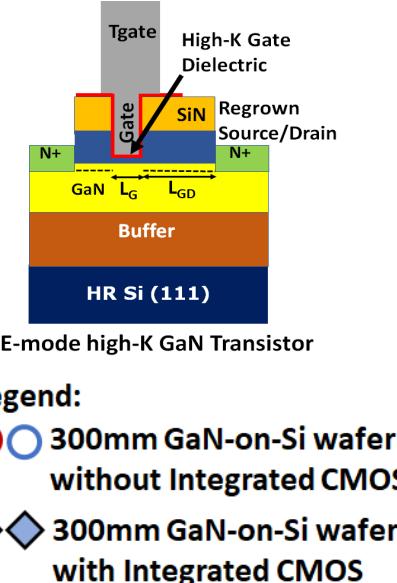
H. Then, VLSI2020

- Transistor high frequency performance

- High  $f_{MAX}$  and  $f_T$  wo. FP
- Record  $f_{MAX}$  of 680GHz w. source FP

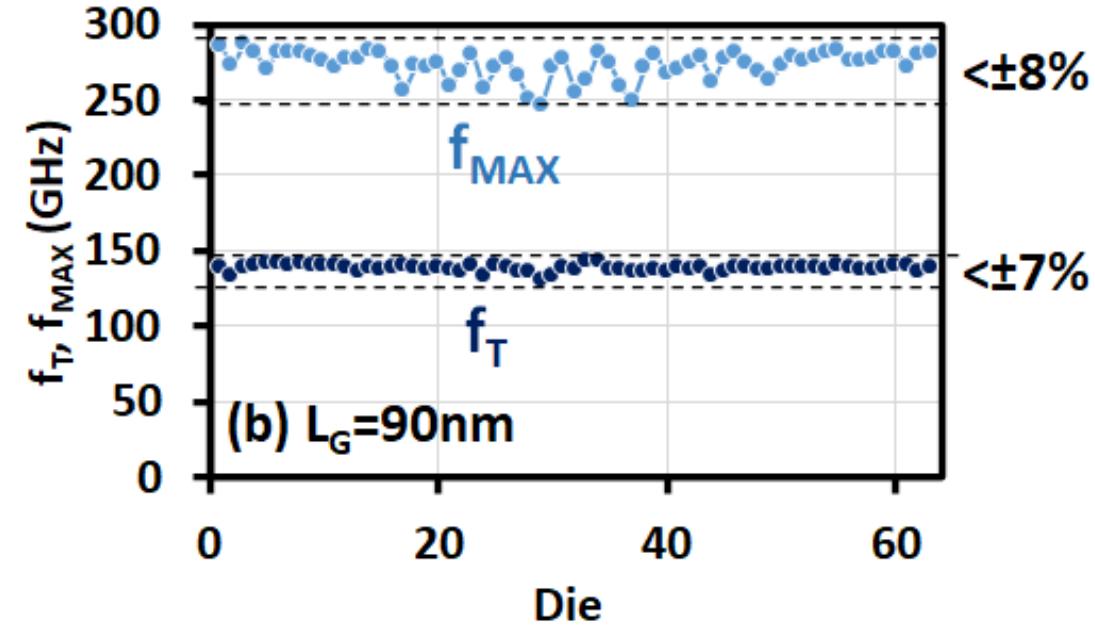
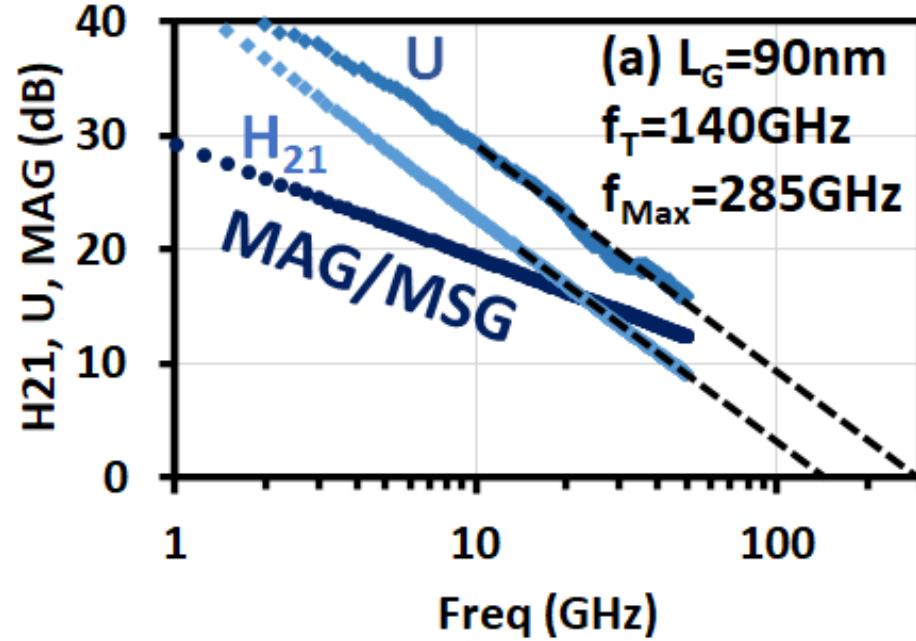


H. Then, IMS2023



H. Then, IEDM2022

- Transistor selected for this work
  - $L_G=90\text{nm}$
  - Neutralized differential pair to enhance  $f_T$

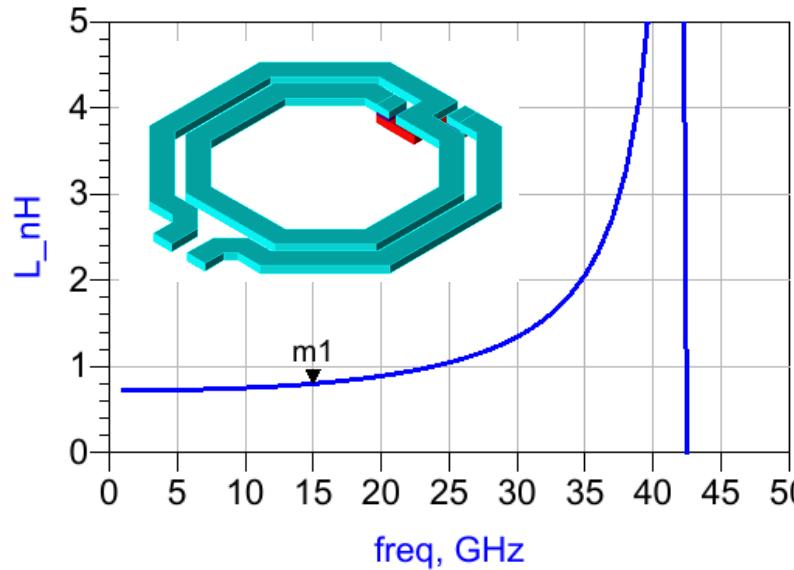


U: unilateral gain

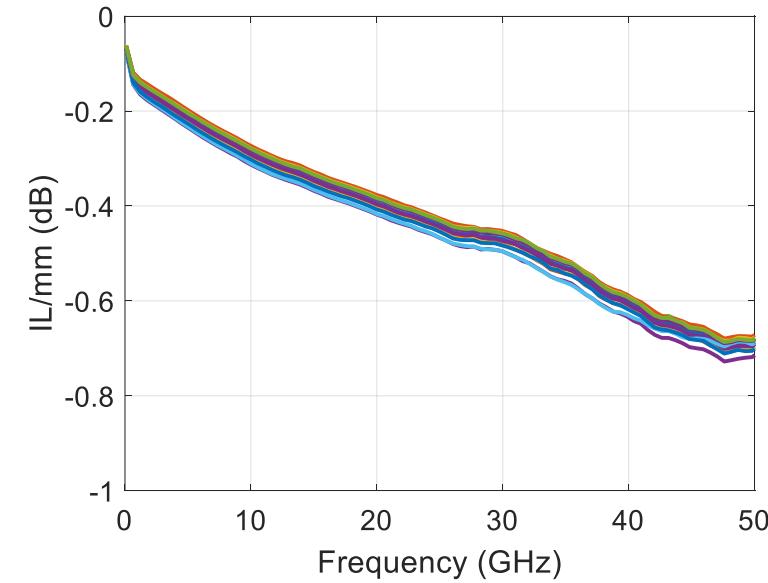
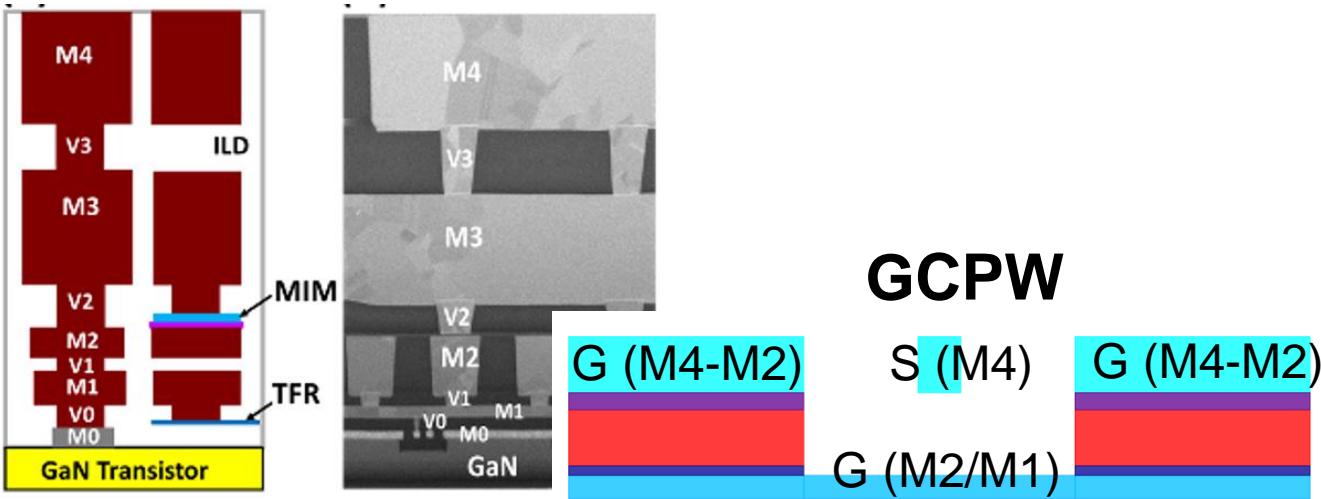
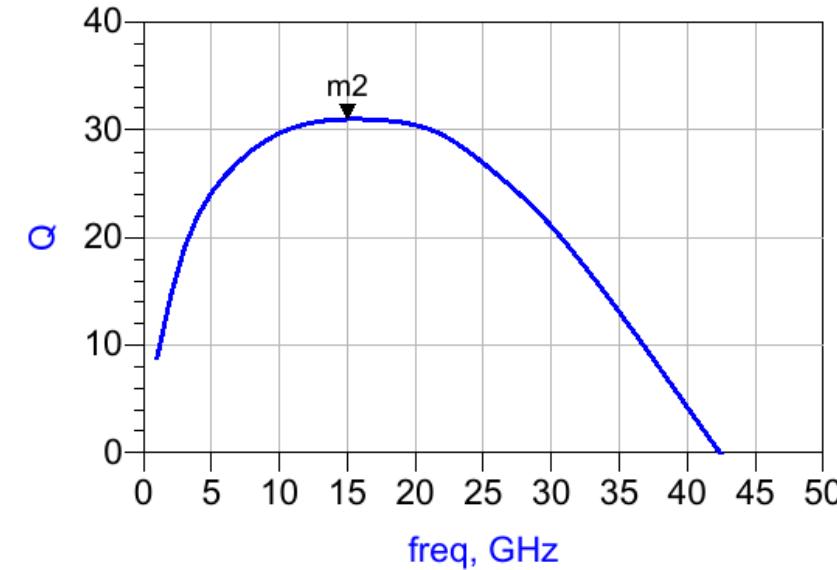
## • RF optimized BEOL

- High res ( $>1000\Omega\text{-cm}$ ) substrate
- High Q inductor/transformer
- Low loss transmission line

m1  
freq=15.0GHz  
 $L_{nH}=0.80$



m2  
freq=15.0GHz  
Q=30.98

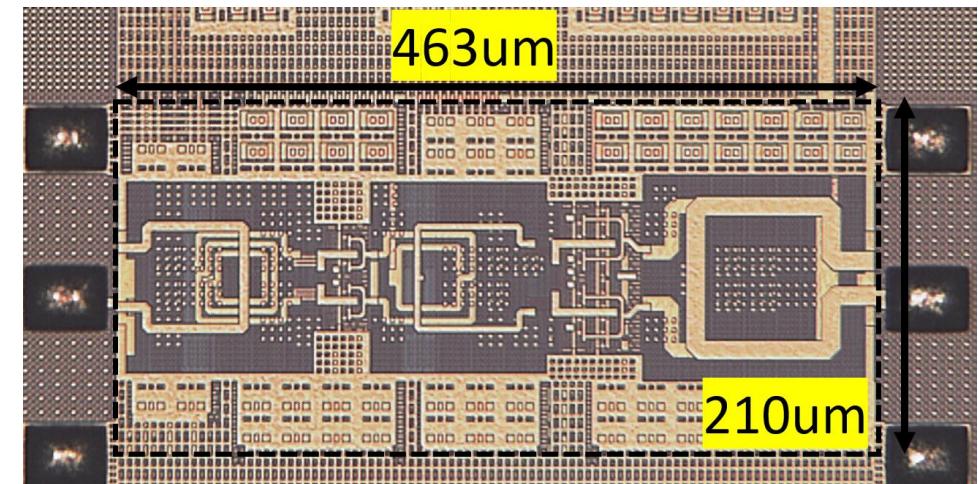
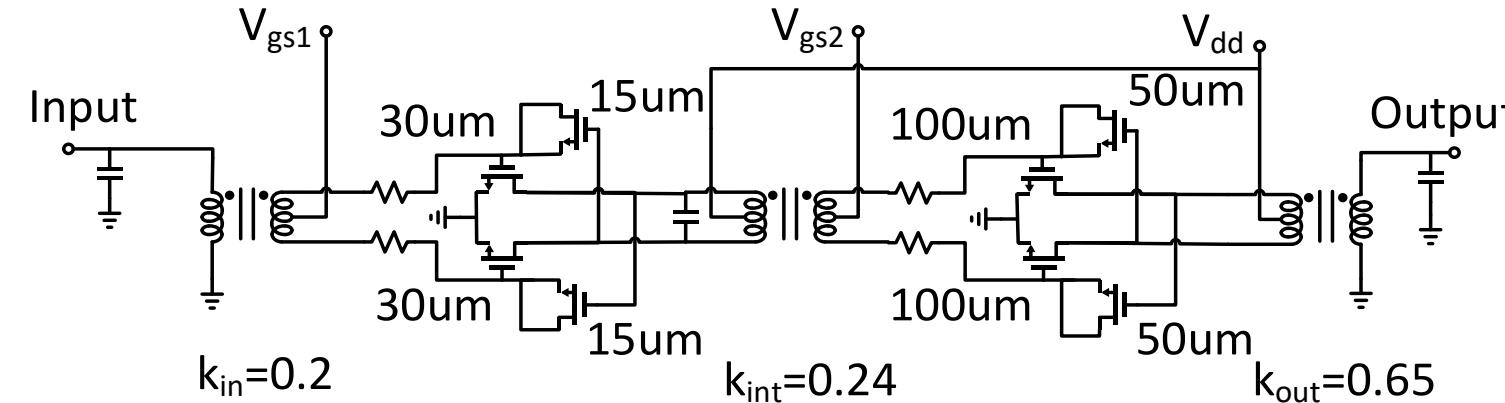


- If interested in knowing more technology details -
  - Tu2B-1, “Enhancement-mode 300mm GaN-on-Si(111) with integrated Si CMOS for future mm-Wave RF applications,” **IMS\_MWTL 2023**.

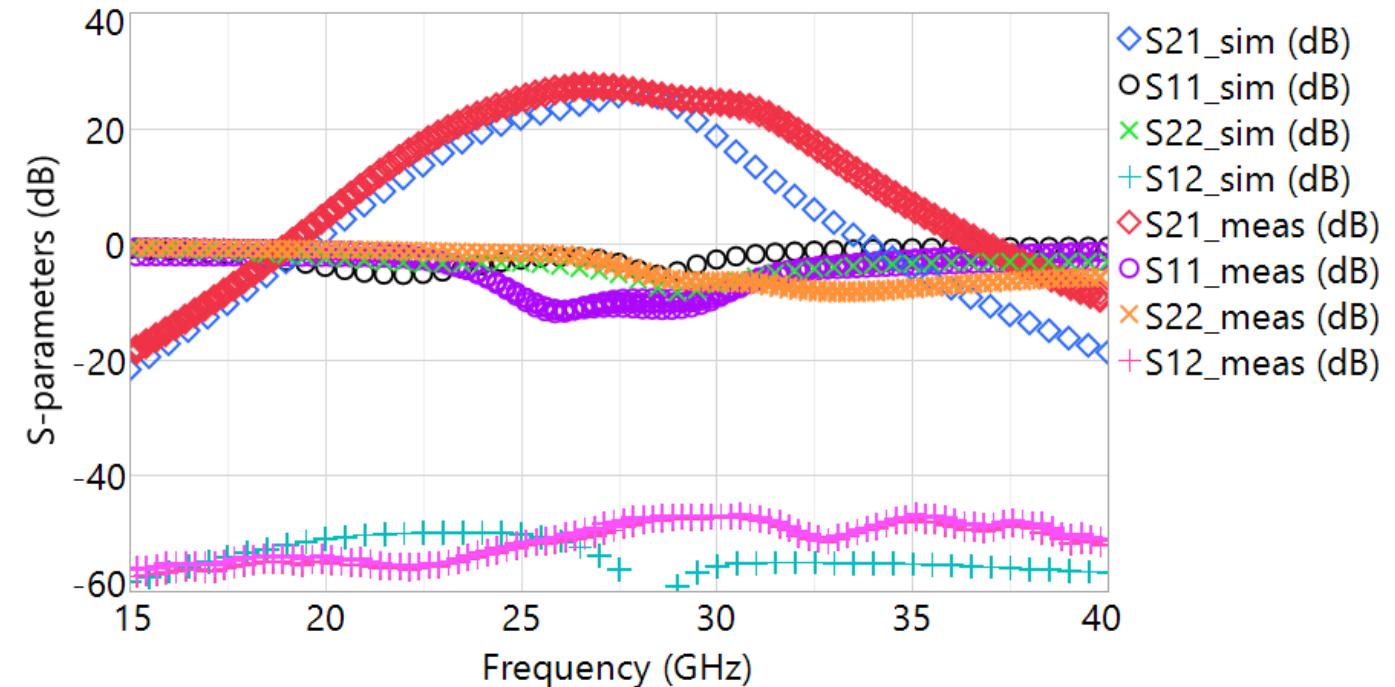
# Outline

- Introduction
- 300mm E-mode GaN MOS-HEMT technology
- mmWave power amplifier implementation
- Measurement results
- Conclusion

- 2-stage class-AB PA
  - Neutralized differential pair (transistor as neutralization cap)
  - Probe pad absorbed into matching
  - Compact layout

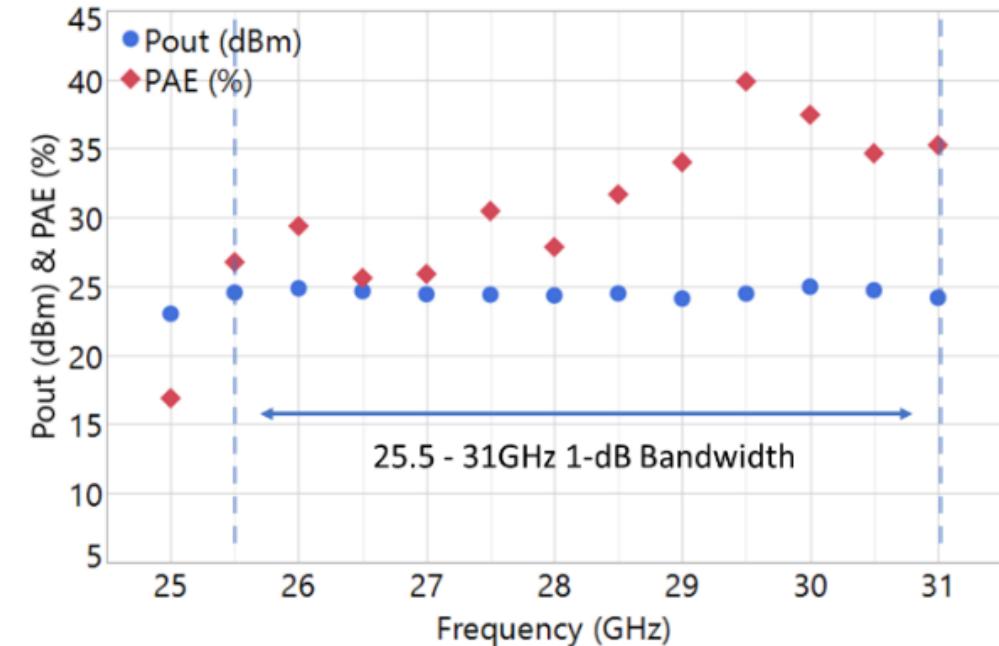
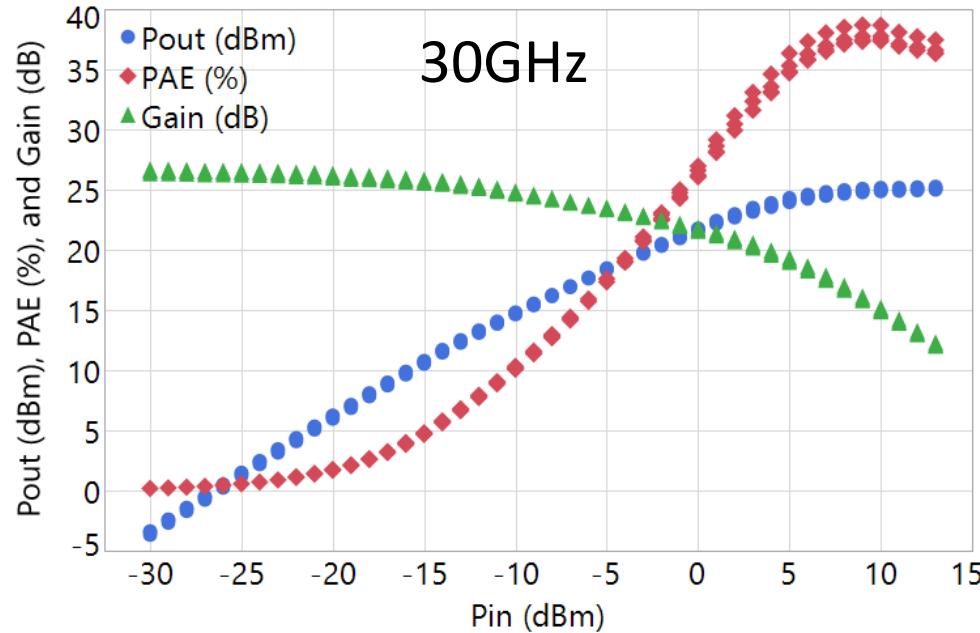


- Small-signal performance
  - 4 dies measured
  - Reasonable agreement w. simulation.



# Power Amplifier Measurements II

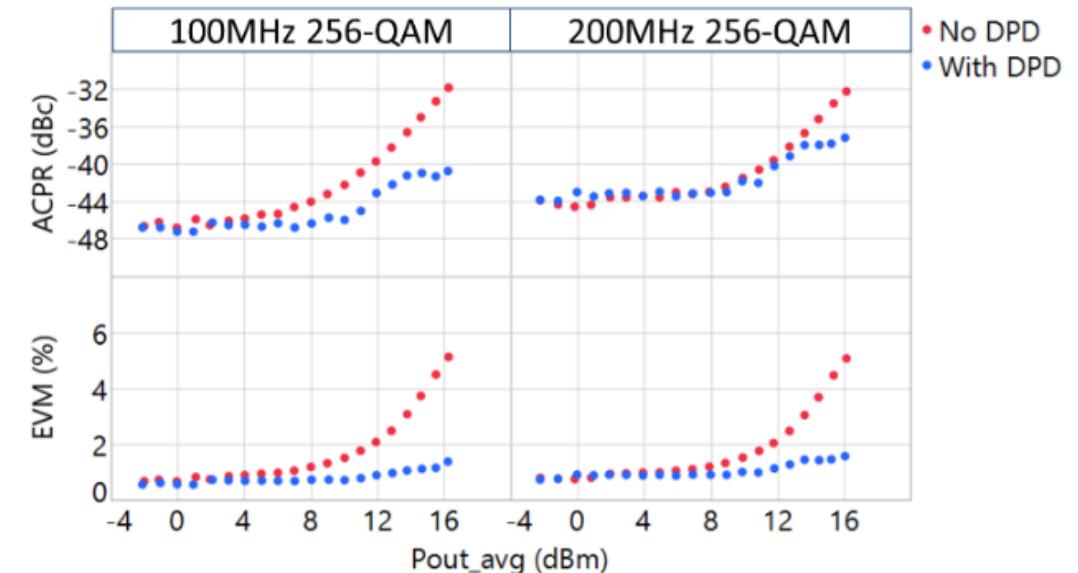
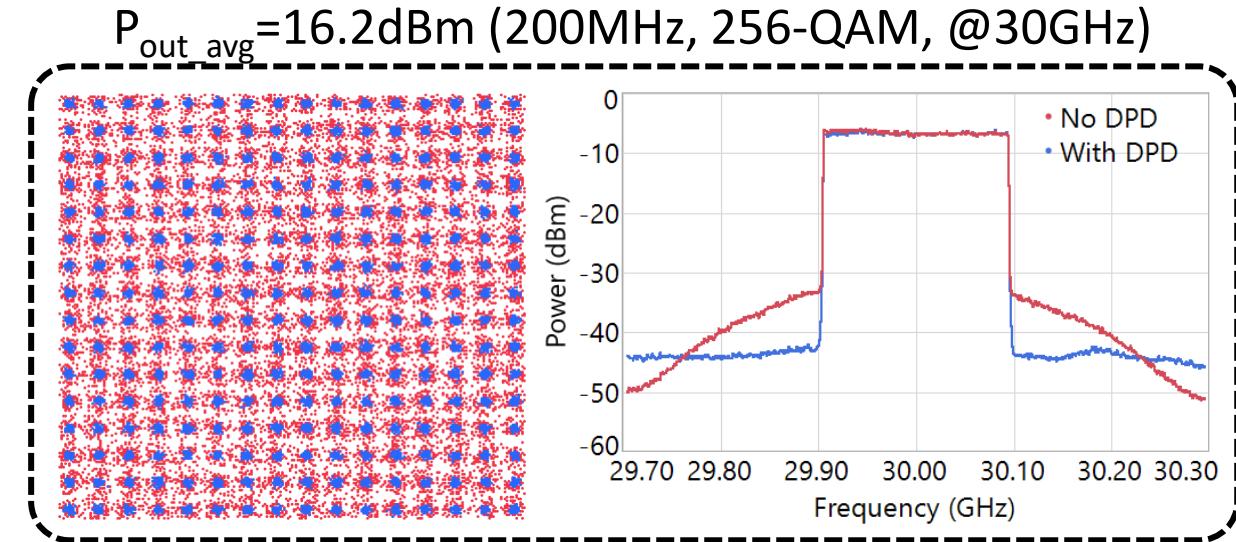
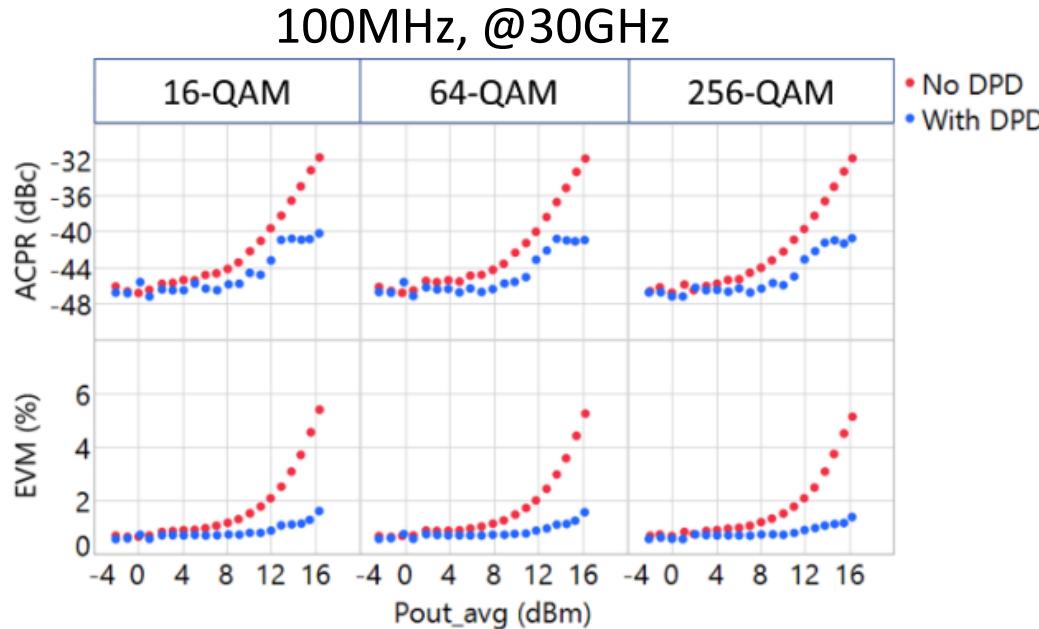
- Large-signal performance
  - Covers both n257 (26.5-29.5GHz) and n261 (27.5-28.35GHz) bands.



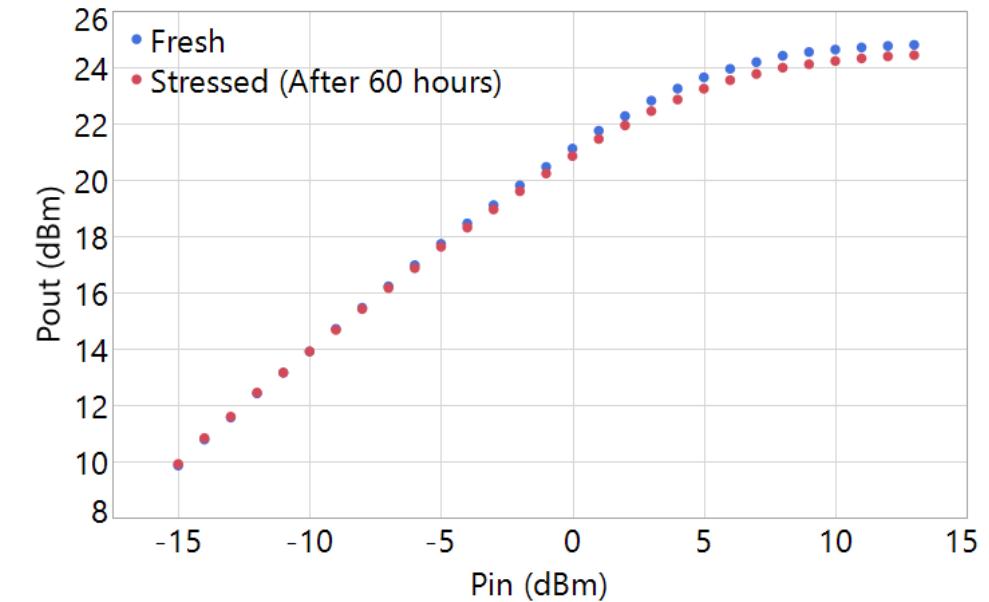
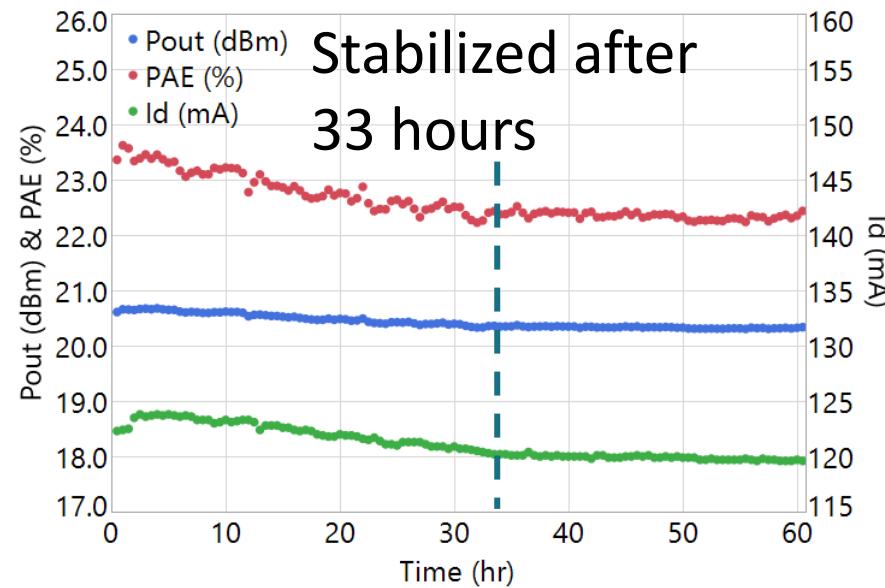
# Power Amplifier Measurements III

- Modulated measurements

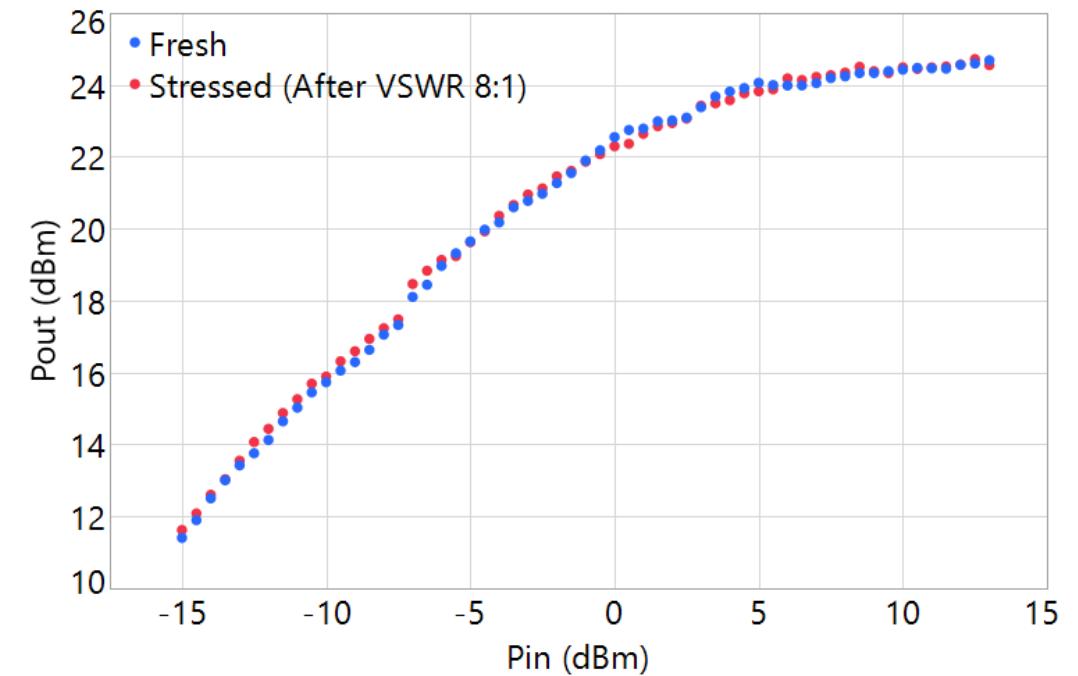
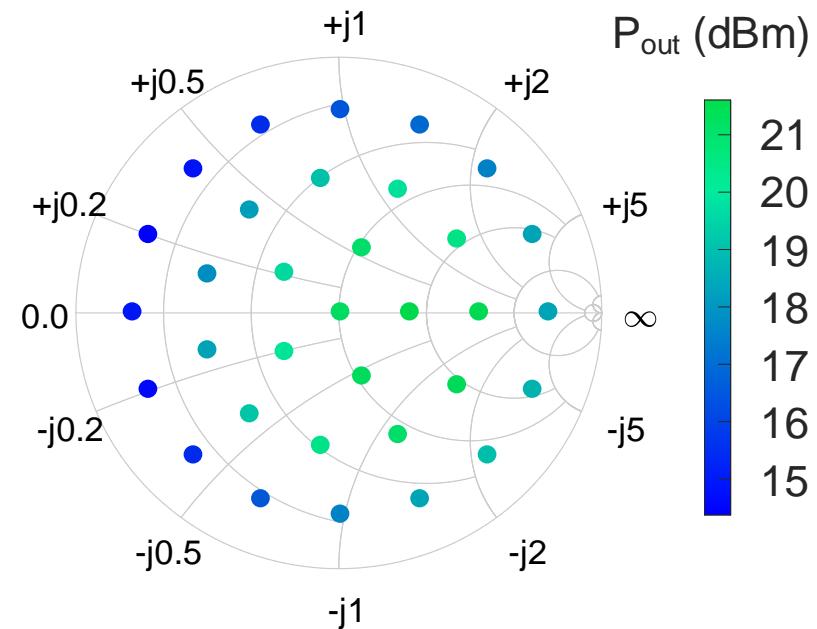
- 30GHz,  $P_{avg}$  up to 16.2dBm
- 5G NR FR-2 signals - 16-/64-/256-QAM (100MHz, 11.7dB PAPR)
- 5G NR FR-2 signals - 100MHz/200MHz (256-QAM, 11.7dB PAPR)



- Aging test
  - 30GHz CW @OP4dB, 60 hours
  - $P_{out}$ , PAE, and  $I_D$  reduced by 0.2dB, 1%, and 2mA in the first 33 hours, stabilized thereafter.



- Ruggedness test
  - 30GHz CW @OP4dB, VSWR up to 8:1
  - Fresh vs. stressed results show no significant degradation





- Higher P<sub>sat</sub> and linear gain
- Significantly higher PA FOM with smallest area

} FEOL and BEOL RF DTCO

	This work	Chuang, RFIT2021	Tsai, RFIC2021	Wang, JSSC2019	Asoodeh, JSSC2021
Technology	E-mode GaN MOS-HEMT on 300mm Si <sup>#</sup>	0.15μm GaAs pHEMT	0.13μm SiGe	45nm RF SOI	65nm CMOS
Topology	2-stage diff.	2-stage differential	Diff. cascode	Mixed-Signal Doherty	4-way combining
V <sub>DD</sub> [V]	4	5	3.2	2	2.2
f <sub>c</sub> [GHz]	30	27	28	27	28
3-dB bandwidth [GHz]	5.5	5 <sup>\$</sup>	10.5	13.5	3.5
Linear G <sub>p</sub> [dB]	26.6	21.2	19.4	19.1	18
P <sub>sat</sub> [dBm]	25.3	24.4	22.7	23.3	23.2
PAE <sub>max</sub> [%]	38.7	43.4	38.1	40.1	35.5
Modulation	5G OFDM 64-QAM 11.7dB PAPR <sup>&amp;</sup>	5G OFDM 64-QAM N/A	64-QAM 8.3dB PAPR	64-QAM 6.5dB PAPR	64-QAM 8.3dB PAPR
P <sub>out_avg</sub> @EVM/ACPR	16.2	21.3*	16.2	15.9	16.1
EVM [%]	5.2 <sup>&amp;</sup>	3*	5.5	5.4	4.9
ACPR [dBc]	-31.8 <sup>&amp;</sup>	-20 <sup>\$*</sup>	-32	-29.6	-28.3
Core area [mm <sup>2</sup> ]	0.097	2	0.162	0.52	0.2
FOM <sup>+</sup> [dB]	97.3	90.6	86.9	87.1	85.6

<sup>#</sup>Multiple L<sub>G</sub> available; <sup>\$</sup>Estimated; <sup>&</sup>No DPD or CFR; <sup>\*</sup>Equalized results; <sup>+</sup>FOM[dB]=P<sub>sat</sub>[dBm]+G<sub>p</sub>[dB]+10log(PAE<sub>max</sub>[%])+20log(f<sub>c</sub>[GHz])

# Conclusion

- Demonstrated industry's first E-mode GaN MOS-HEMT mmWave circuit in 300mm GaN-on-Si process
  - Reasonable measurements vs. simulation
  - Competitive performance
  - Compact footprint

- Possibilities to explore
  - Monolithic GaN + CMOS system
  - SOI like CMOS

