

Tu2B-1

# Enhancement-mode 300mm GaN-on-Si(111) with Integrated Si CMOS for Future mm-Wave RF Applications

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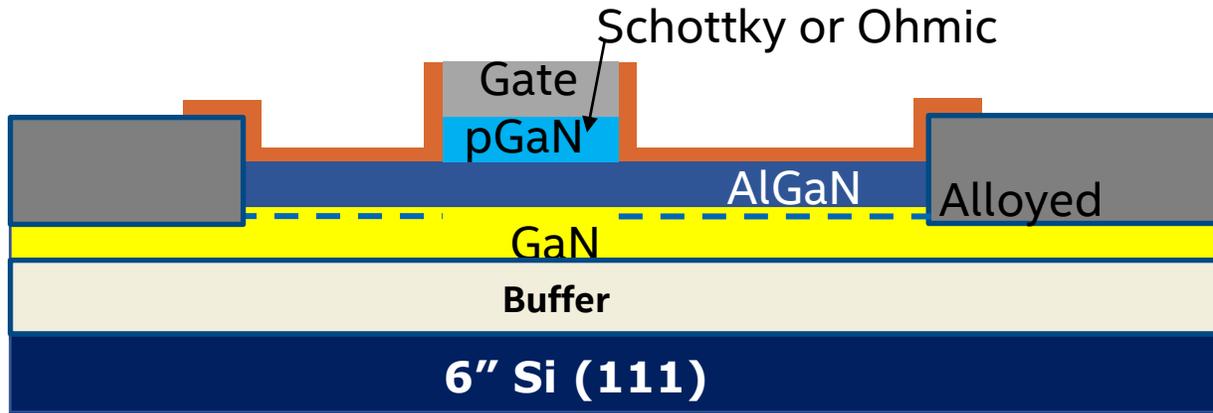
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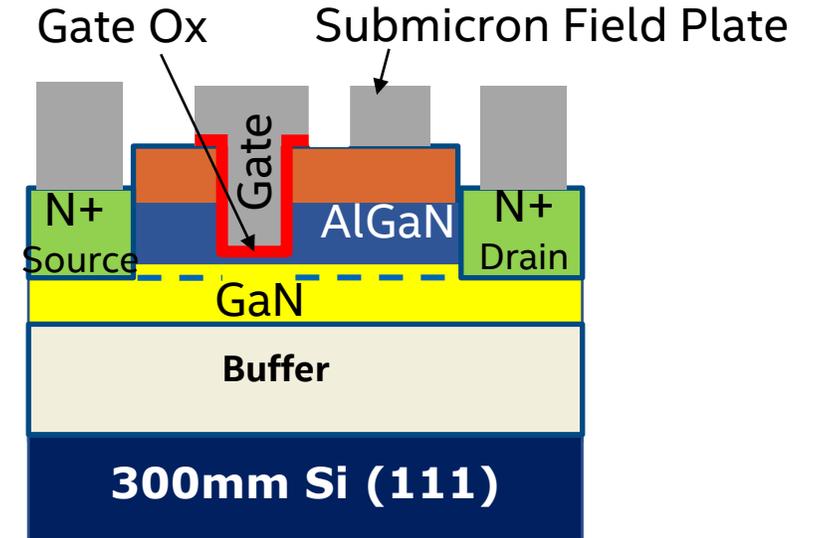
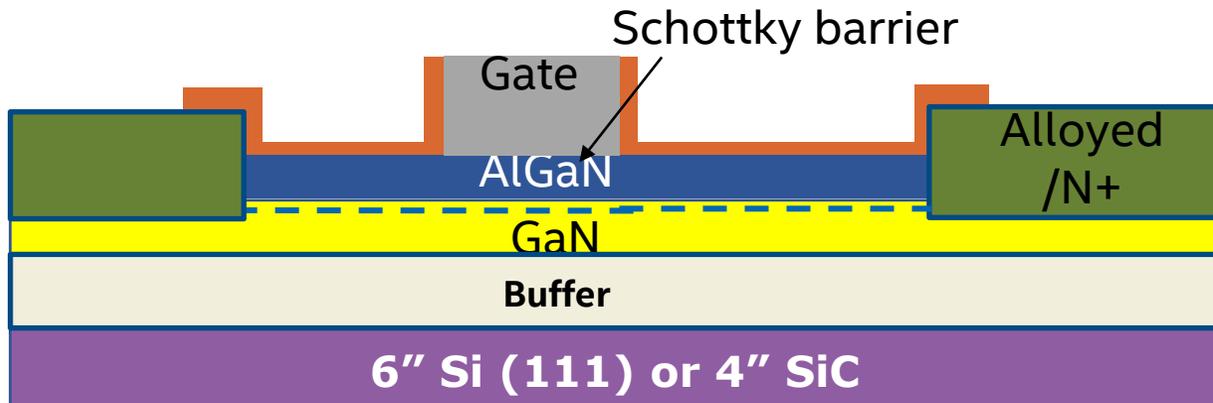
- ❑ E-mode 300mm GaN-on-Si(111)
  - ❑ Process and Device
  - ❑ mm-wave PA with e-mode GaN MOSHEMT
  - ❑ Improving  $f_T/f_{Max}$  and  $BV_D$  in GaN MOSHEMT
- ❑ Integration of GaN and Si CMOS
- ❑ Compact Model Development

# E-mode GaN MOSHEMT

## P-GaN JFET E-mode (Power)



## Schottky HEMT D-mode (RF)

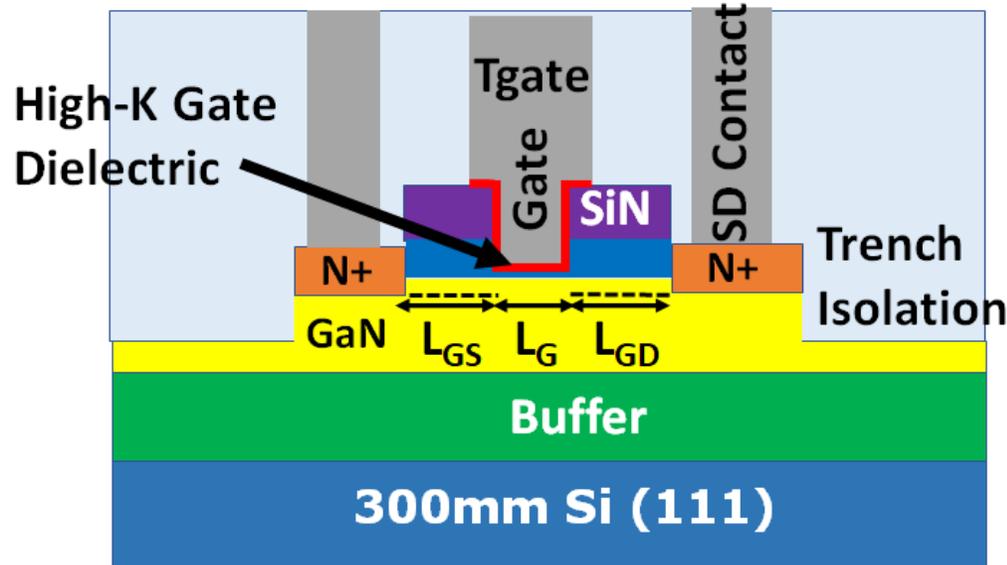


## E-mode MOSHEMT (Power & RF)

- Gate oxide (hi-K), low-leakage  
→ transistor scaling to lg30nm
- Regrown S/D  
→ low R, small contact areas, high density
- Submicron field plate  
→ high voltage, low parasitics
- Gate rel needs research

# E-mode 300mm GaN-on-Si(111) Process and Device

(a) E-mode high-K GaN Transistor



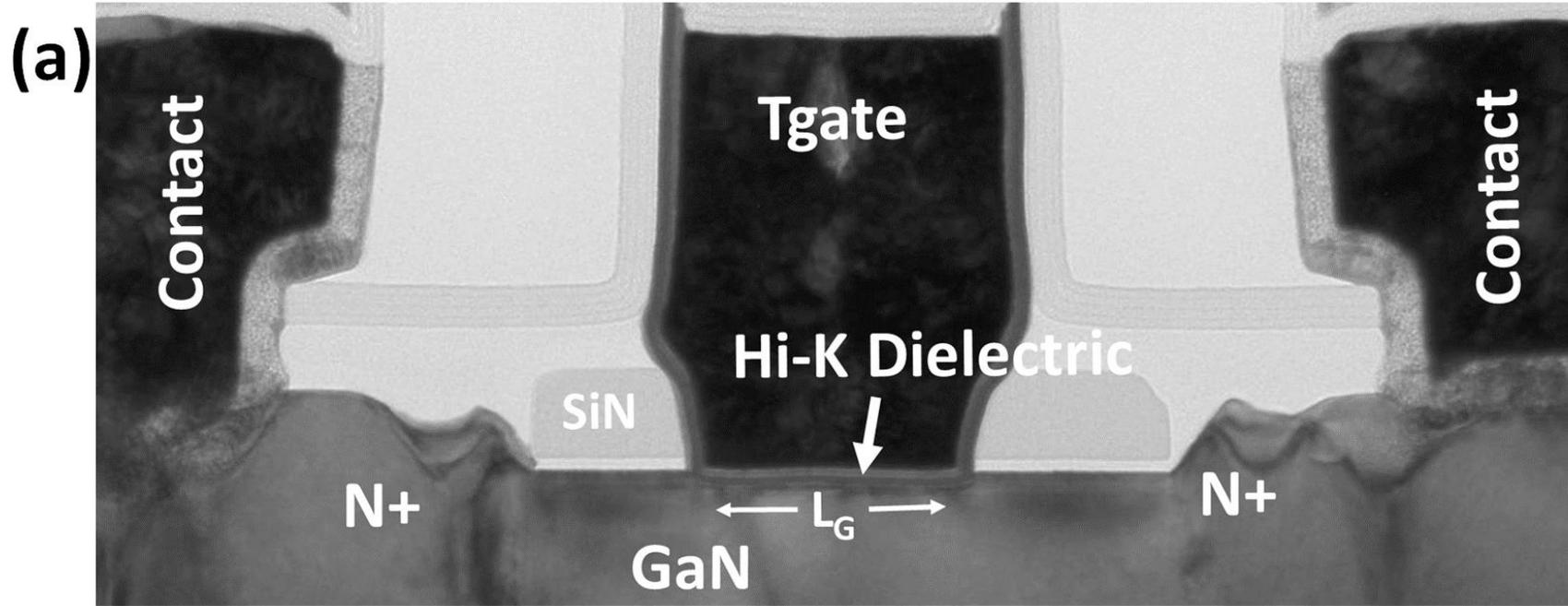
(b) Process Flow

- 300mm GaN Epitaxy by MOCVD
  - Trench Isolation and Dielectric Fill
  - Passivation
  - Epitaxial regrowth of III-N Source/Drain
  - Formation of Dummy Gate
  - Gate Recess by ALE<sup>#</sup>
  - High-K Gate Dielectric by ALD<sup>#</sup>
  - Metal Gate-Last and T-Gate Formation
  - Source/Drain Contact Formation
  - Cu Damascene BE Metal Layers and Vias
- <sup>#</sup>step is skipped for D-mode Schottky GaN HEMT*

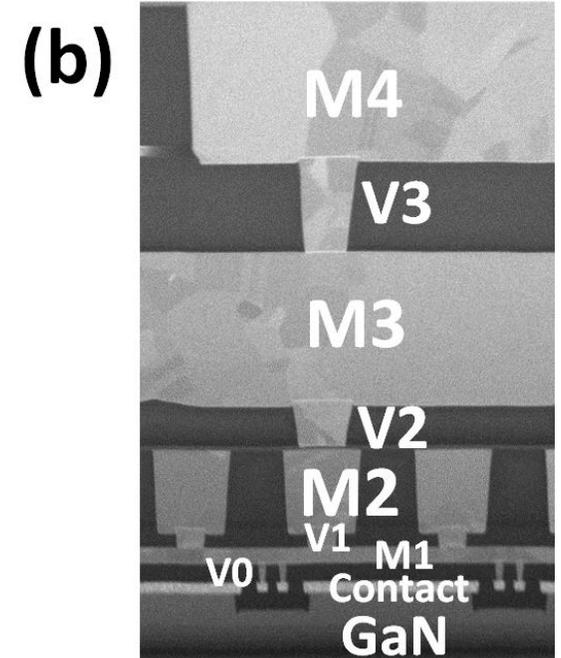
Process steps unique to this technology:

- 300mm GaN MOCVD epitaxy, epitaxial regrowth of III-N source/drain
- Deep UV (DUV) 193nm lithography
- Atomic layer processing: ALE, ALD high-k
- Metal gate-last process, and Cu damascene BE metal

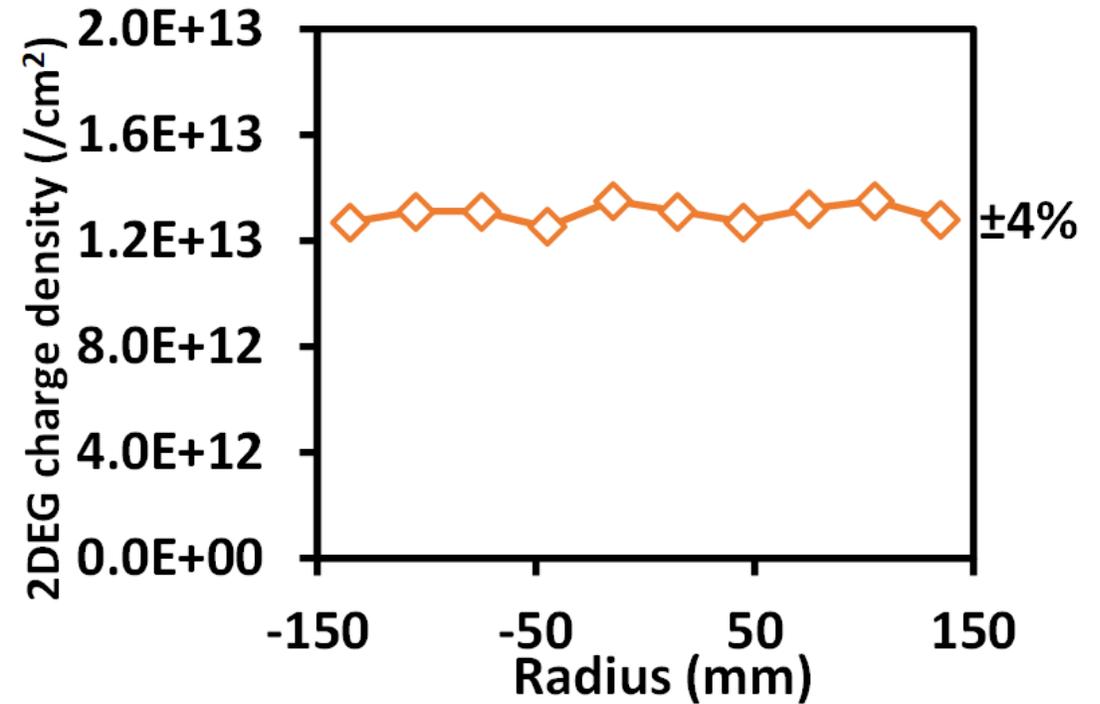
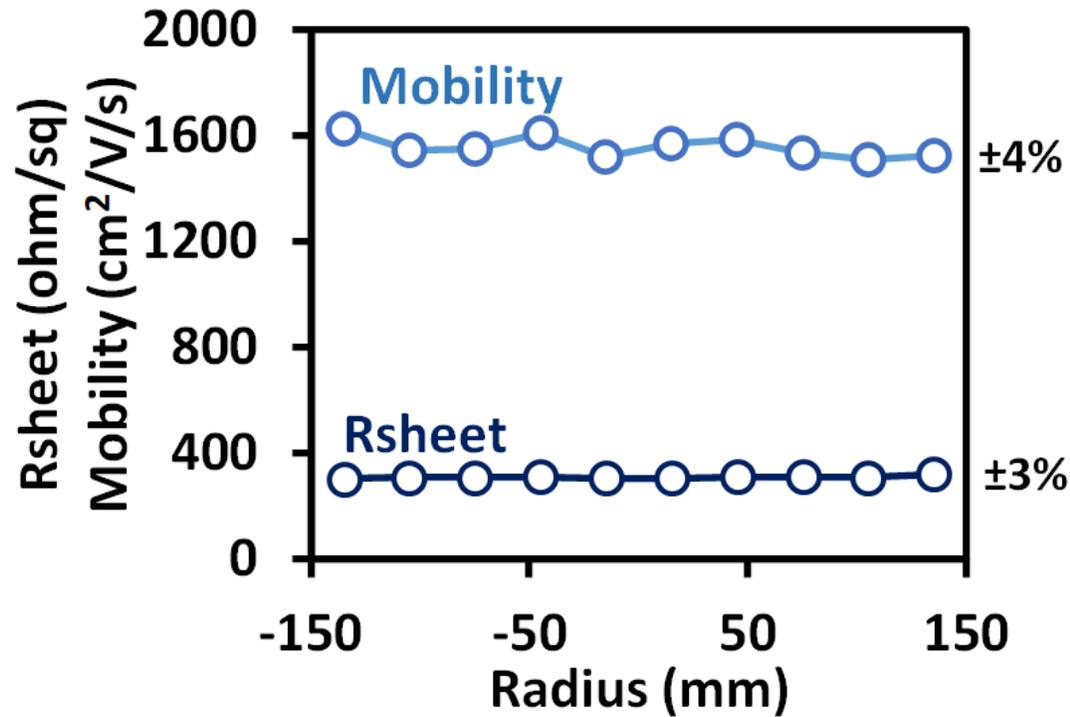
# E-mode 300mm GaN-on-Si(111) Process and Device



$$L_G/L_{GS}/L_{GD} = 90/80/80\text{nm}$$



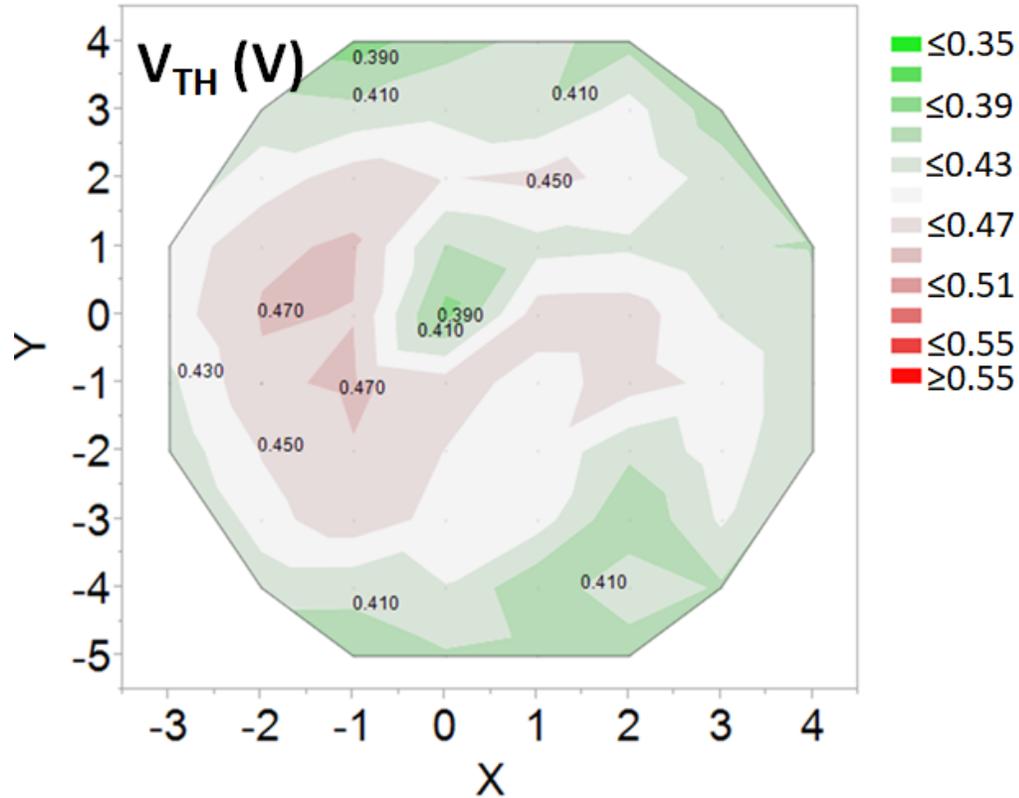
# 300mm GaN-on-Si(111) MOCVD Epitaxy



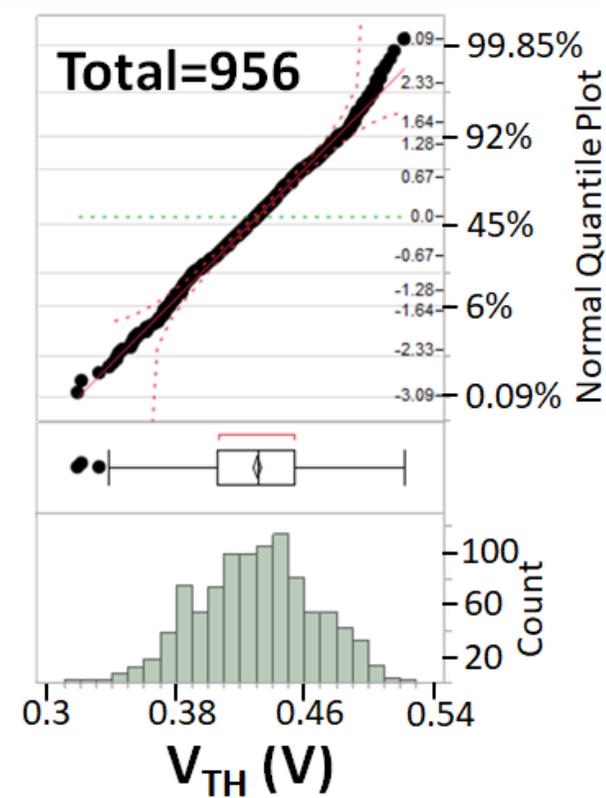
**Excellent Uniformity across 300mm wafer**

# 300mm GaN-on-Si(111) $V_{TH}$ Uniformity

(a)  $L_G=90\text{nm}$ ,  $L_{GS}=80\text{nm}$ ,  $L_{GD}=80\text{nm}$

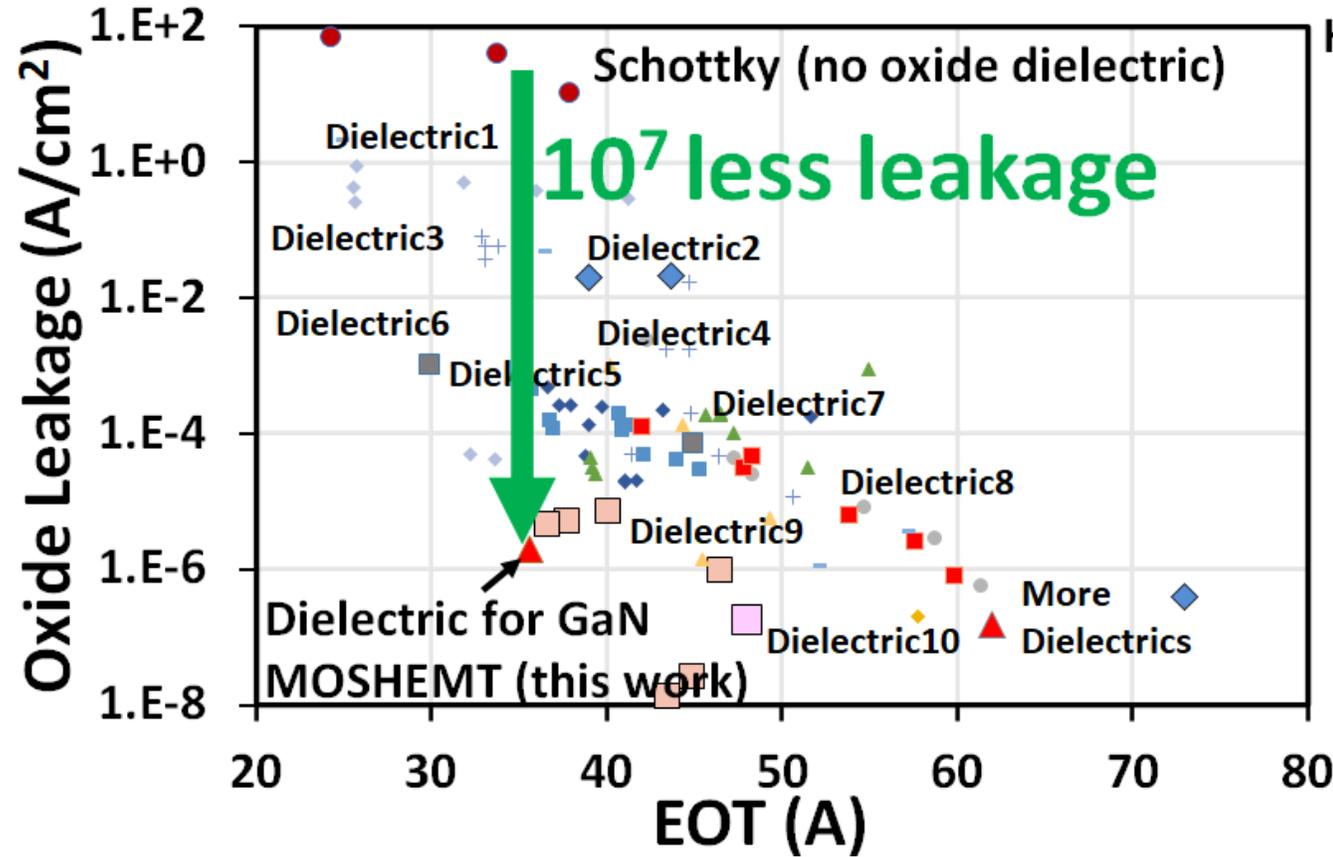


(b)  $V_{TH1\sigma}=35\text{mV}$

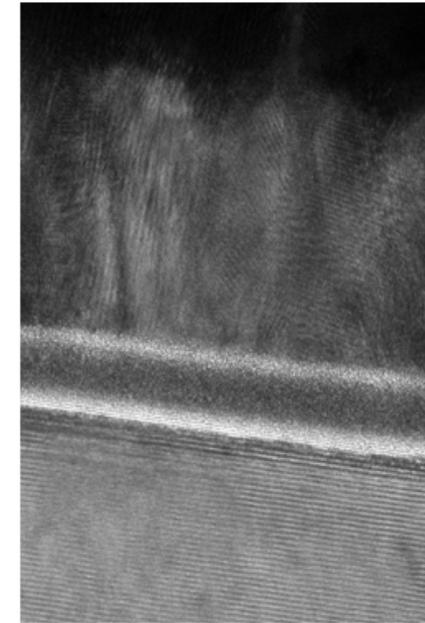


**Excellent Uniformity across 300mm wafer**

# High-K Gate Dielectric For GaN MOSHEMT



High-K Metal Gate Stack



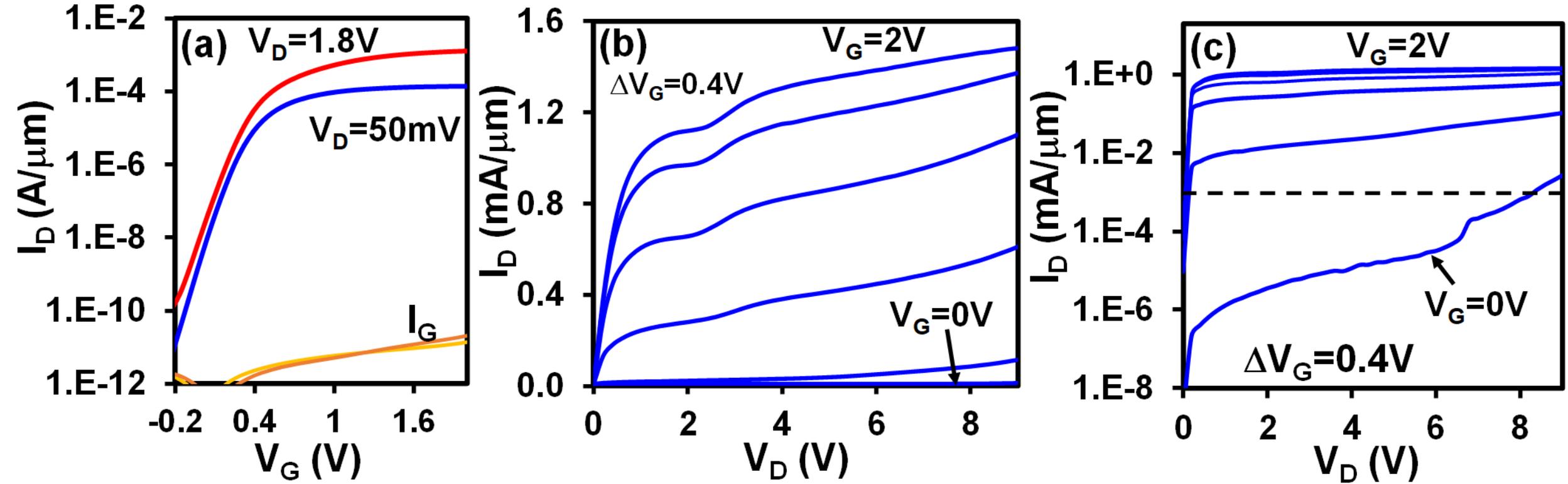
TiN  
HfO<sub>2</sub>  
Al<sub>2</sub>O<sub>3</sub>  
AlN  
GaN

Ref [7]

Low leakage with MOS gate vs Schottky gate

# High-K Gate Dielectric GaN MOSHEMT

## I-V Characteristics

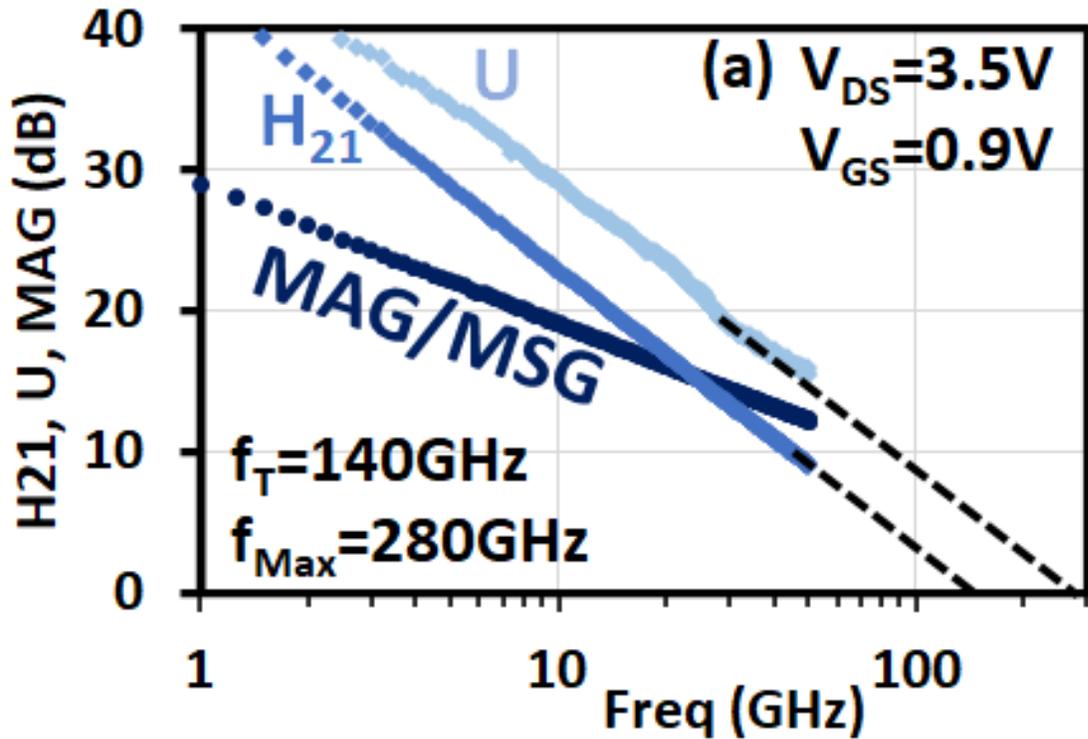


$L_G/L_{GS}/L_{GD}=90/80/80nm$

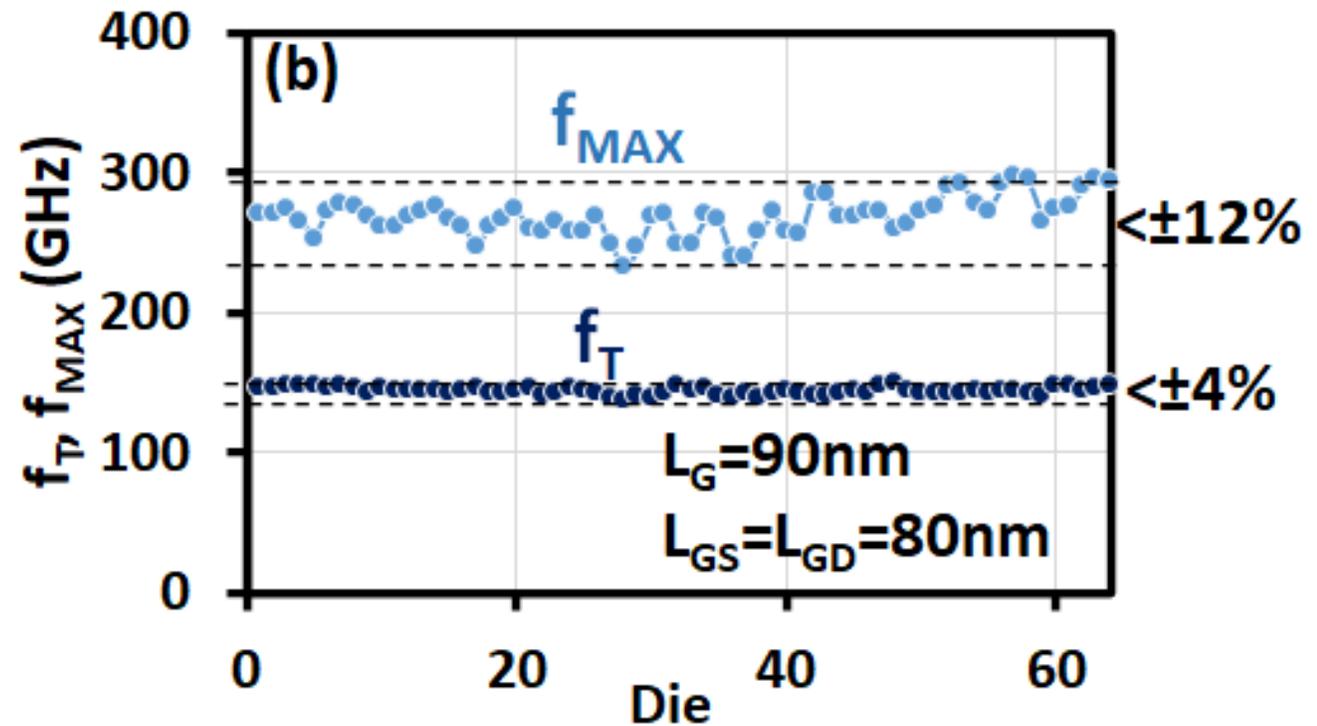
High drive current  
 Low  $R_{ON}$

$BV_{DS} \sim 8.4V$

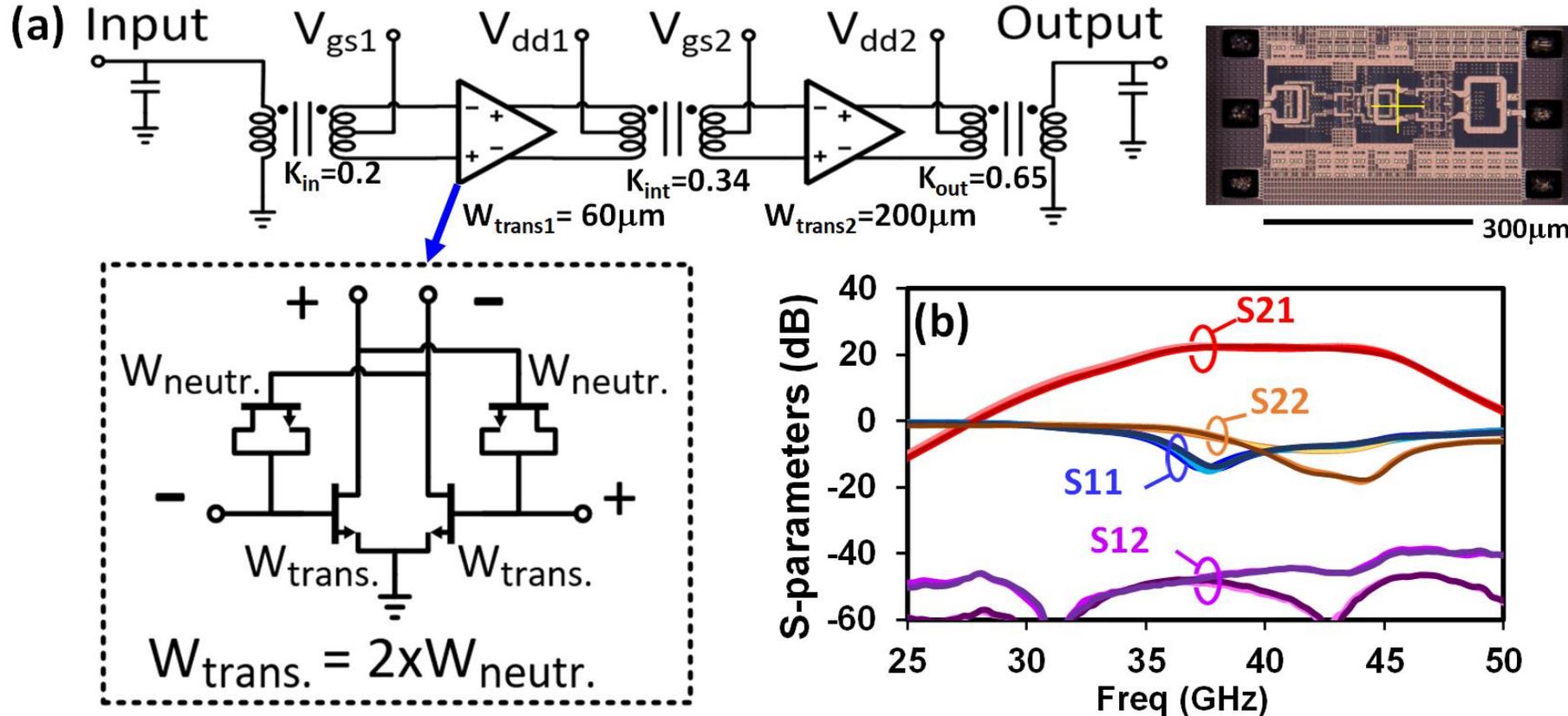
# High-K GaN MOSHEMT RF Characteristics



$L_G/L_{GS}/L_{GD}=90/80/80nm$

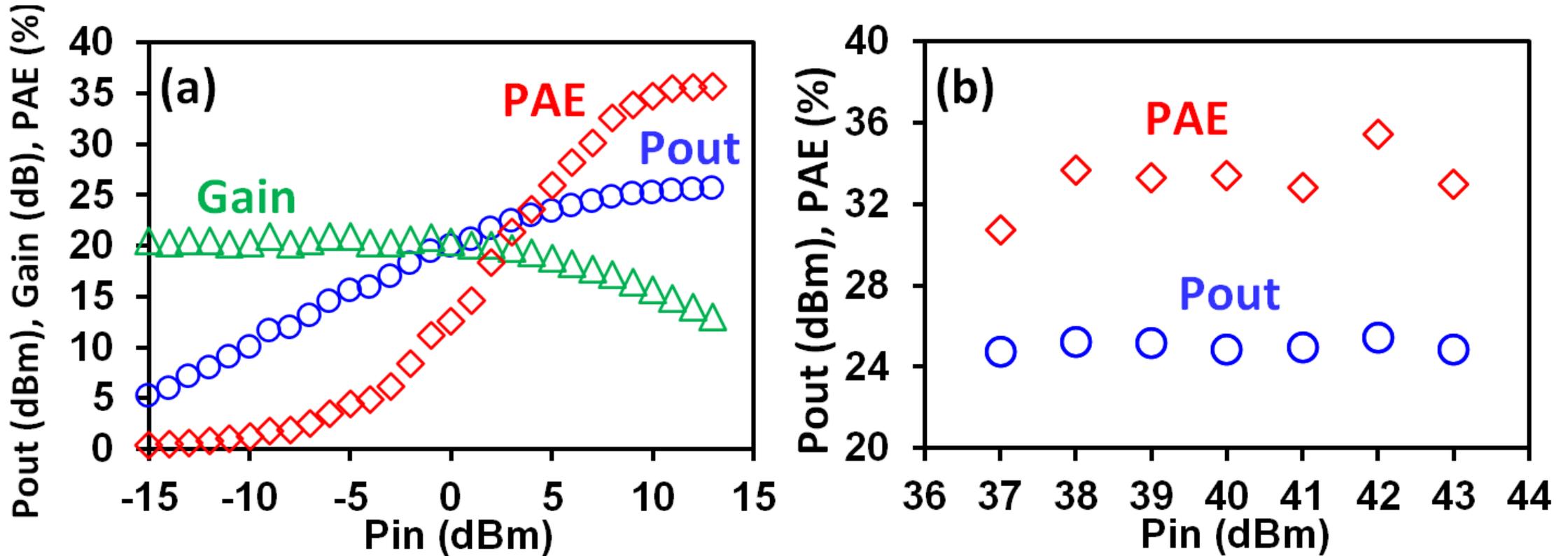


# 1<sup>st</sup> mm-wave PA in High-K GaN MOSHEMT on 300mm GaN-on-Si(111)



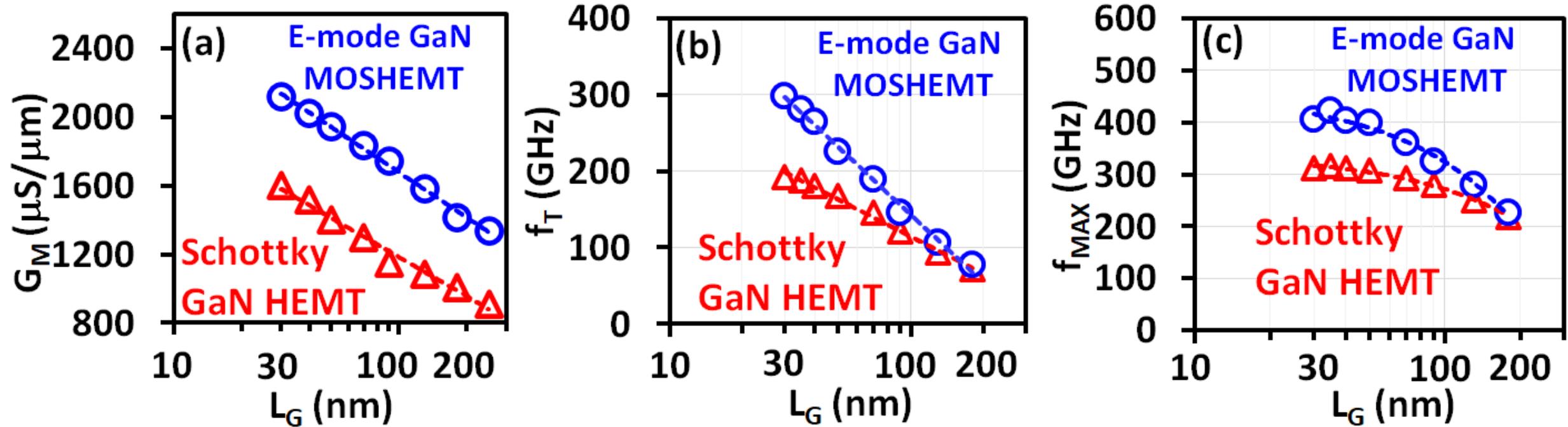
Peak  $S_{21}=25.6\text{dB}$  at  $35.3\text{GHz}$  with a 3-dB bandwidth from  $33.1$  to  $42.8\text{GHz}$  (fractional BW 25.6%)

# 1<sup>st</sup> mm-wave PA in High-K GaN MOSHEMT on 300mm GaN-on-Si(111)



$f=42\text{GHz}$ :  $P_{\text{sat}}=25.6\text{dBm}$ , peak PAE=35.7%, linear gain=20.5dB,  $OP_{1\text{dB}}=22.9\text{dBm}$

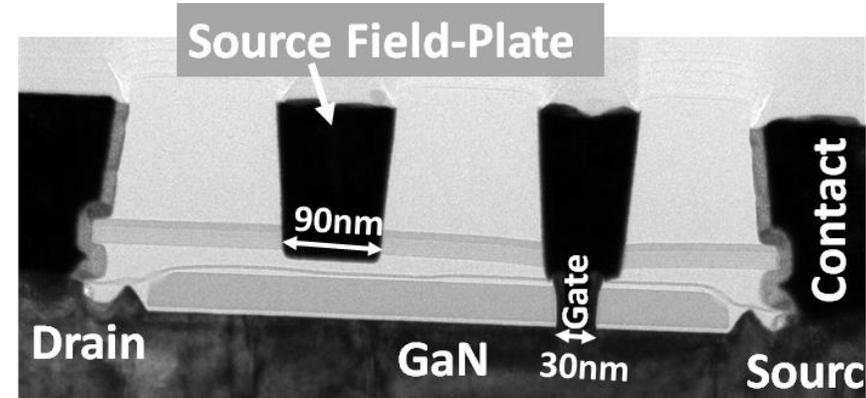
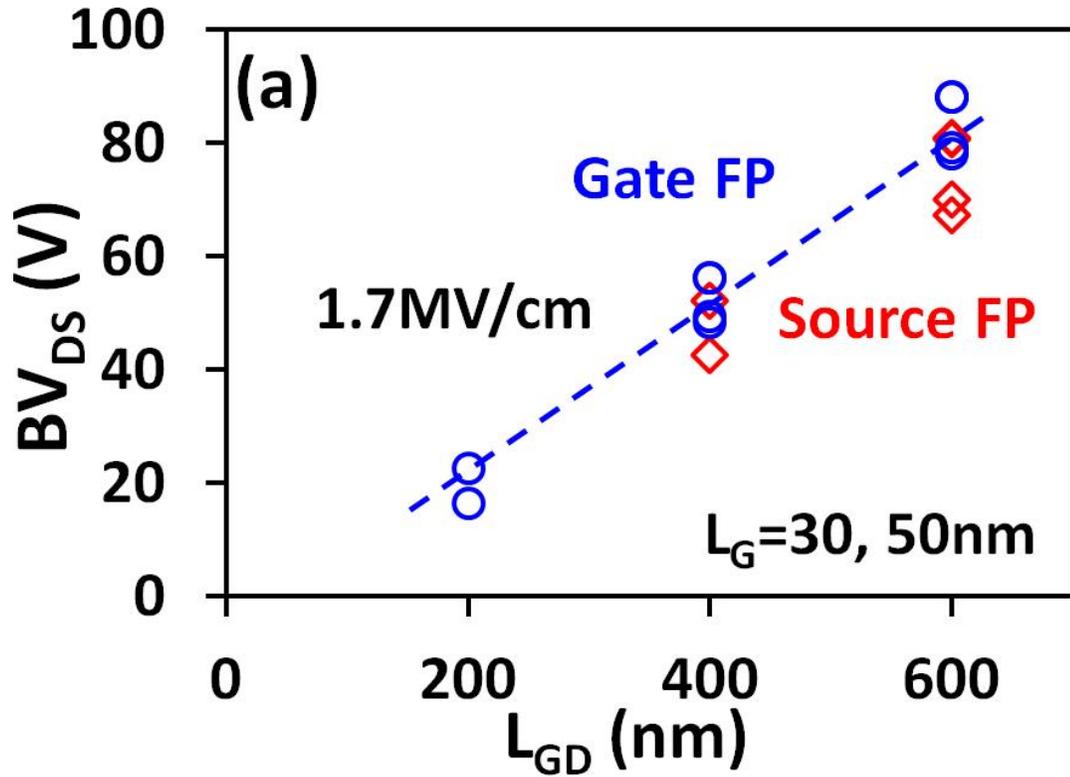
# High-K GaN MOSHEMT vs Schottky HEMT



$L_{GD} = 160\text{nm}$

- GaN MOSHEMT uses thin EOT of  $14.8\text{\AA}$
- Scaling of  $L_G$  to improve  $f_T/f_{MAX}$

# Thin Gate Dielectric and High-Voltage



E-mode high-K GaN Transistor (Source Field-Plate)



E-mode high-K GaN Transistor (Gate Field-Plate)

- Extended drain,  $L_{GD}$
- Source/Gate Field-Plate

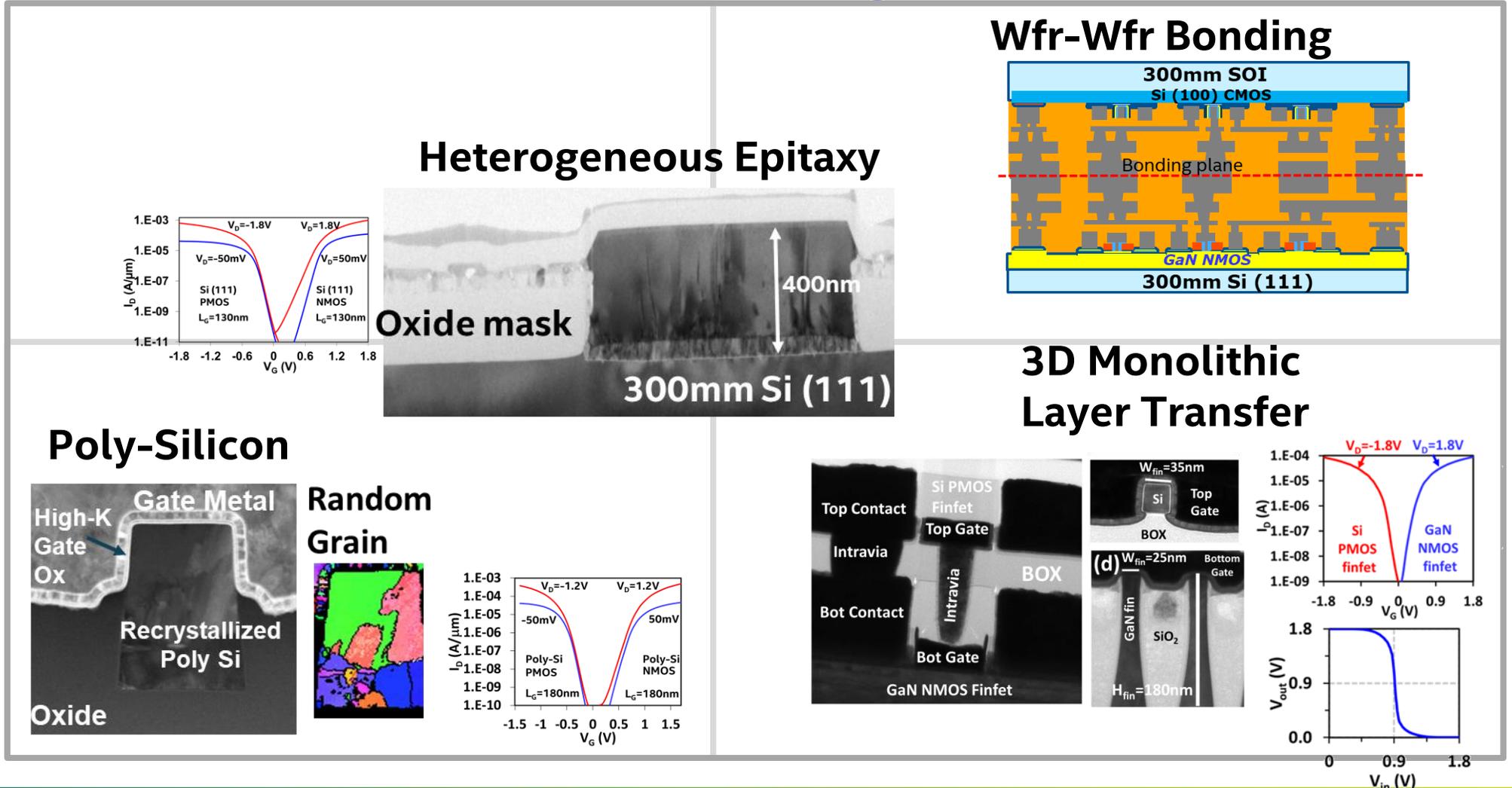
# GaN and Integration of Si CMOS

## Low Performance

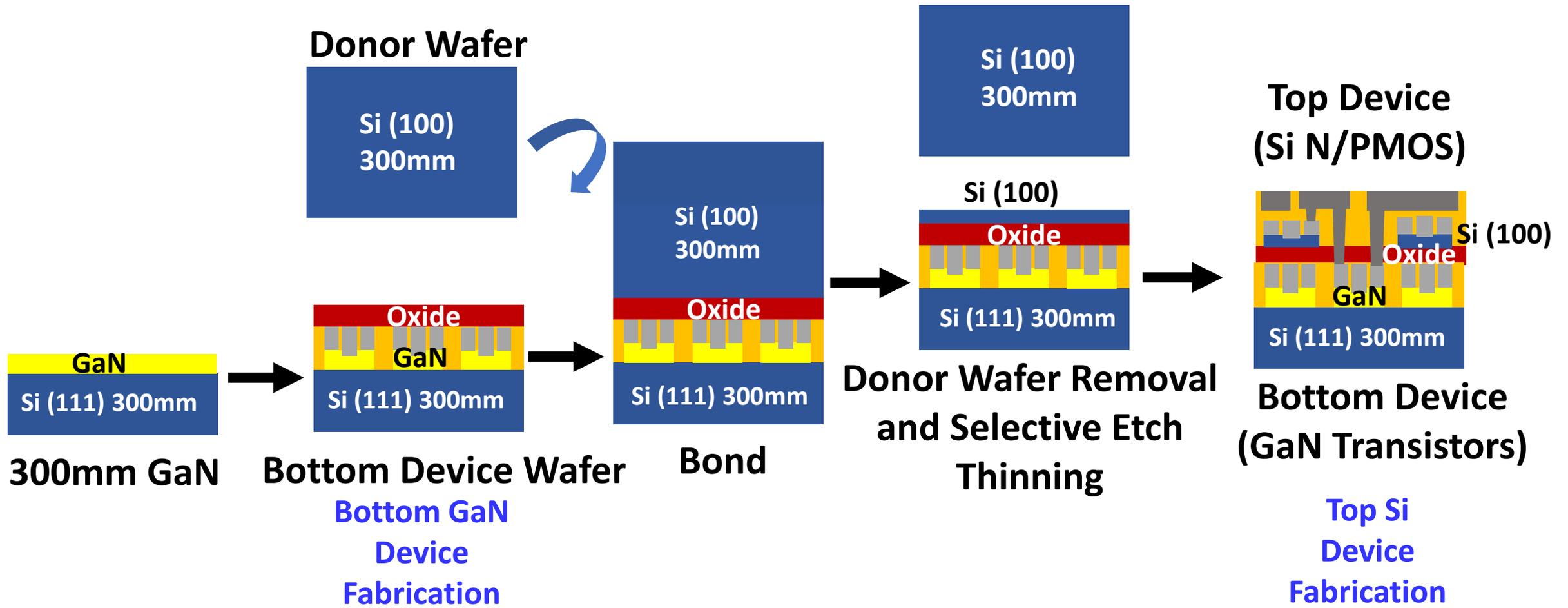
## High Performance CMOS

**Low Density**

**High Density**  
Interconnections between GaN and CMOS

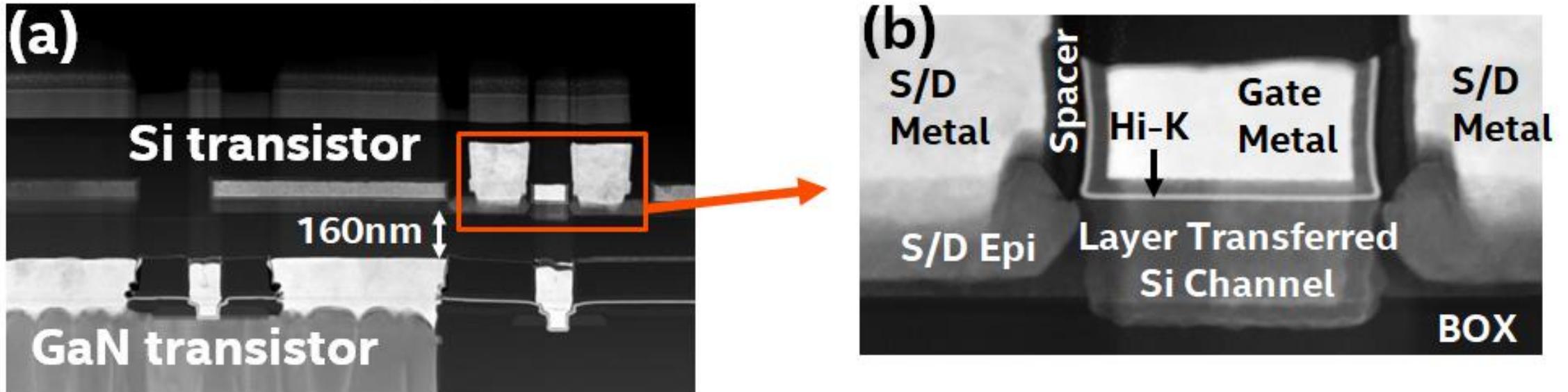


# GaN MOSHEMT and Integration of Si CMOS



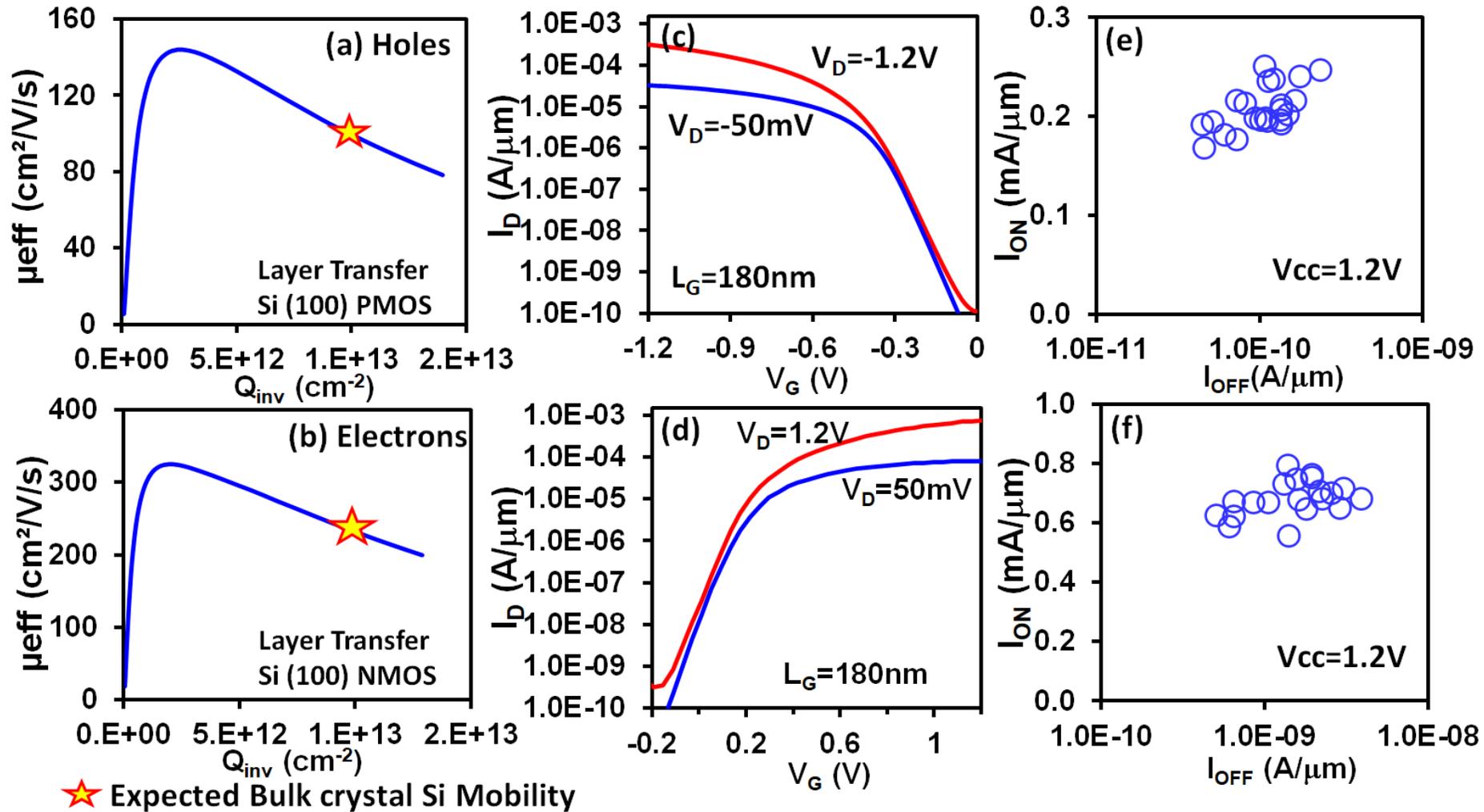
# GaN MOSHEMT and Integration of Si CMOS

## 3D Monolithic Layer Transfer

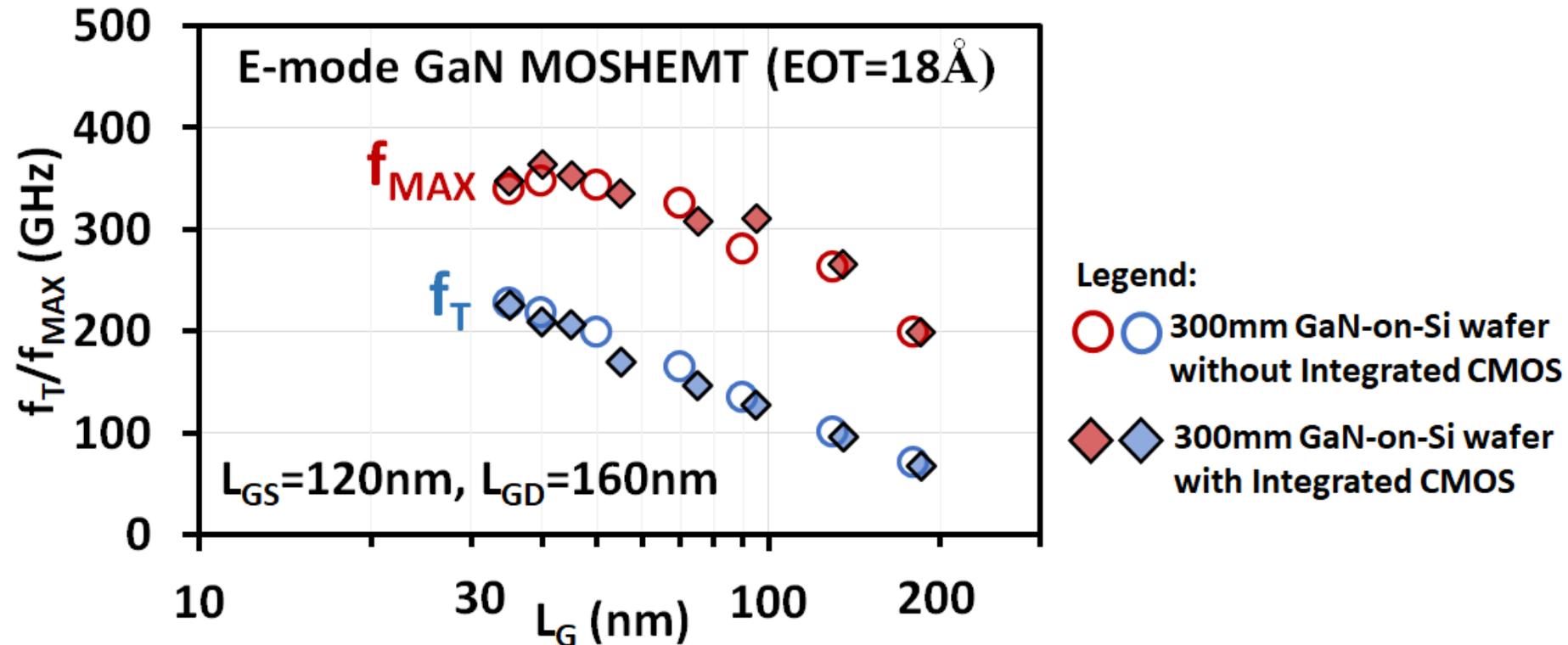


- Submicron proximity placement of CMOS near GaN
- Single-crystalline quality of the silicon channel (high performance)

# Integrated Si CMOS Characteristics

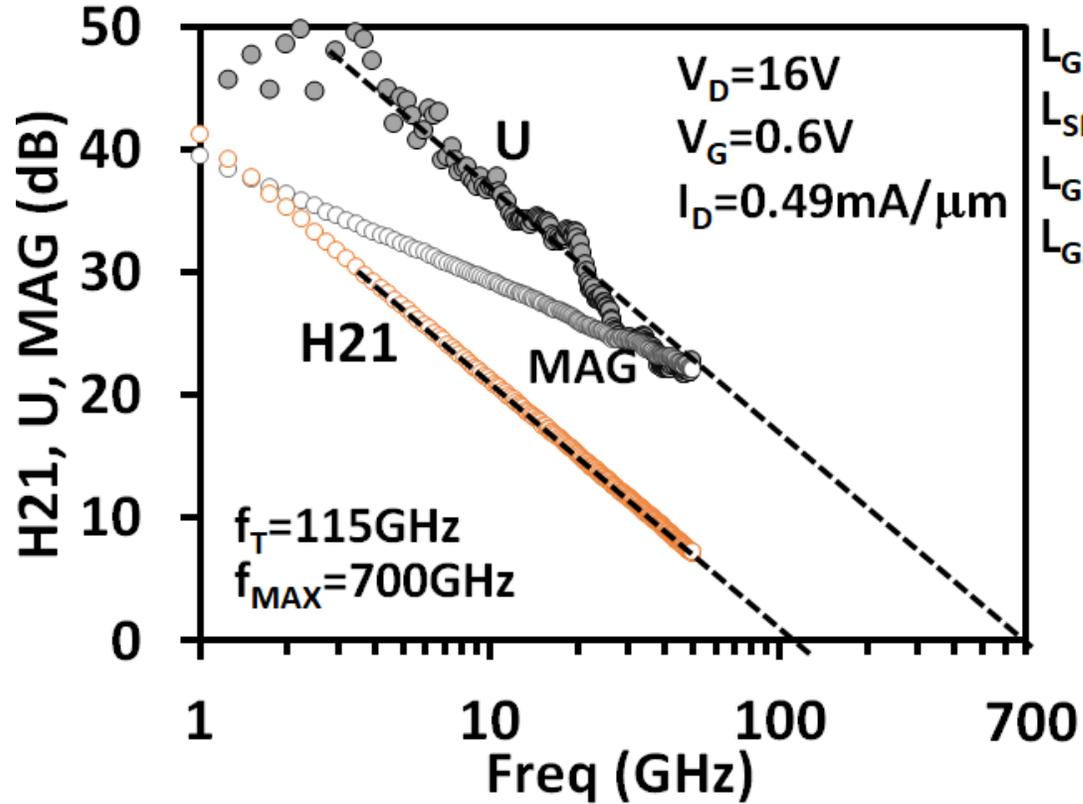


# RF Performance of GaN MOSHEMT post Integration with Si CMOS

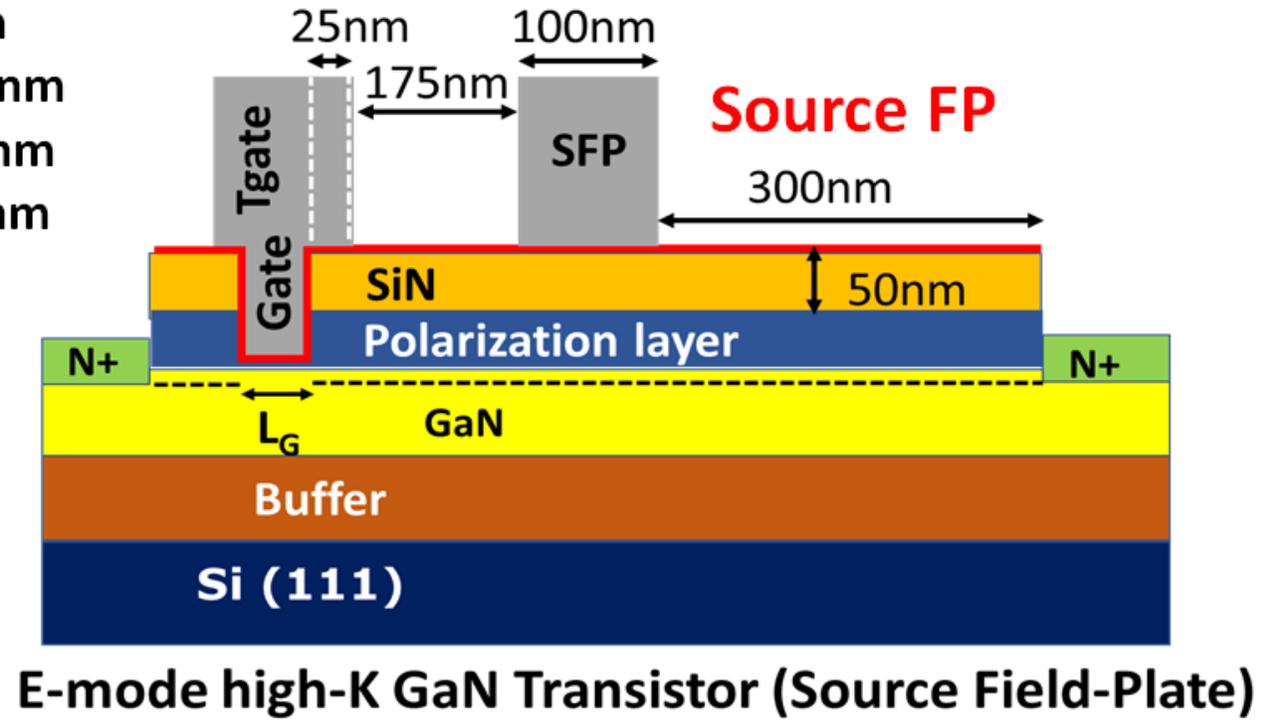


- Integrating Si CMOS using 3D layer transfer does not alter the RF performance of GaN

# Record $f_{MAX}=700\text{GHz}$ for GaN-on-Si



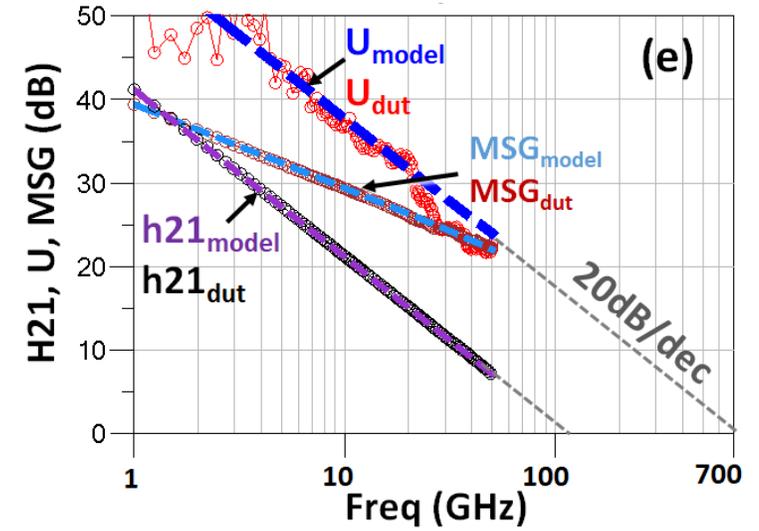
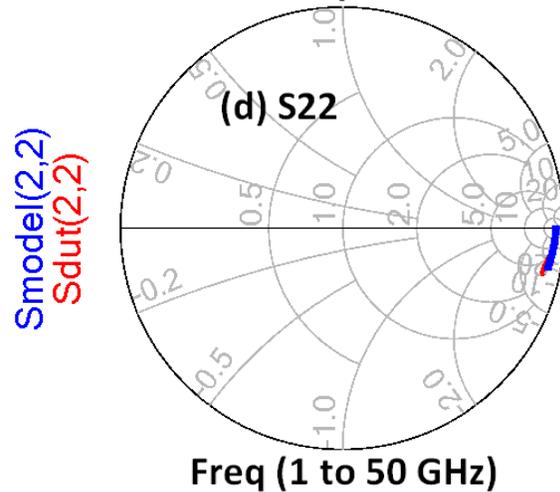
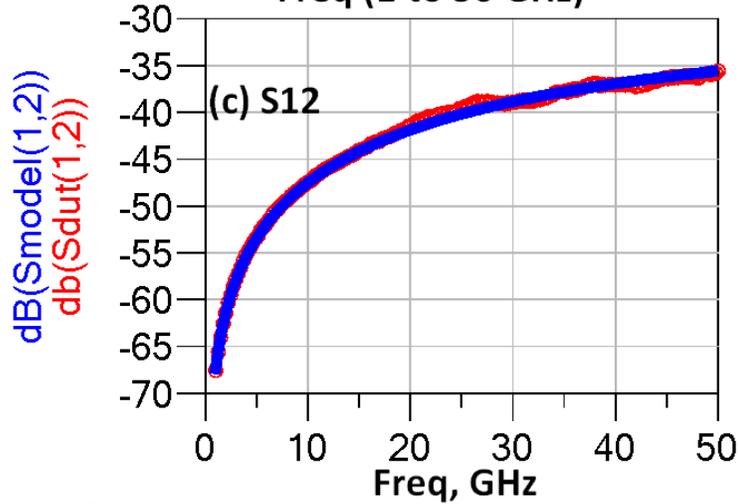
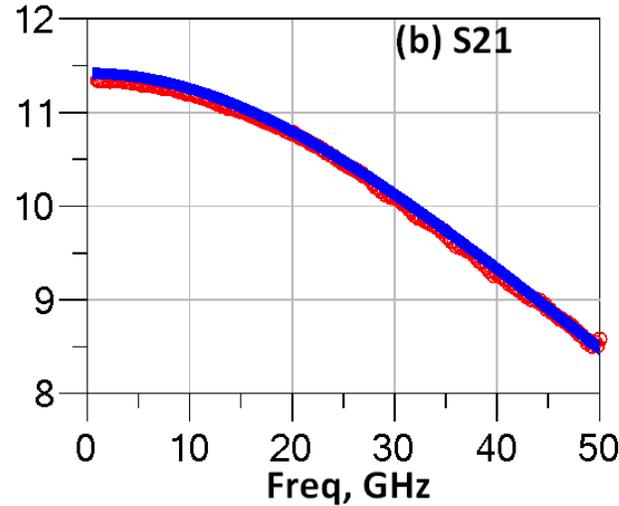
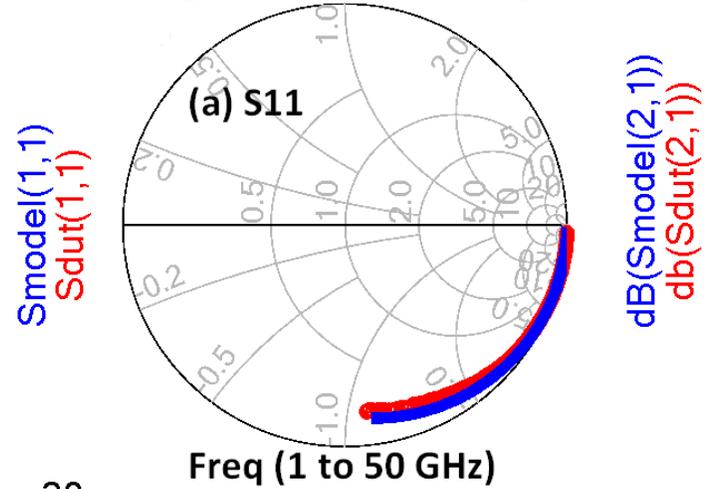
$L_G=50\text{nm}$   
 $L_{SFP}=100\text{nm}$   
 $L_{GD}=600\text{nm}$   
 $L_{GS}=120\text{nm}$



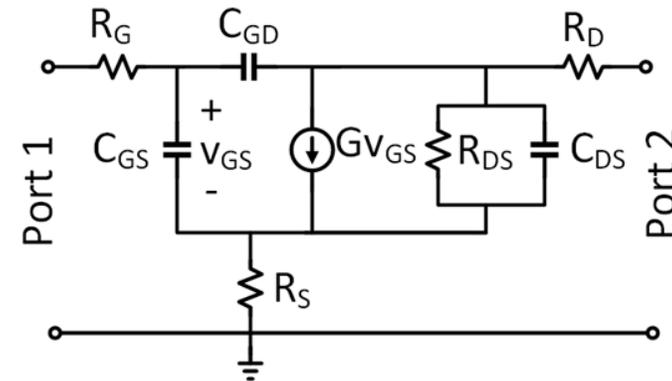
300mm GaN-on-Si wafer with Integrated CMOS

# Record $f_{MAX}=700\text{GHz}$ for GaN-on-Si

Source FP E-mode GaN MOSHEMT



(f) Small-Signal Model

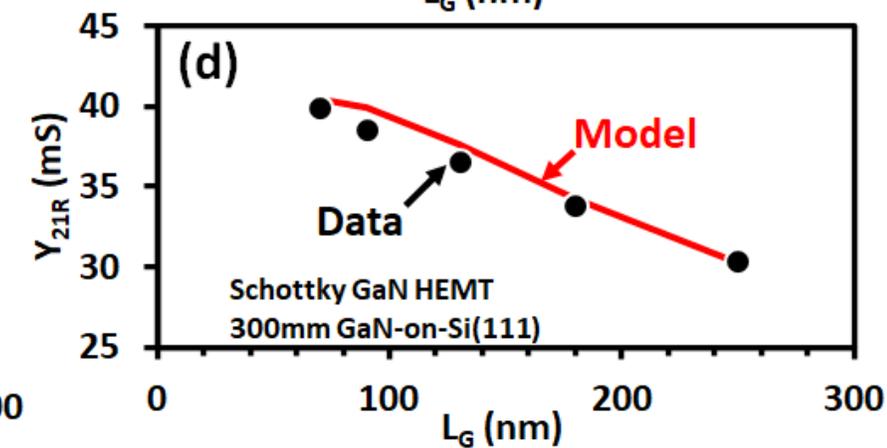
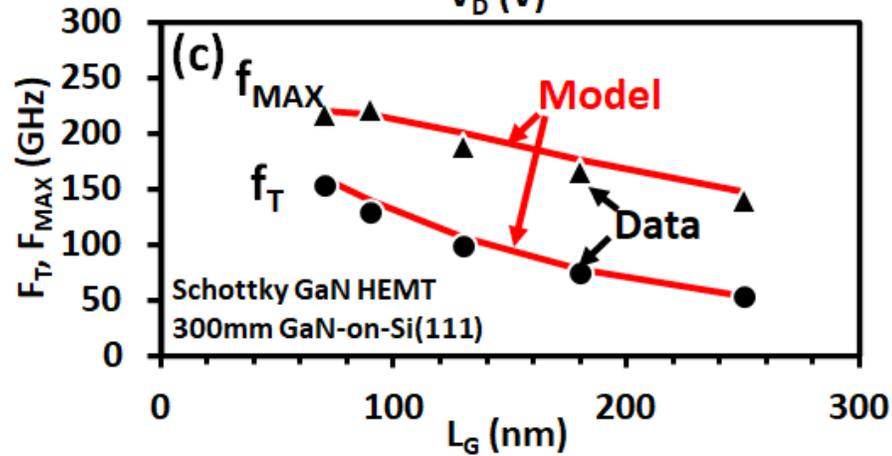
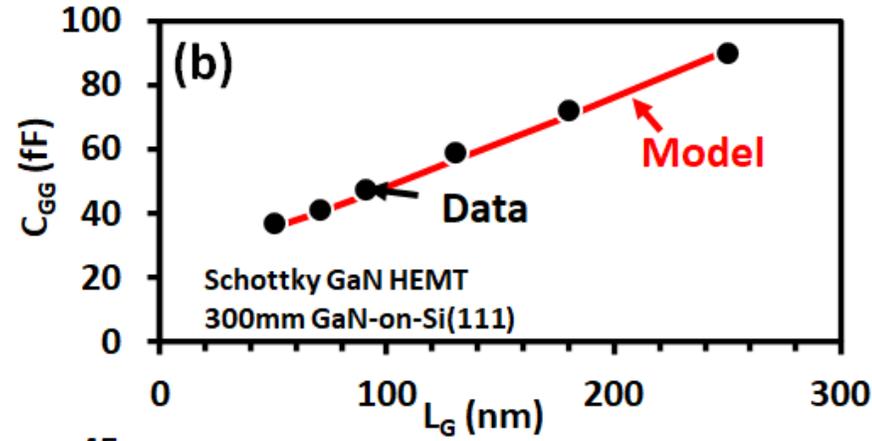
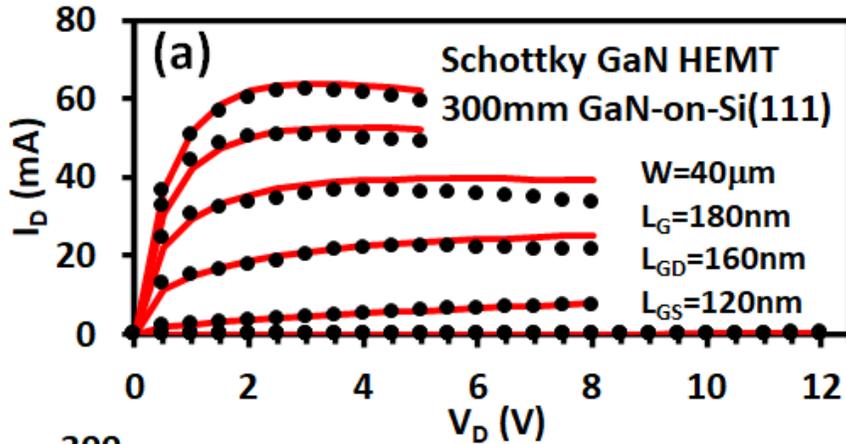


- $G=43.2\text{ mS}$
- $R_S=3.2\text{ ohm}$
- $R_G=4.8\text{ ohm}$
- $C_{GS}=60\text{ fF}$
- $C_{GD}=0.61\text{ fF}$
- $R_{DS}=2045\text{ ohm}$
- $C_{DS}=5.5\text{ fF}$
- $R_D=9.7\text{ ohm}$

# PDK In-Development

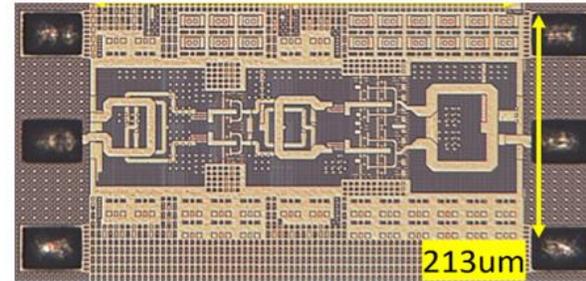
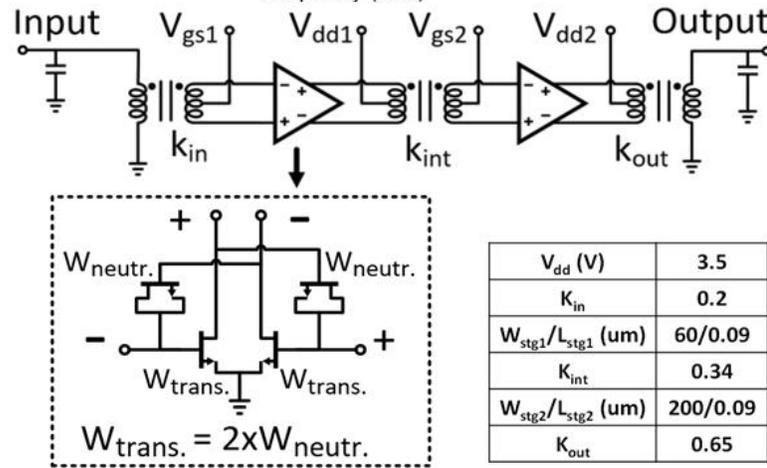
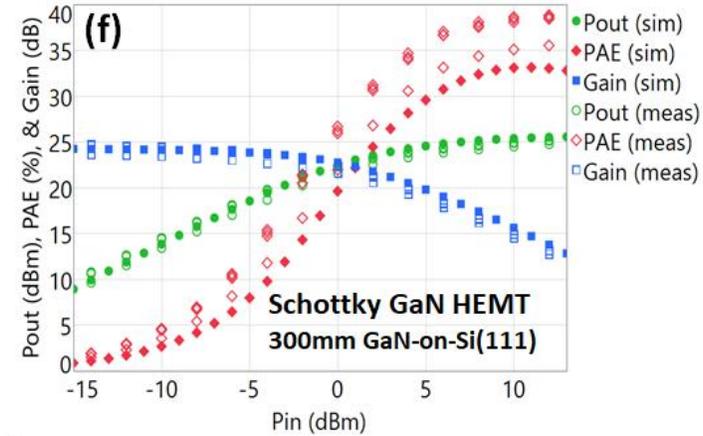
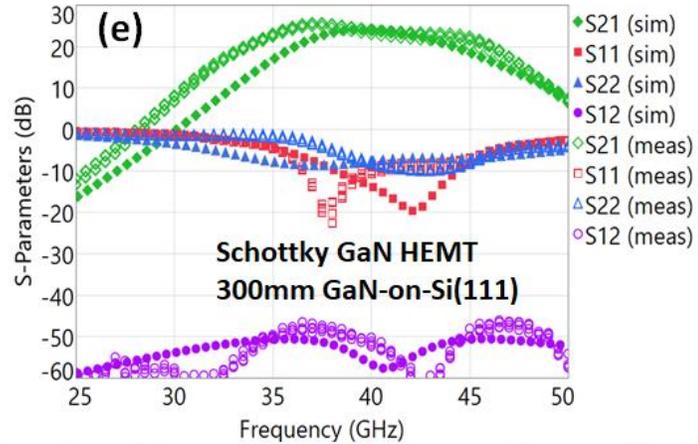
- Transistor and interconnect design/layout rules**
- GaN and Si CMOS transistor compact models**
- Parameterized cell (Pcells)**
- Tape-in collaterals**
- Layout-vs-schematics (LVS)**
- Extraction**
- Electromagnetic (EM) simulation**
- Custom logic cell library, etc**

# Development of Compact Model



- Derived from charge equations with self-consistent DC and AC models
- Includes short channel effects, quantum effects, leakage currents, extrinsic capacitances, and self-heating effect, but does not include trapping

# Development of Compact Model



Ref [2]

- Good fit for Schottky HEMT circuit designs
- Work in-progress to extend this Schottky GaN model to E-mode GaN MOSHEMT
- More results will be shown in Q.Yu et al, IMS, Session Th1G-1, 2023

- **High-k E-mode GaN MOSHEMT transistors on 300mm GaN-on-Si(111)**
- **Outstanding electrical, RF characteristics, excellent 300mm wafer uniformity**
- **1st 37-43GHz PA in GaN MOSHEMT: gain 22.5dB,  $P_{SAT}=25.6\text{dBm}$  and PAE=35.7%**
- **High  $f_T/f_{MAX}$  by scaling high-k &  $L_G$**
- **High-voltage by longer  $L_{GD}$  and field-plates**
- **Integration with Si CMOS using 3D layer transfer**
  - **Does not alter the RF performance of the GaN MOSHEMT.**
  - **Record  $f_{MAX}=700\text{GHz}$  ( $f_T=115\text{GHz}$ ) with a  $L_G=50\text{nm}$  GaN MOSHEMT**
- **Progress made on the PDK development for this technology**