# N-Polar GaN Deep Recess HEMTs for mm-Wave Power Amplification

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With support from ONR (Dr. Paul Maki) and DARPA (Dr. Dan Green, Dr. Y.-K. Chen)

October 10, 2019

# Outline

I. Introduction
  - mm-Wave Application Space
  - Status of Competing Device Technologies
  - Demonstrated Advantage of N-Polar GaN

II. The N-Polar GaN Deep Recess HEMT
  - Enabling Features of the Device Structure
  - Fabrication Process for Self-Aligned Gate

III. Experimental Results: Large Signal Performance
  - W-Band Device Performance (94 GHz)
  - Ka-Band Device Performance (30 GHz)

IV. Conclusion

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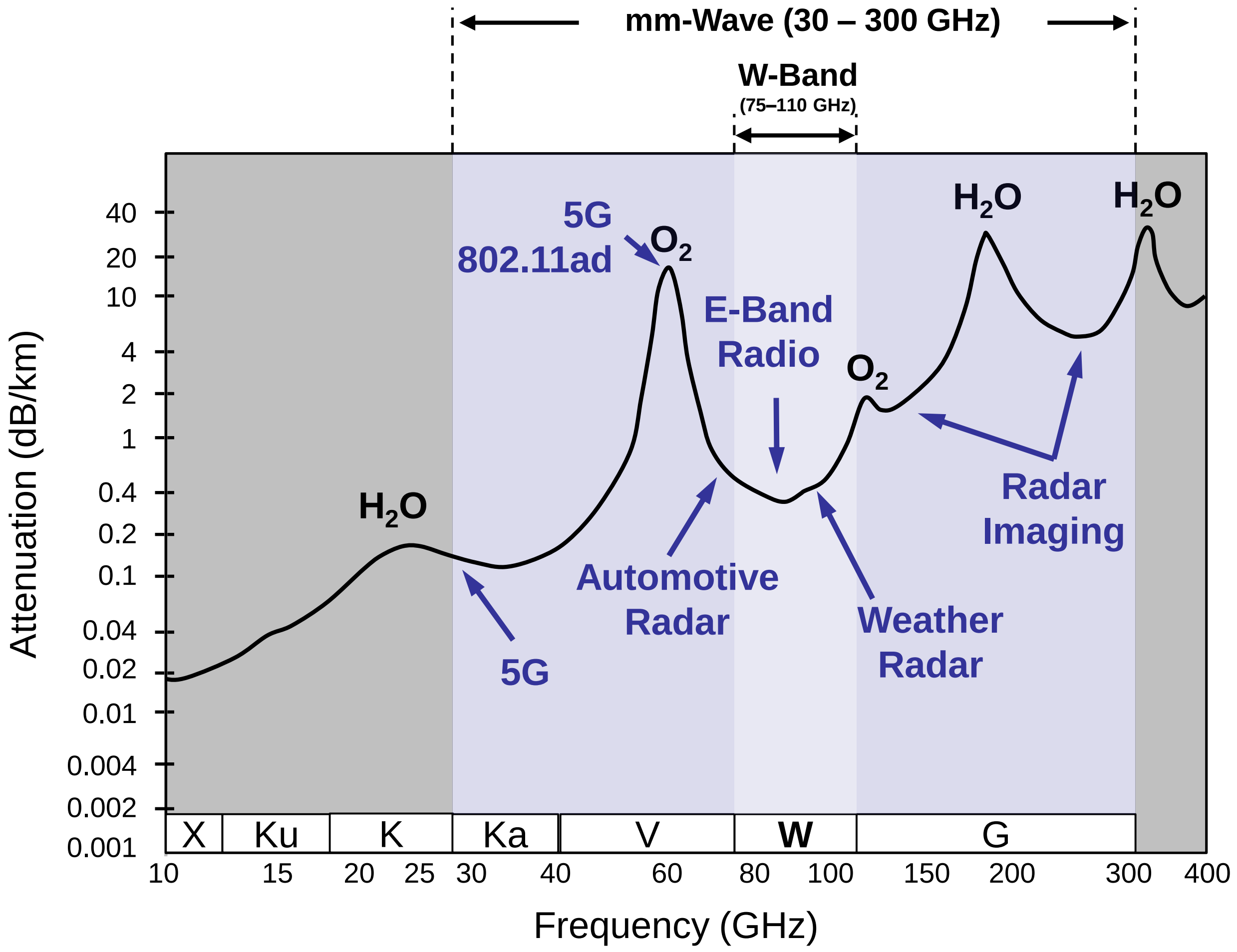
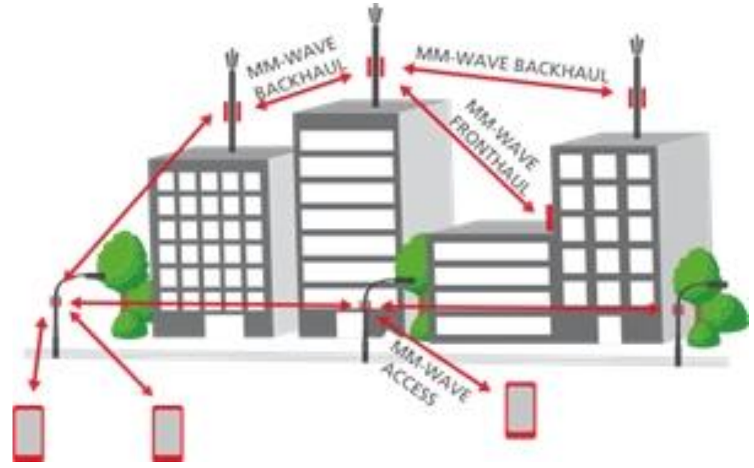
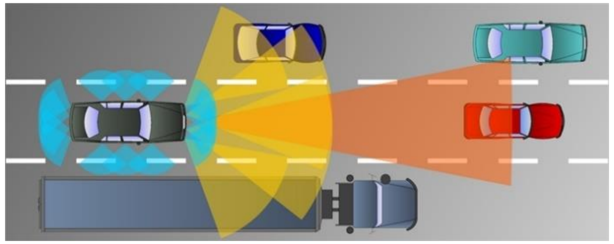
# mm-Wave Applications



5G Communication



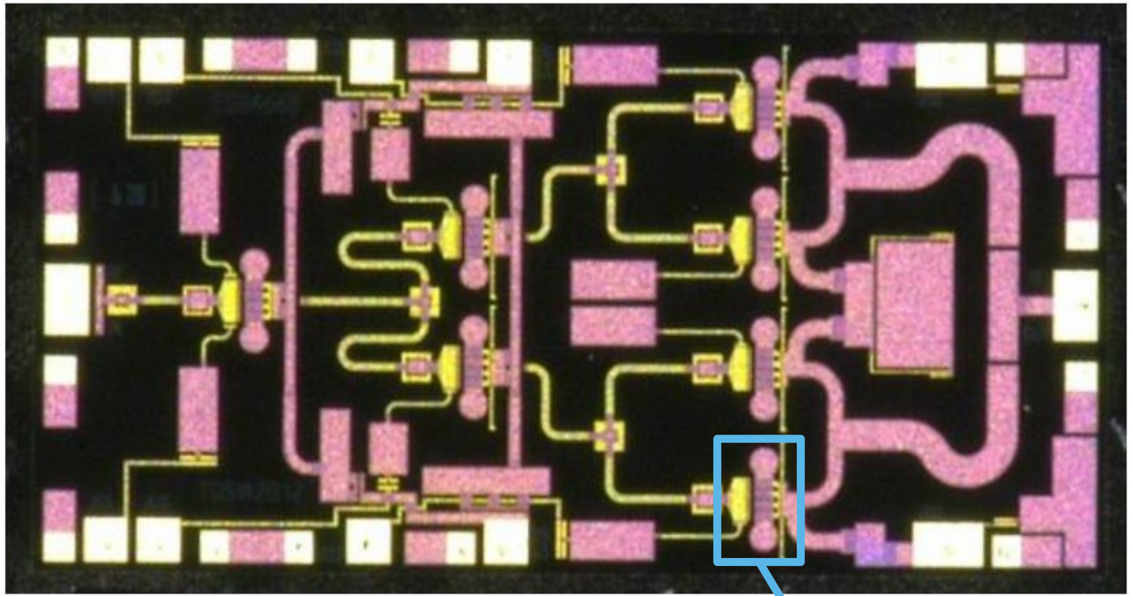
79 GHz: Automotive Radar / Collision Avoidance



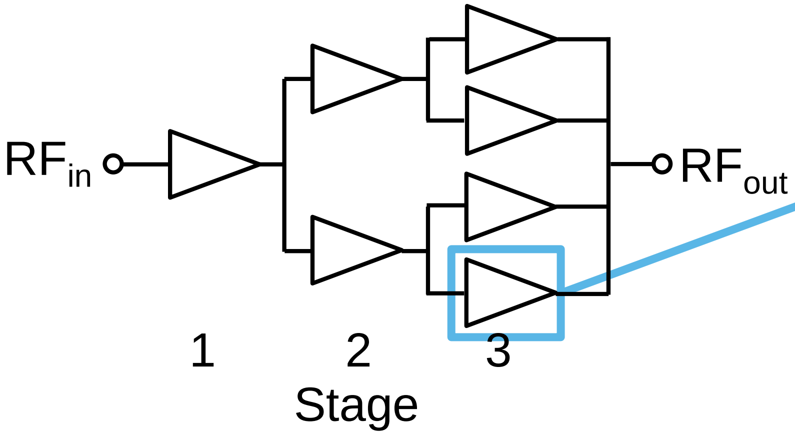
Atmospheric absorption windows and attenuation peaks useful for a variety communication and sensing of applications

# Solid-State Power Amplifiers

Qorvo TGA2594: 27-31GHz 5W GaN Power Amplifier



Qorvo TGA2594 datasheet

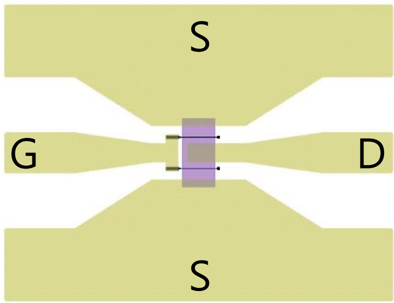


Transistor Unit Cell

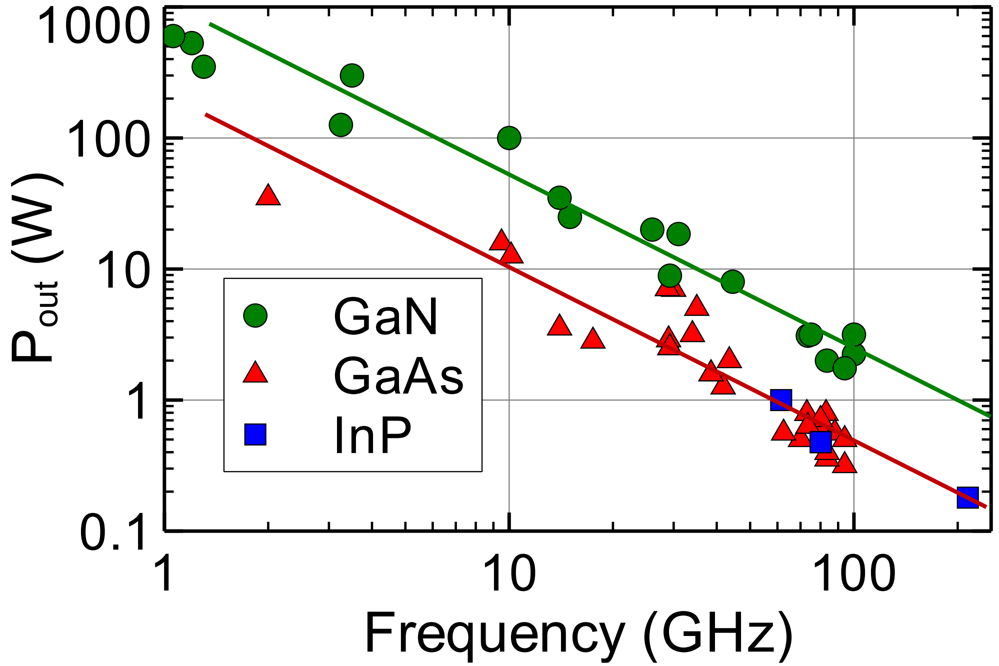
Typical mm-Wave PA’s cascade multiple transistors to provide useful level of gain and power

This Work: Fabricate only transistor unit cells to characterize the device

This Work



# GaN: Proven Material for Solid-State RF Power Generation



**GaN provides highest output power from 1 to 100 GHz**

Plotted data from commercial product datasheets and select publications
Data compiled with M. Guidry

## Key Properties of GaN
## (Ga- & N-Polar)

**Polarization:**
Large 2DEG Charge without Doping (High Mobility & Current)

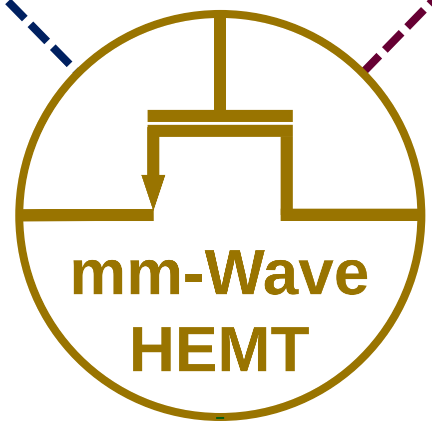
**Wide Bandgap:**
Large Breakdown Voltage

# Key Device Metrics for Power Amplifiers

## Gain

- High Mobility & Velocity
- Electrostatic Control
- Physical Scaling
- Reduced Parasitics

$$G = \frac{P_{RF,out}}{P_{RF,in}}$$



## Output Power

- Large Current Swing
- Large Voltage Swing
- Low Dispersion

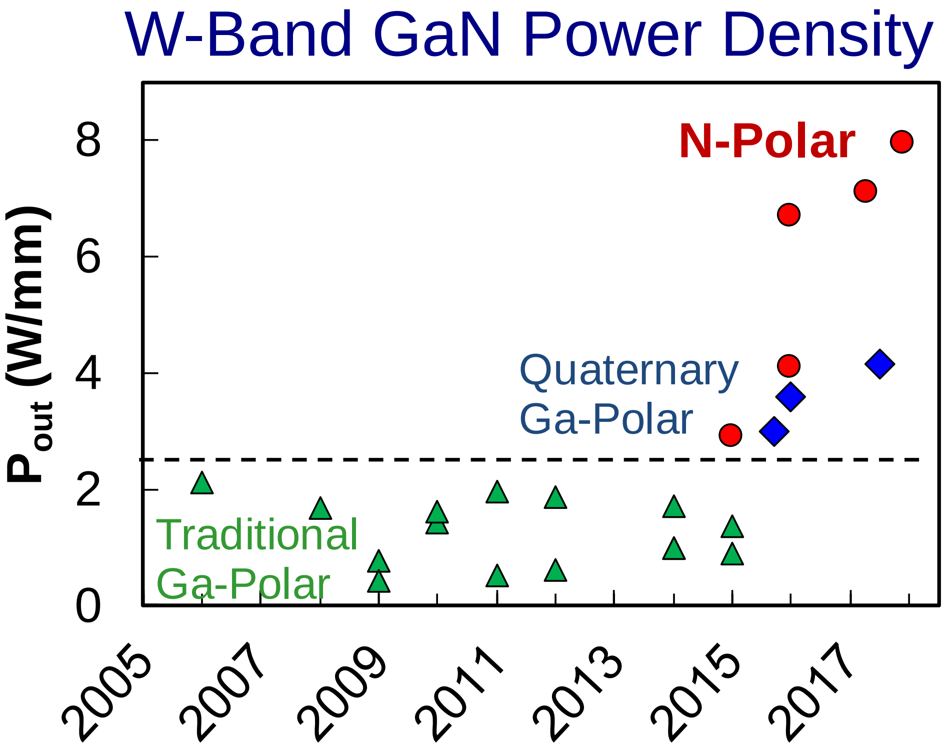
$$P_{out} = \frac{V_{swing}\ I_{swing}}{8}$$
$$= \frac{2(V_{DD} - V_{knee})I_{knee}}{8}$$

## Power-Added Efficiency

- High Gain
- High Power
- DC Bias Point
- Low leakage

$$PAE = \frac{P_{RF,out} - P_{RF,in}}{P_{DC}} = \left(1 - \frac{1}{G}\right)\frac{P_{RF,out}}{P_{DC}}$$

# N-Polar GaN: **Record 8.85 W/mm $P_{out}$ at 94 GHz**



N-Polar breaks through $P_{out}$ saturation observed for traditional Ga-polar devices with **8 W/mm**

Romanczyk et al., *IEEE Trans. Electron Devices*. Jan. 2018

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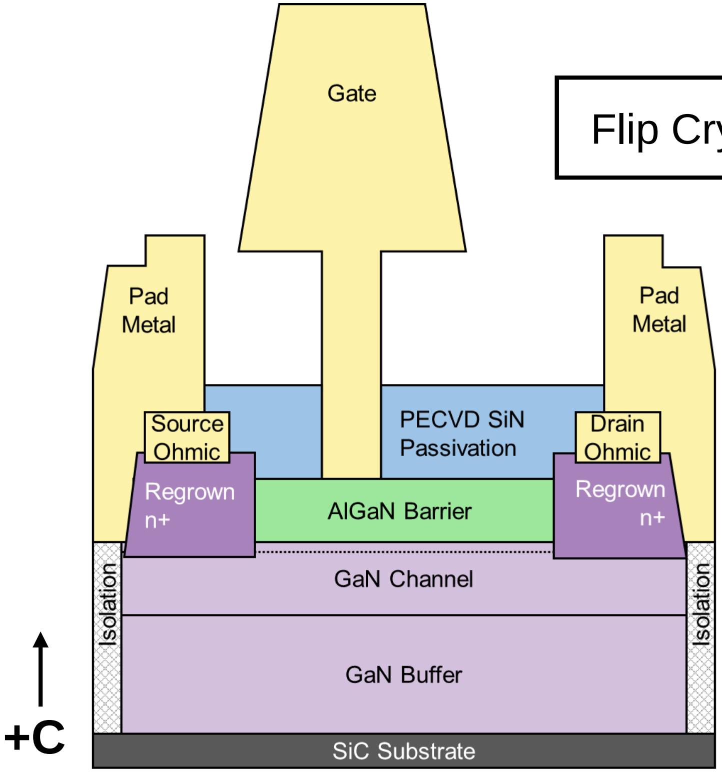
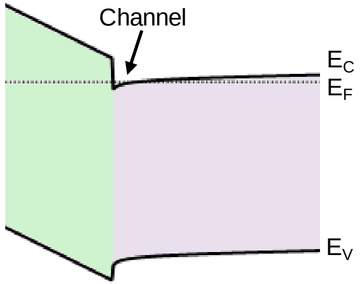
# GaN HEMTs: Ga-Polar & N-Polar

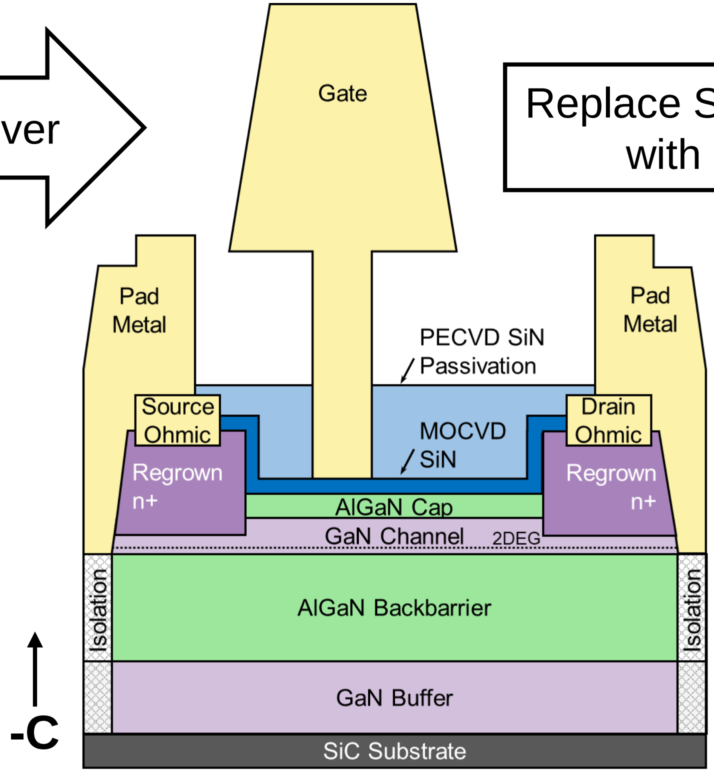
## Ga-Polar HEMT

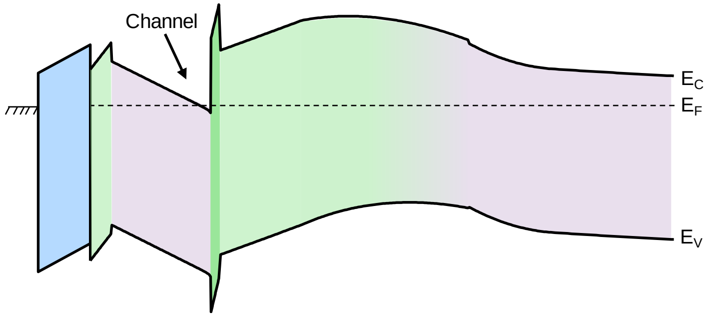




Flip Crystal Over

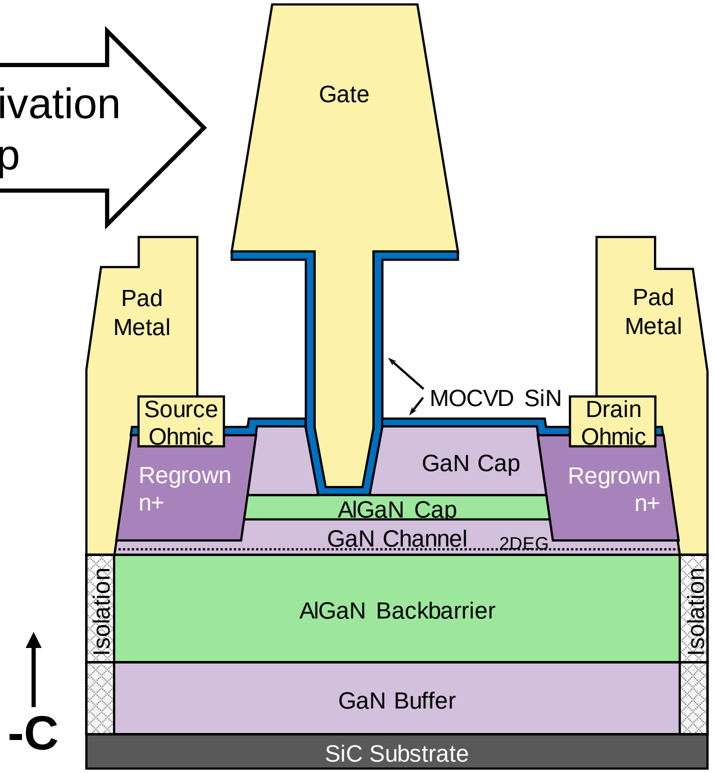
## Planar N-Polar HEMT



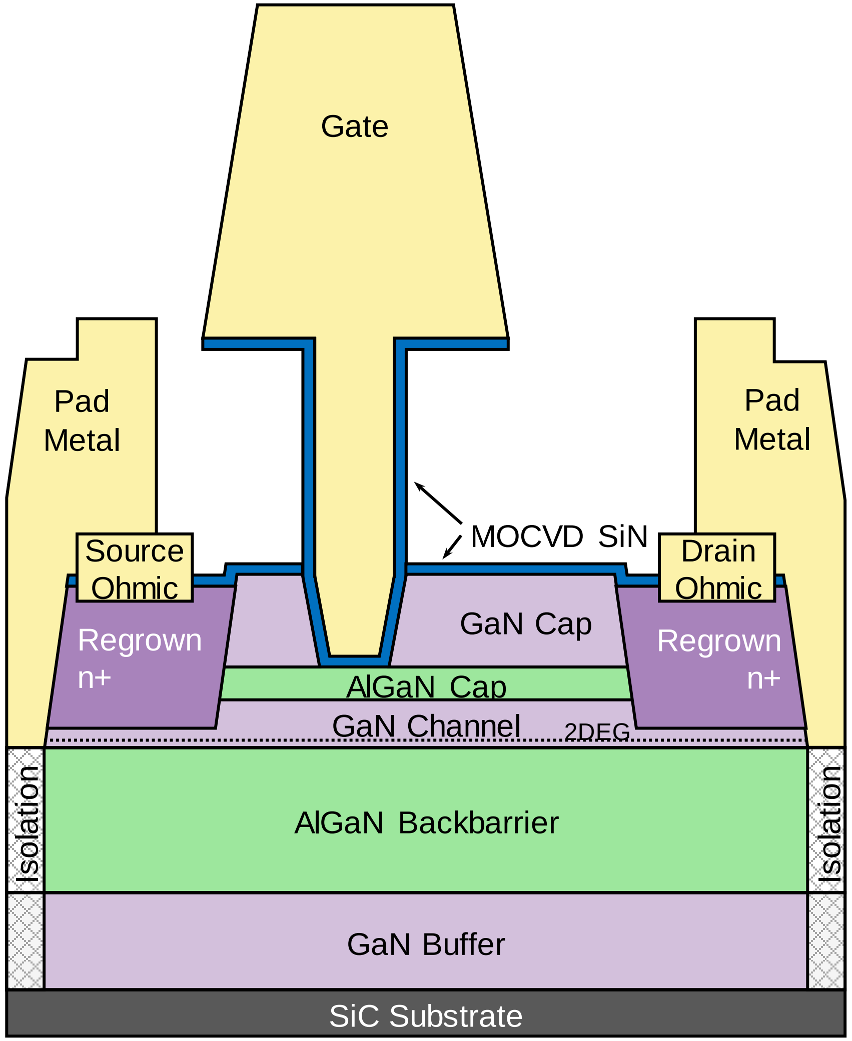


Replace SiN Passivation with GaN Cap

## Deep Recess N-Polar HEMT

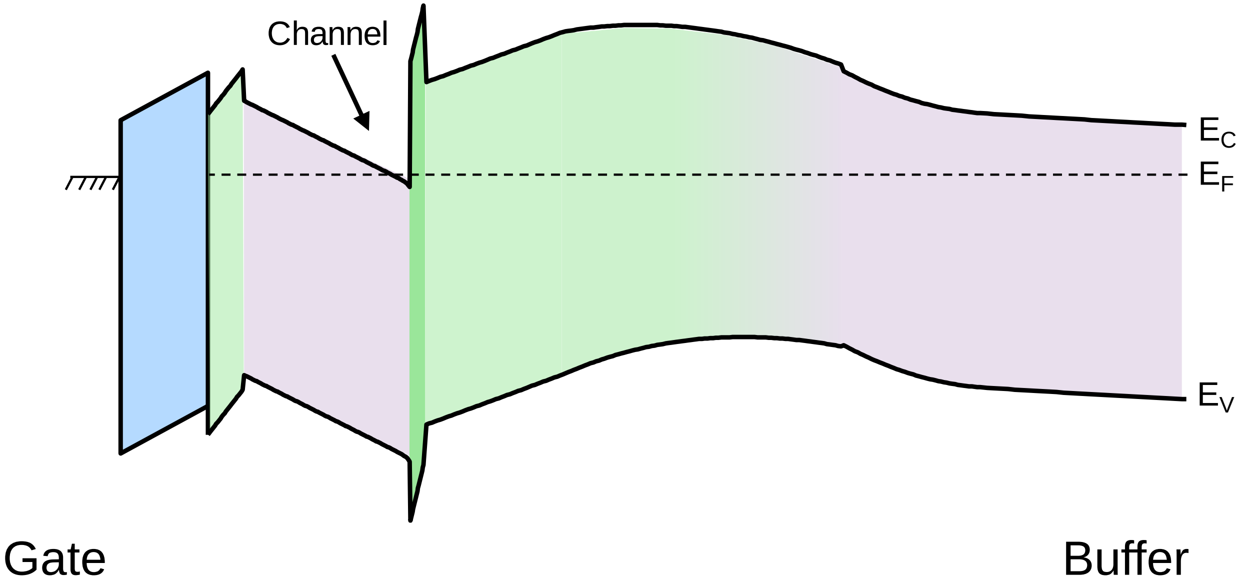


# The N-Polar GaN Deep Recess HEMT Structure

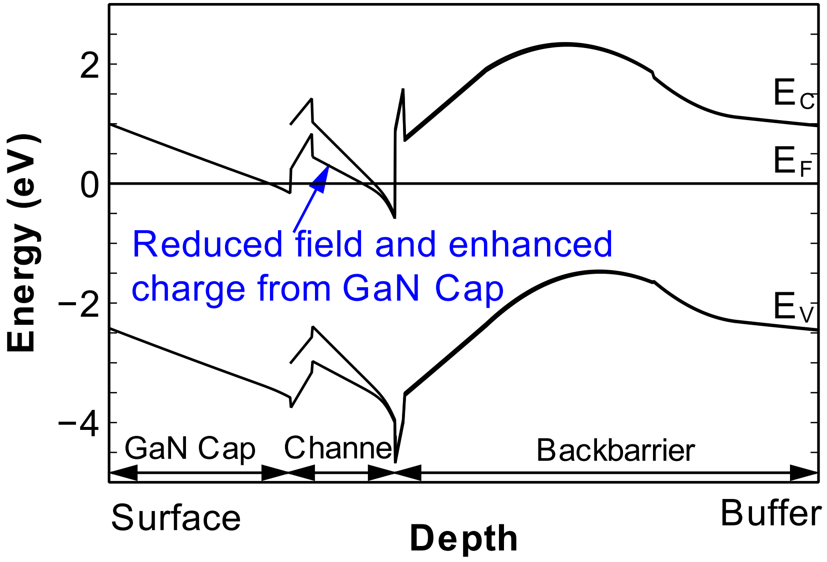


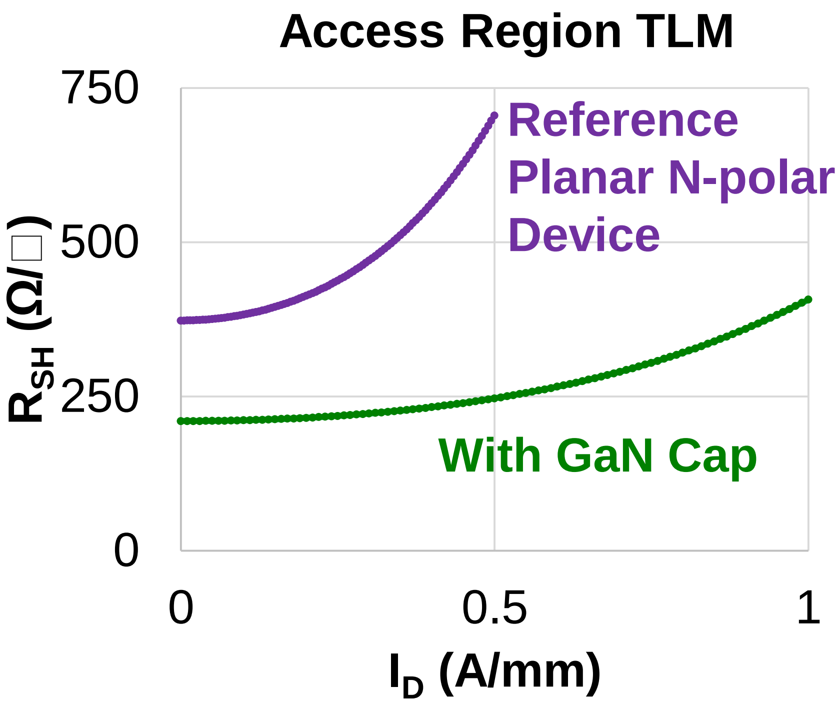
## N-Polar Deep Recess Structure

- ✓ AlGaN backbarrier provides charge and 2deg confinement
- ✓ Low resistance regrown $n^+$ contacts by MBE
- ✓ AlGaN cap & MOCVD SiN Gate Dielectric for low gate leakage
- ✓ **GaN Cap for dispersion control and low access resistance**
- ✓ Self-aligned gate for process control and low dispersion



# GaN Cap Advantage #1: Access Region Conductivity

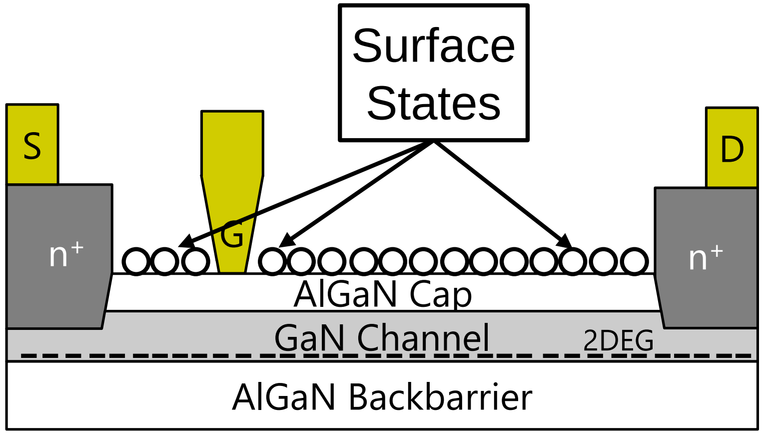


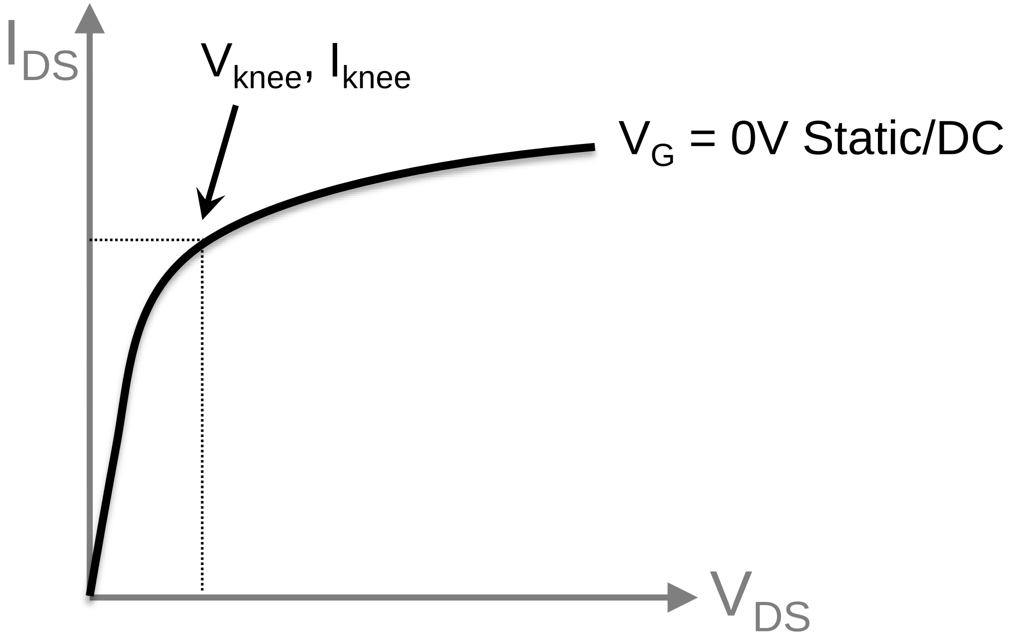


Polarization also reduces |E| in the GaN channel ⇨ improves mobility

- Channel conductivity improved over wide current range
- Necessary for low $V_{knee}$

# mm-Wave Challenge: Controlling DC-RF Dispersion

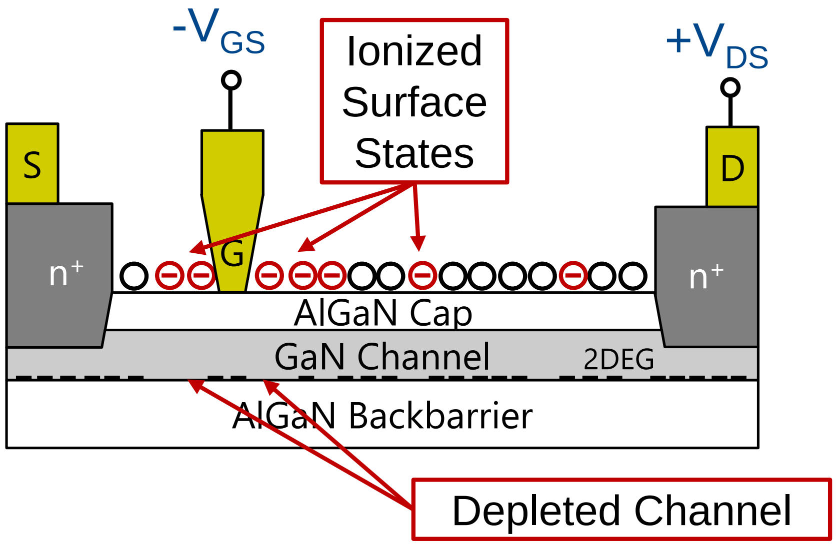


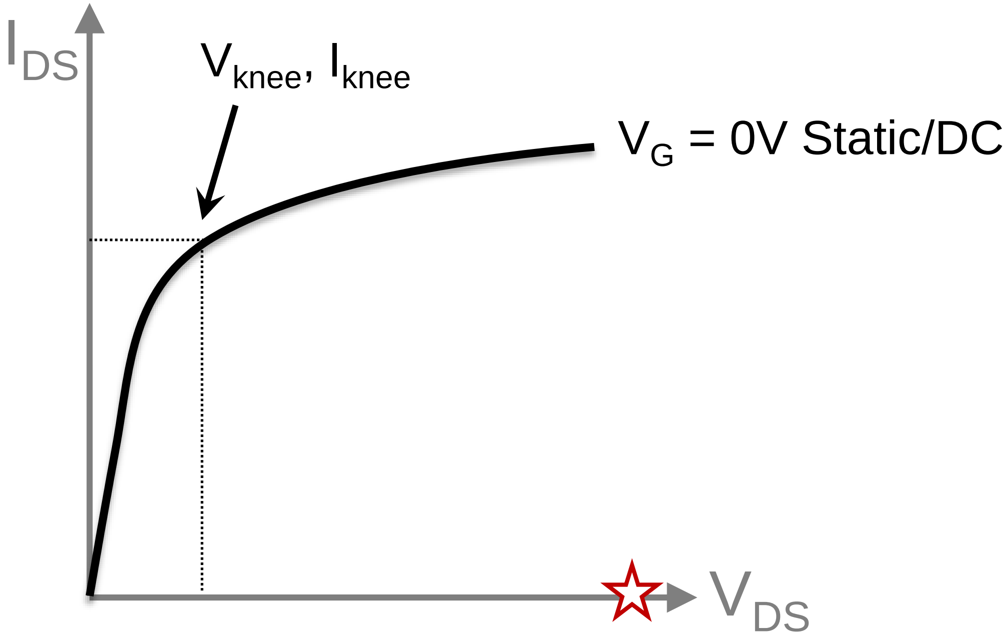


Surface states exist in GaN devices

Charge state responds to DC bias

# mm-Wave Challenge: Controlling DC-RF Dispersion





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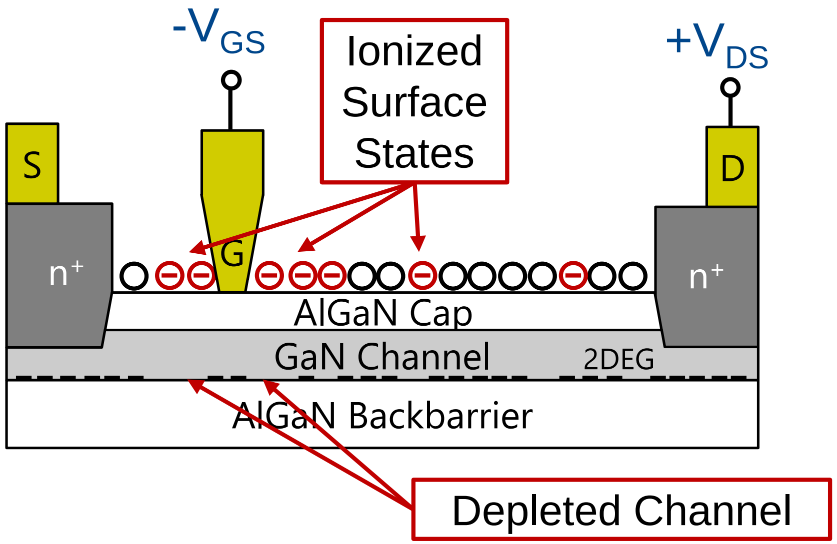
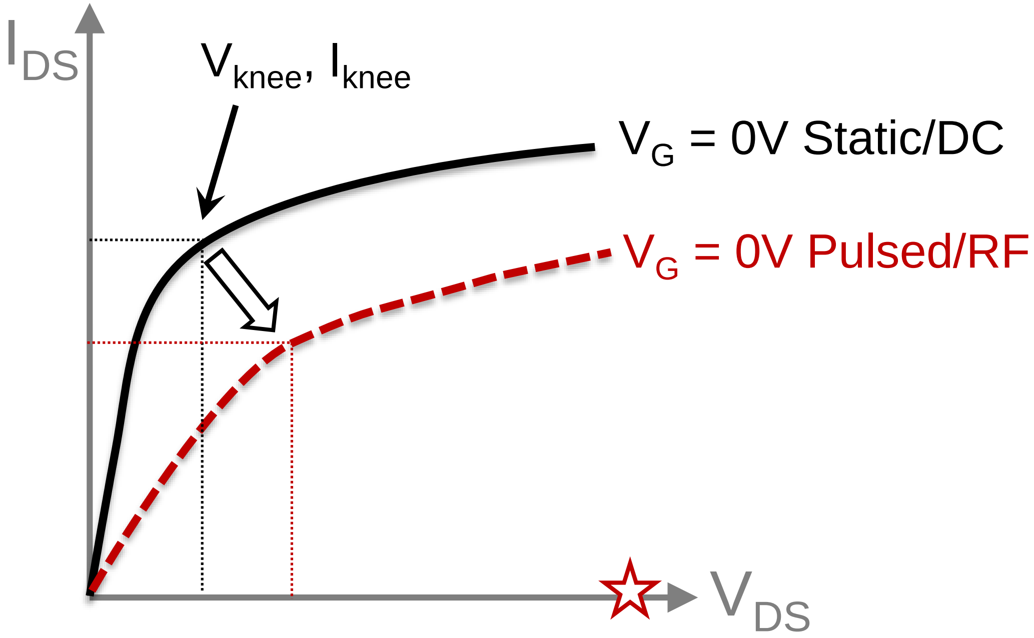


Surface states exist in GaN devices

Charge state responds to DC bias

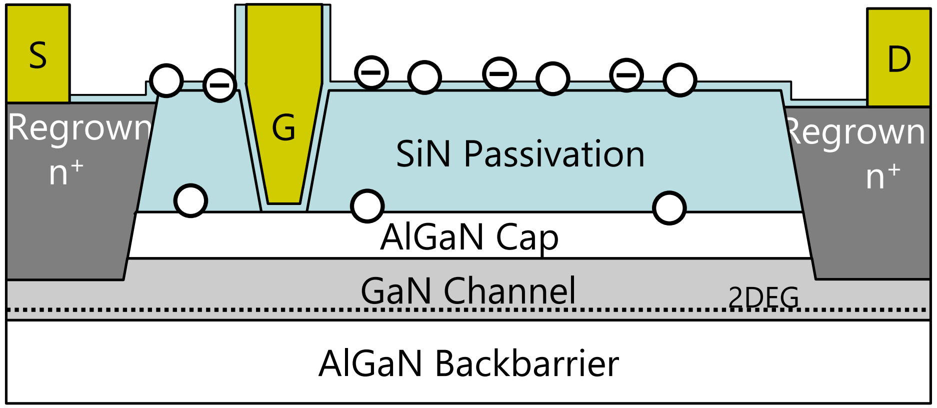


$$P_{out} = \frac{(V_{DD} - \boldsymbol{V_{knee}})\boldsymbol{I_{knee}}}{4}$$

$P_{out}$ and Drain Efficiency are degraded relative to results expected from DC data

# Traditional Solutions to Dispersion

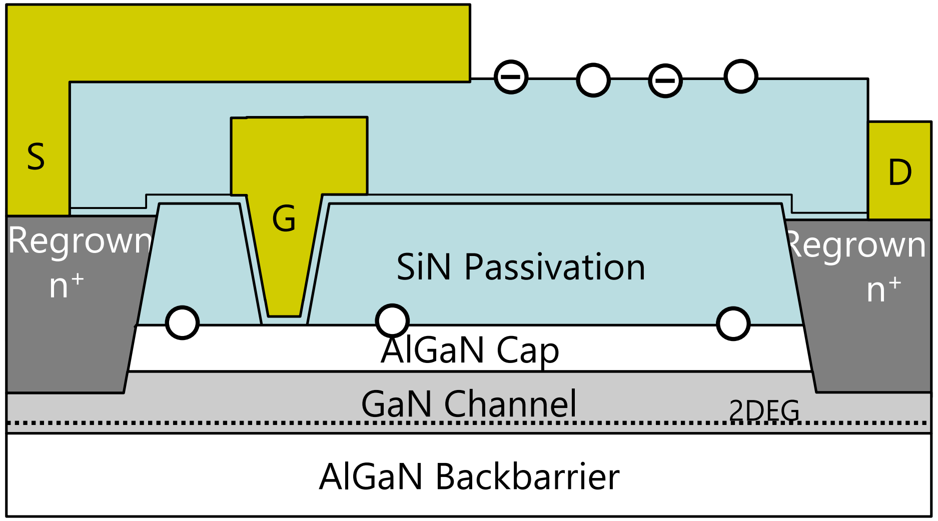
## SiN Passivation



SiN passivates surface states & moves external surface far from channel

$$V_{T,access} = \frac{qn_s}{C}$$

## SiN + Field Plates

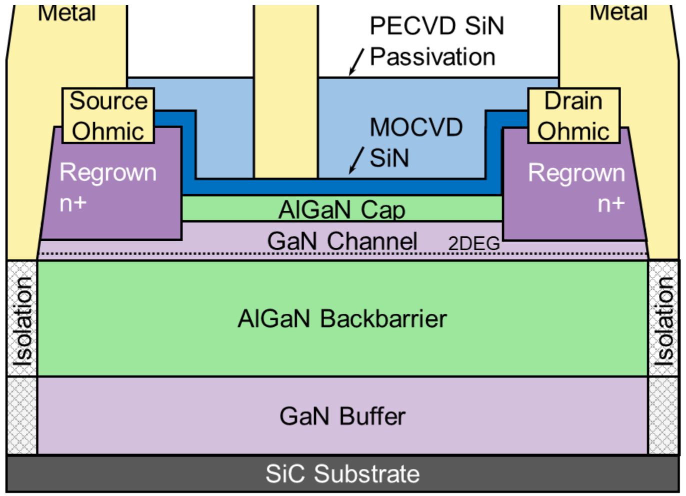


Reduced electric field prevent trap ionization

**Capacitance penalty disallows use at mm-wave frequencies**

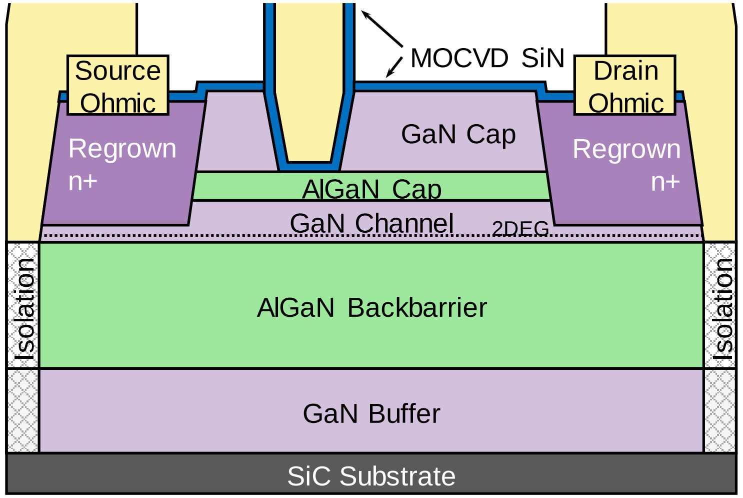
# GaN Cap Advantage #2: Dispersion Control

**Planar N-Polar HEMT**

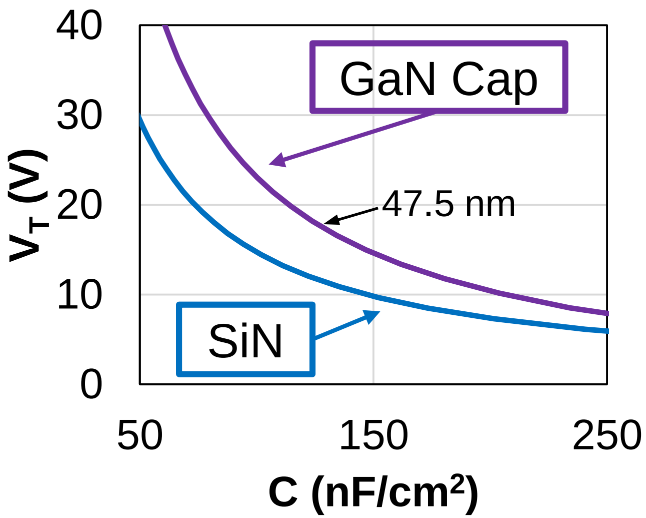


SiN passivation
replaced by GaN cap

**Deep Recess N-Polar HEMT**

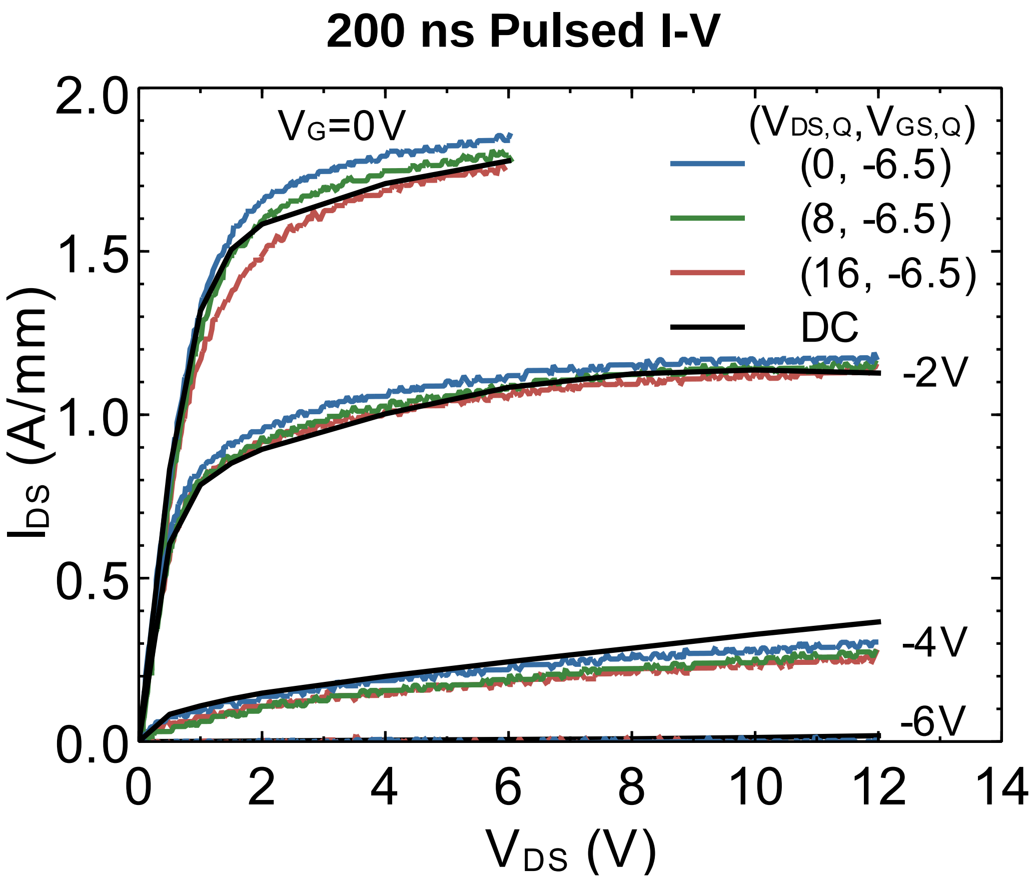


$$V_T = \frac{qn_s}{C}$$



- Increased $n_s$ outweighs differential in $\epsilon_r$
  ⇨ Higher $V_T$ possible for same capacitance
- 47.5 nm GaN cap: $V_{T,access} \approx 17$ V

# Dispersion Control with N-Polar Deep Recess Structure

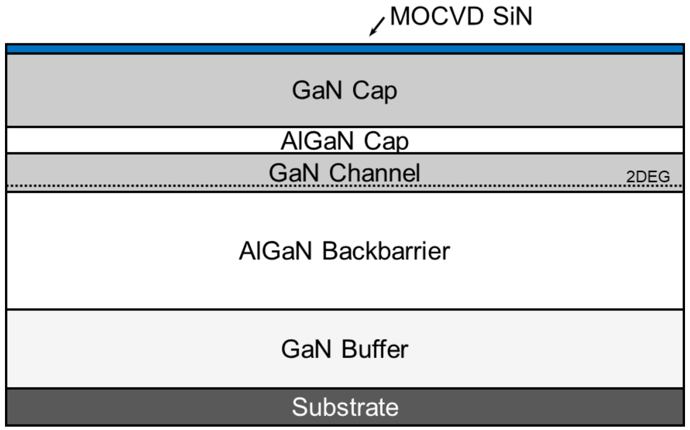


Sub-10% dispersion thru 16 V $V_{DS,Q}$

# Self-Aligned Deep Recess Fabrication Process

**Process**

1. MBE Regrown n⁺ contacts
2. Implant Isolation
3. GaN Cap Recess Etch
4. MOCVD SiN Gate Dielectric
5. Gate Metal
6. Ohmic Metal
7. Pad Metal



Starting Epi:

Grown by MOCVD
(**Haoran Li,** Nirupam Hatui,
Athith Krishna)

# Self-Aligned Deep Recess Fabrication Process

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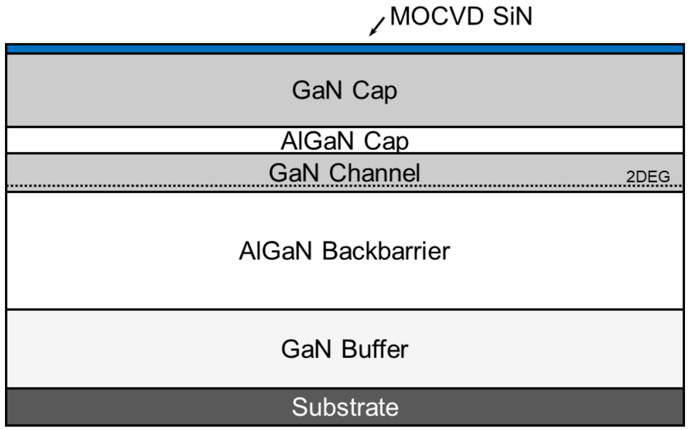

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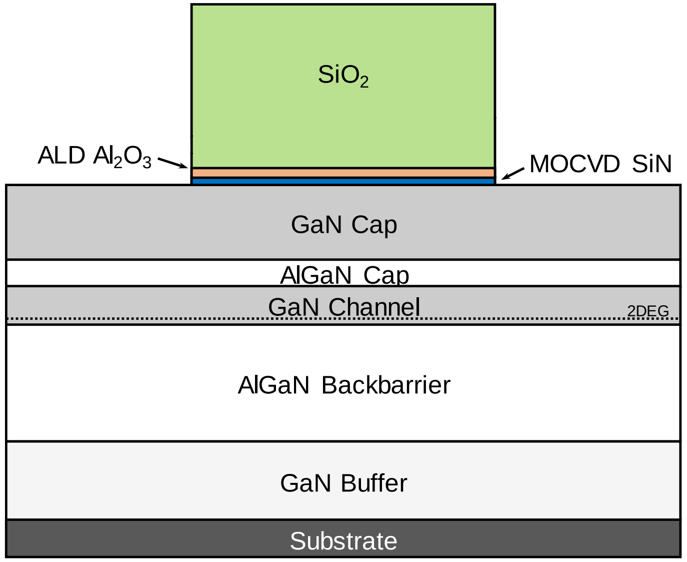
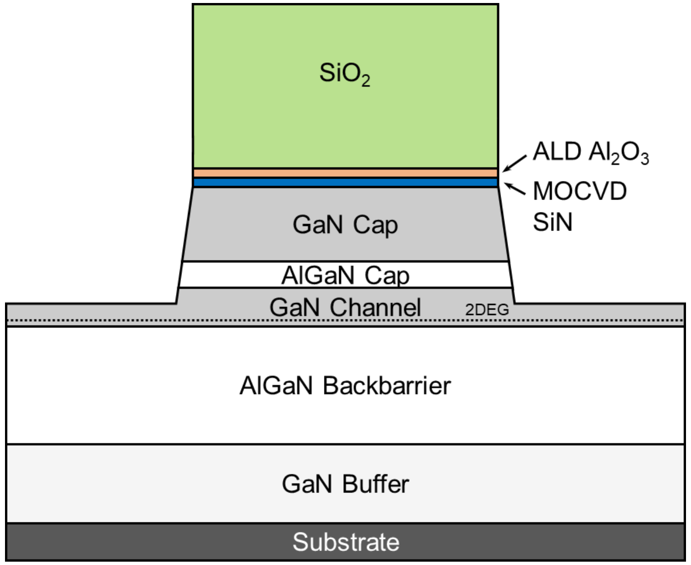


## Regrowth Hard Mask:

- E-Beam Litho UV-N Process
- ICP Etched SiO$_2$ Pillars



## GaN Etch:

- GaN Cap Selectively Etched
  BCl$_3$/SF$_6$ ICP Etch
- AlGaN cap etch: BCl$_3$/Cl$_2$ RIE

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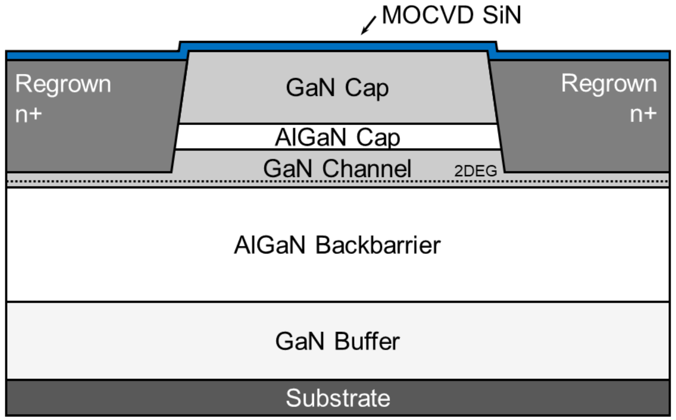

MBE n+ Regrowth:

(**Elaheh Ahmadi,** Karine Hestroffer, Christian Wurm)

- Plasma Assisted MBE

  20 nm UID + 30 nm $n^+$

  $N_{Si} \sim 10^{20}$ cm$^{-3}$

  $R_{sh}$: 85 to 125 Ω/sq.

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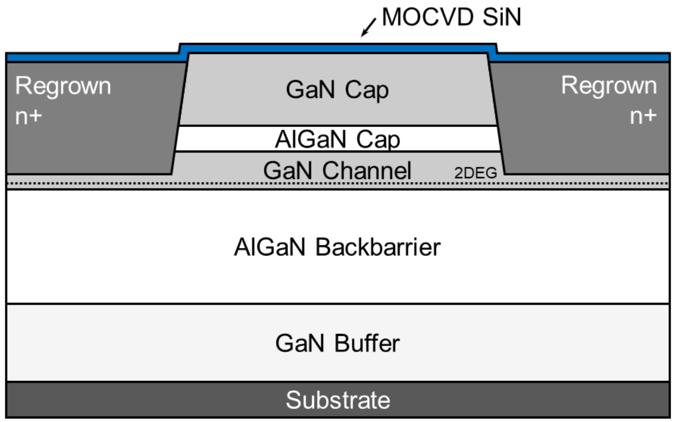

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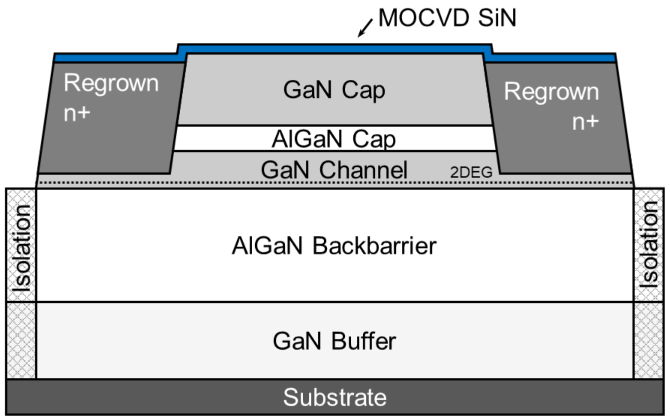

Implant Isolation
(Teledyne Scientific & Imaging)

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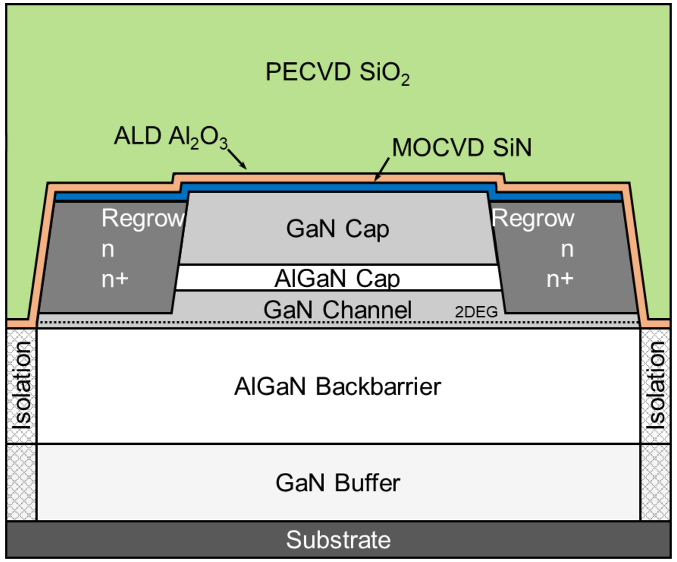
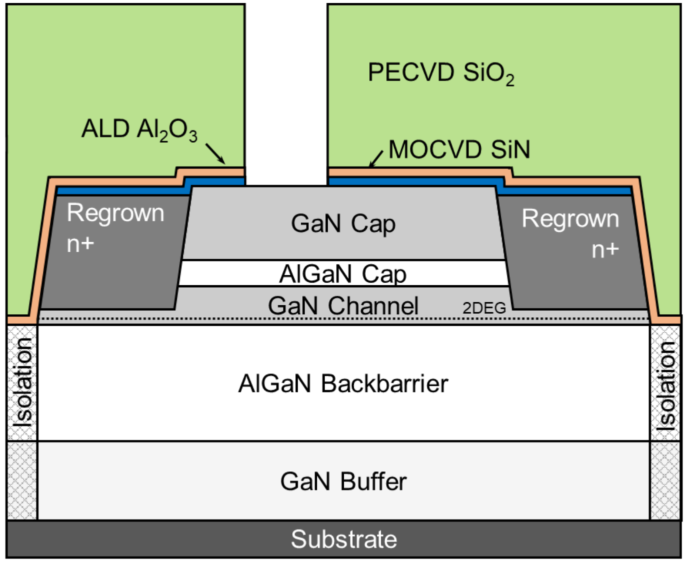
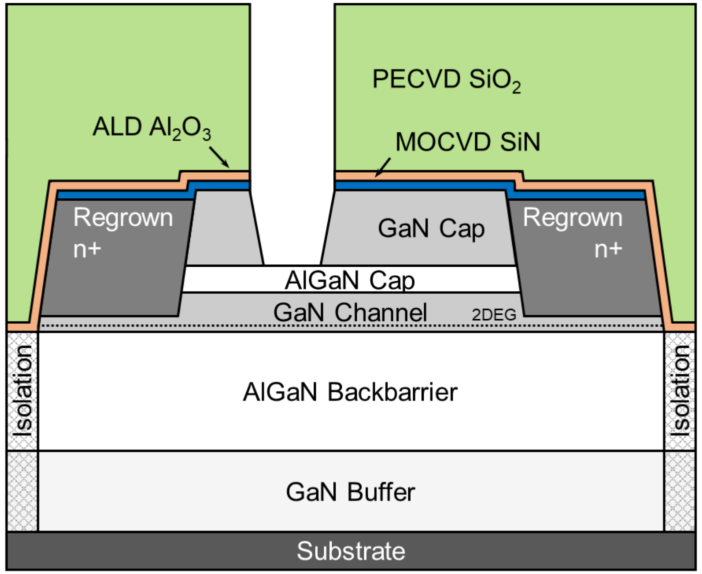


Gate Recess Hard Mask Deposition



SiO$_2$ Patterning

- E-Beam Litho CSAR Mask
- ICP SiO$_2$ Etch



GaN Cap Selective Etch

$BCl_3/SF_6$ ICP Etch

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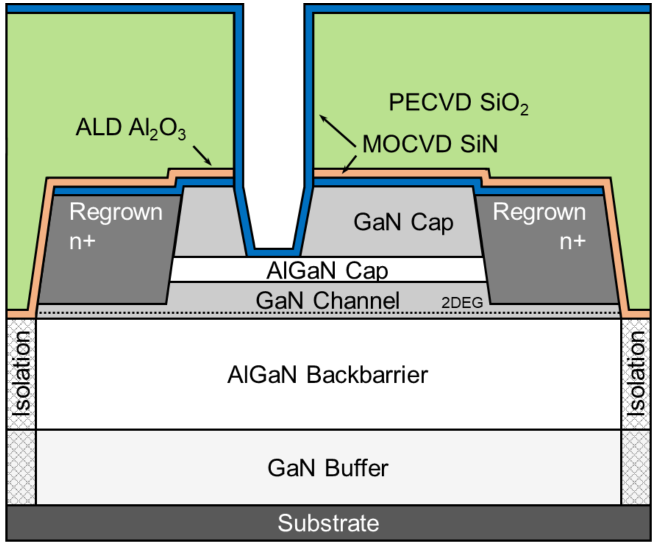

MOCVD SiN Gate Dielectric

(**Haoran Li,** Nirupam Hatui, Anchal Agarwal, Athith Krishna)

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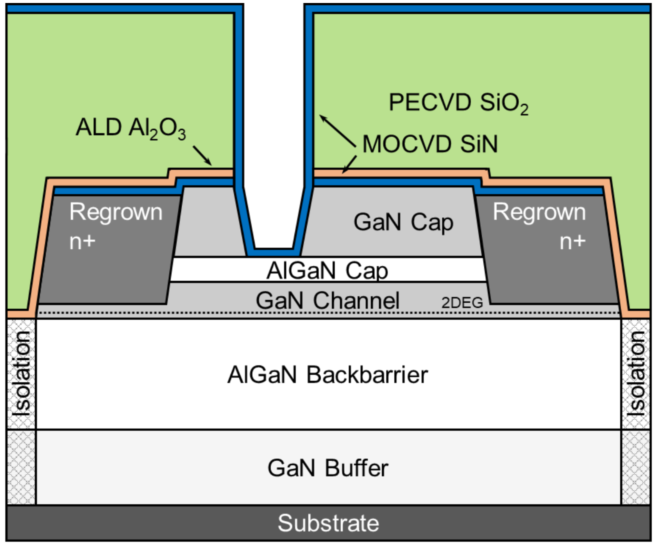

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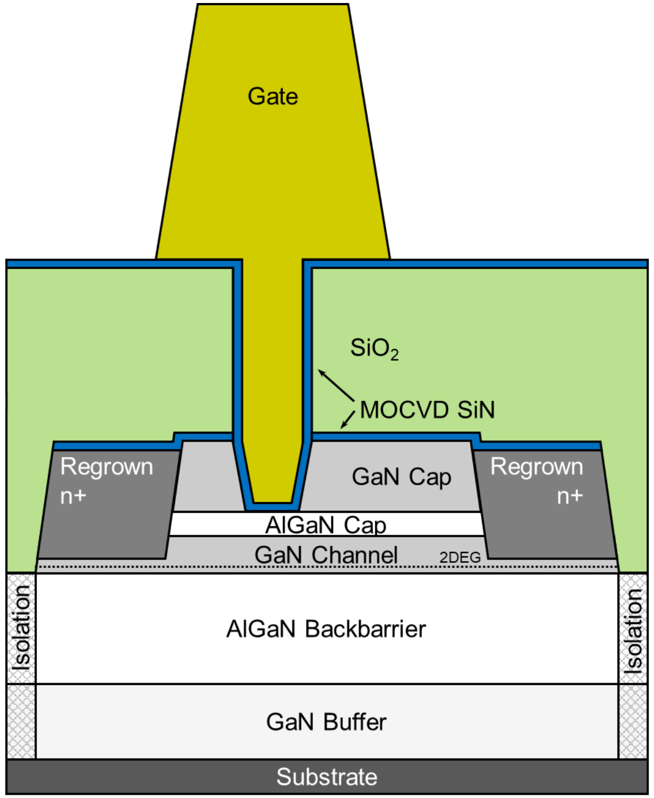
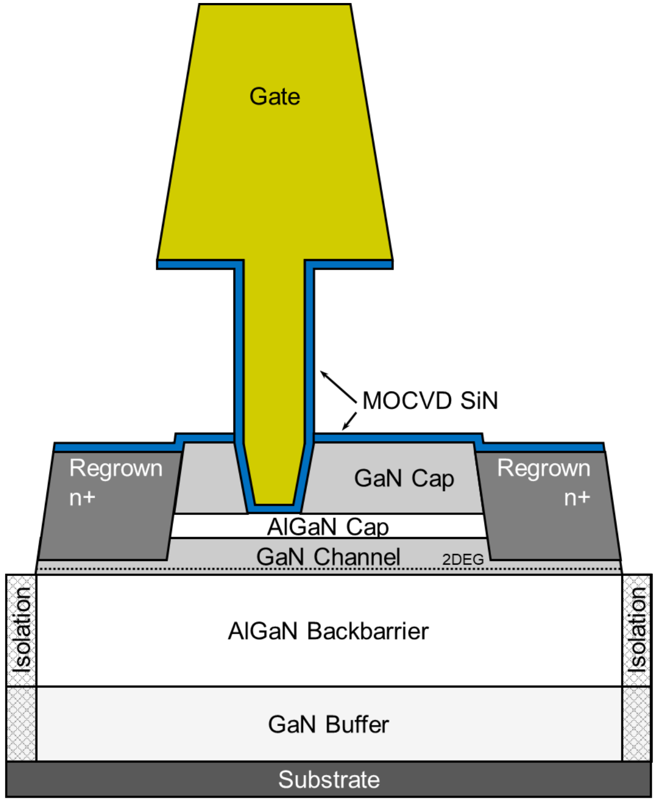


Gate Formation

- EBL UV6 Pattering defines the top gate
- $SiO_2$ Defines the gate stem
- Gate Metal: Cr/Au (45/500nm)



Gate Release

- $SiO_2$ Hard Mask etched

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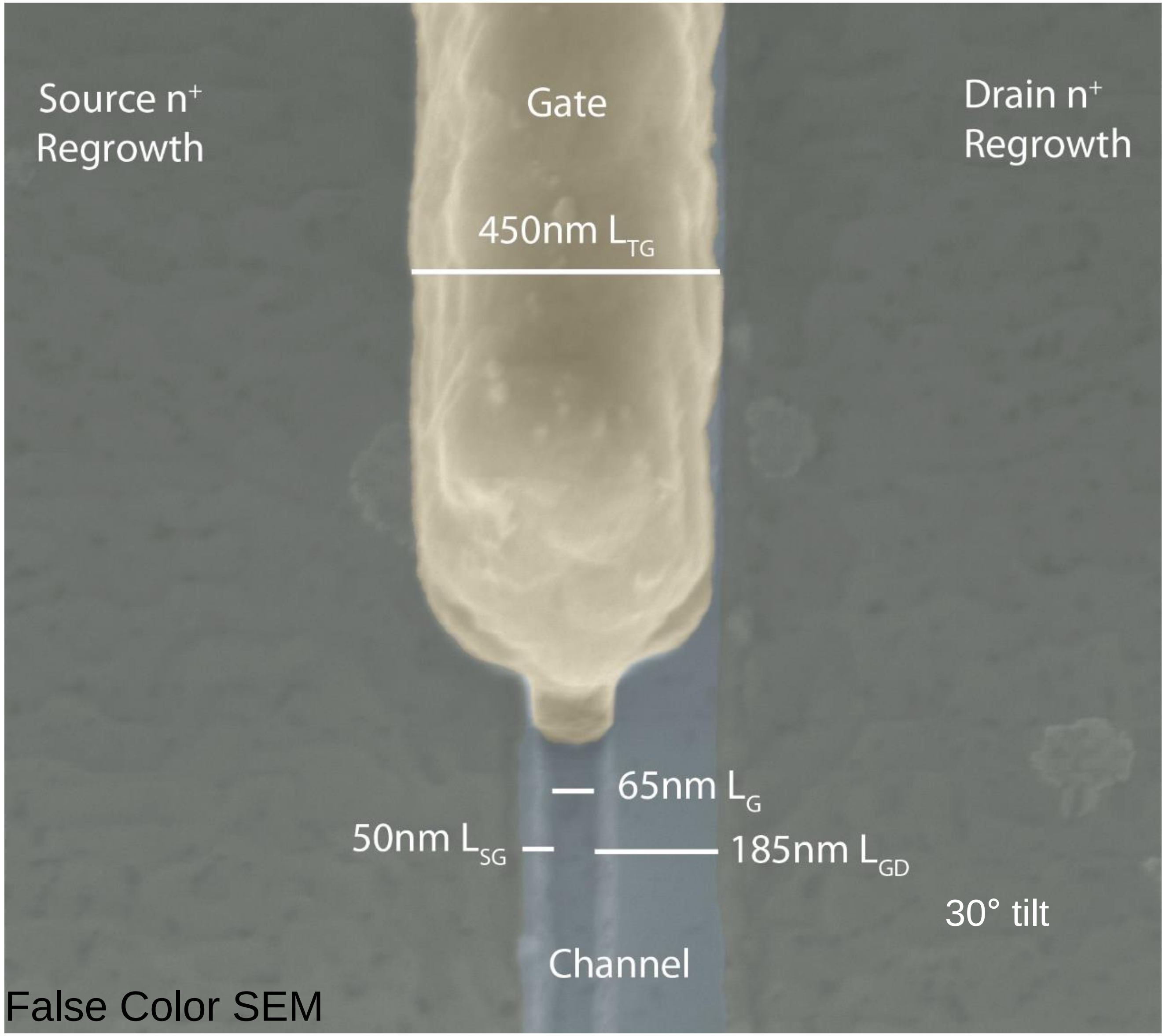
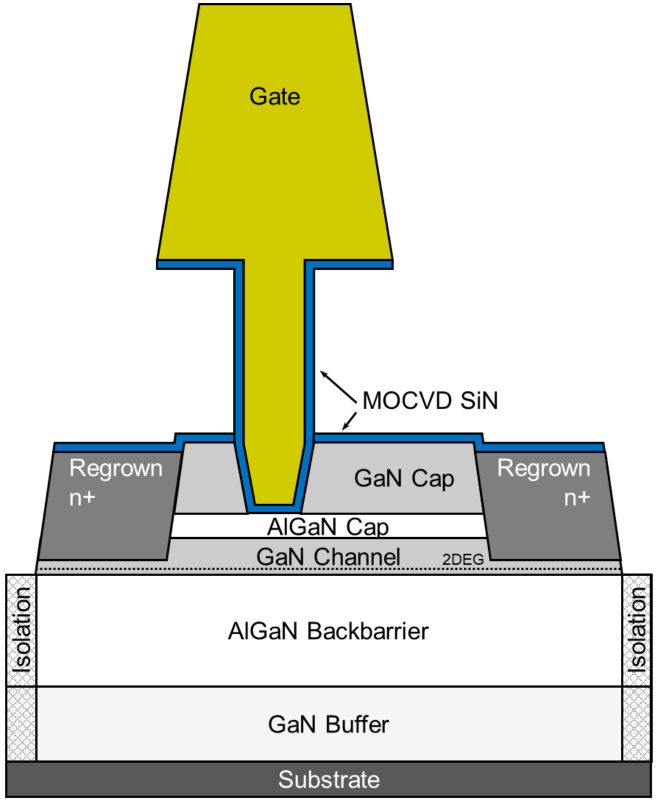


False Color SEM



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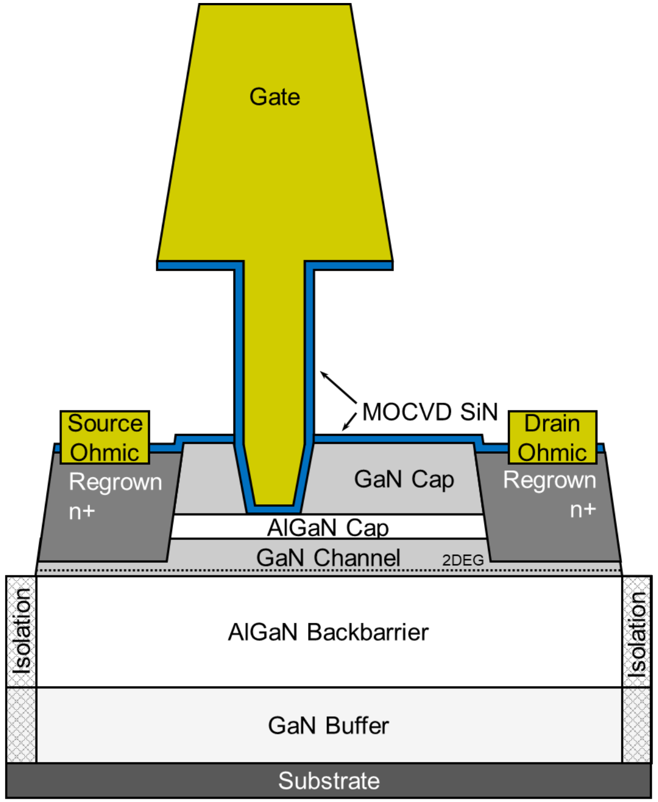
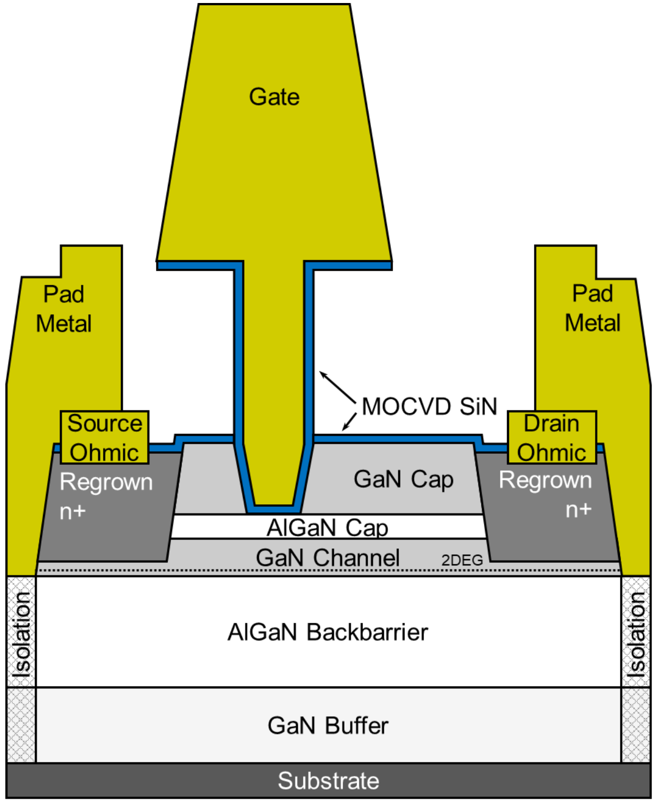
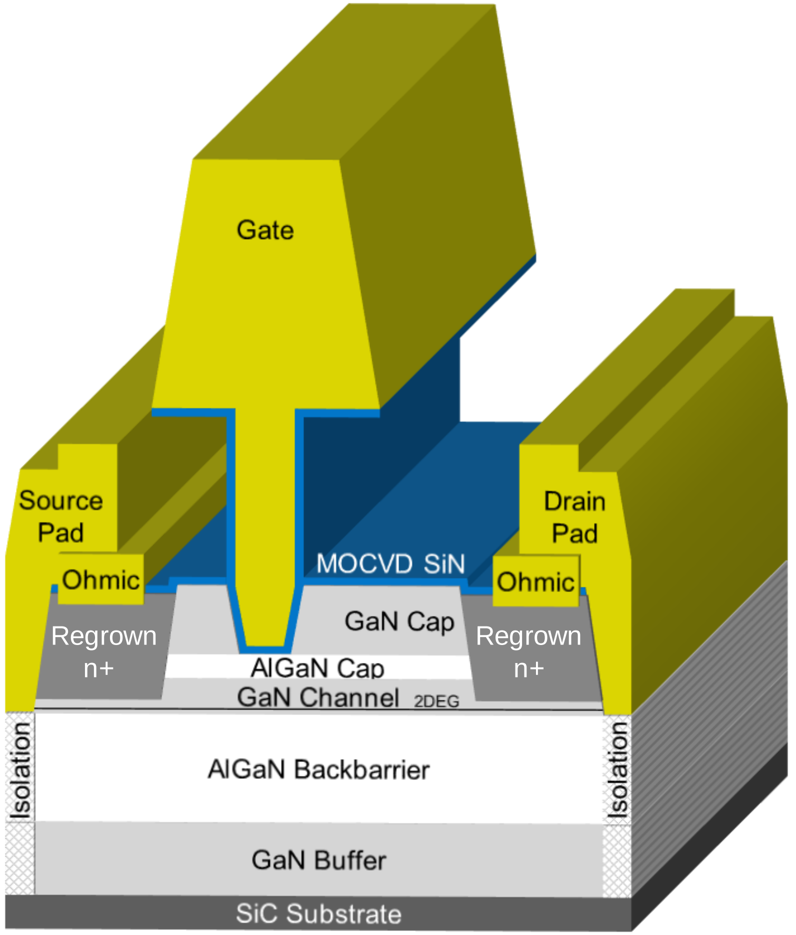


Ohmic Metal
- Ti/Au (20/100 nm)



Pad Metal
- Ti/Au/Ni (30/650/30 nm)



# Outline

I. Introduction
  - mm-Wave Application Space
  - Status of Competing Device Technologies
  - Demonstrated Advantage of N-Polar GaN

II. The N-Polar GaN Deep Recess HEMT
  - Enabling Features of the Device Structure
  - Fabrication Process for Self-Aligned Gate

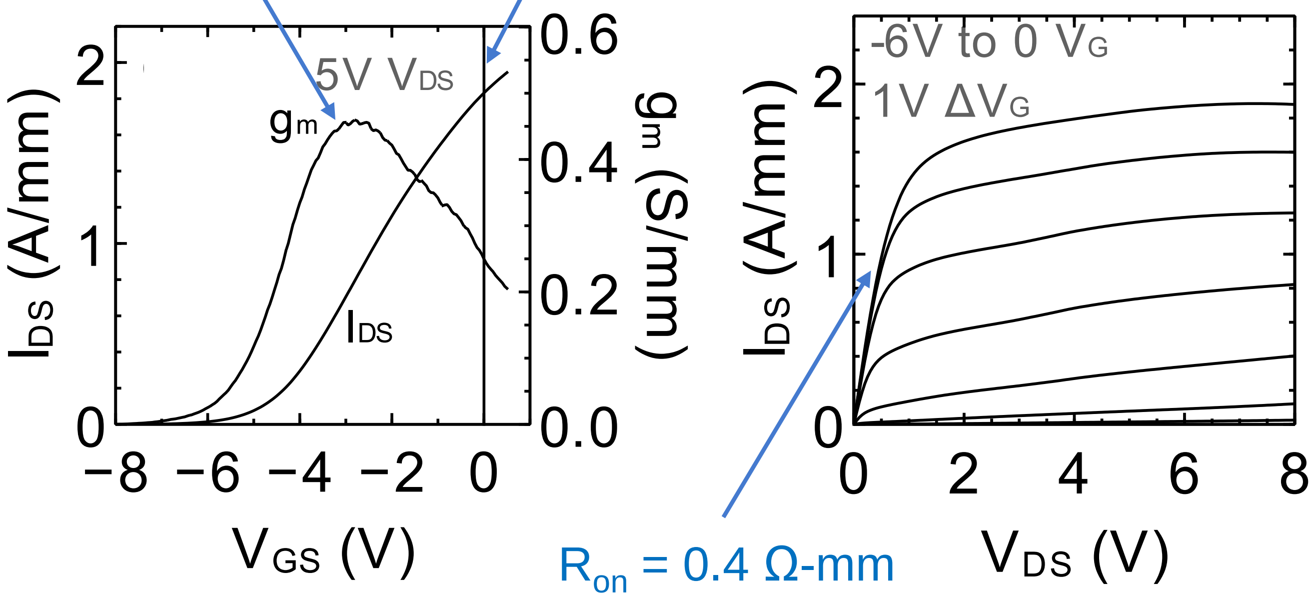
**III. Experimental Results: Large Signal Performance**
  - **W-Band Device Performance (94 GHz)**
  - **Ka-Band Device Performance (30 GHz)**

IV. Conclusion

# N-Polar GaN Deep Recess Device Overview

**Physical Parameters**

$W_G$ = 2×37.5 µm  $t_{channel}$: 12 nm
$L_G$ = 75 nm  $L_{GS}$ = 75 nm  $L_{GD}$ = 250 nm

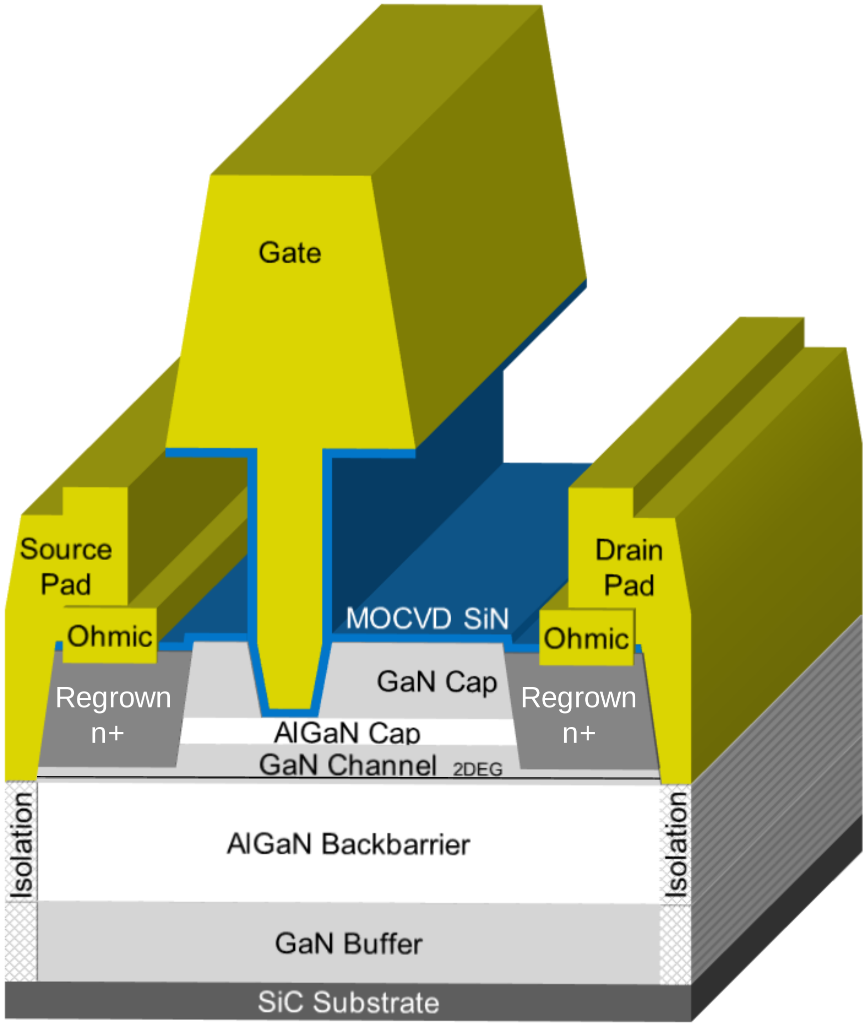


460 mS/mm

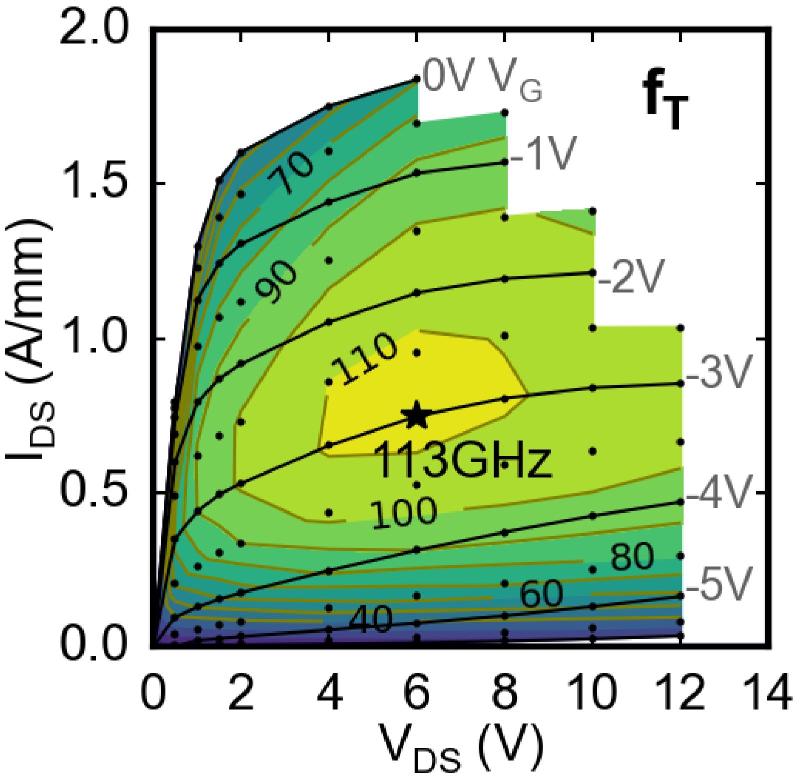
$I_D$ = 1.8 A/mm

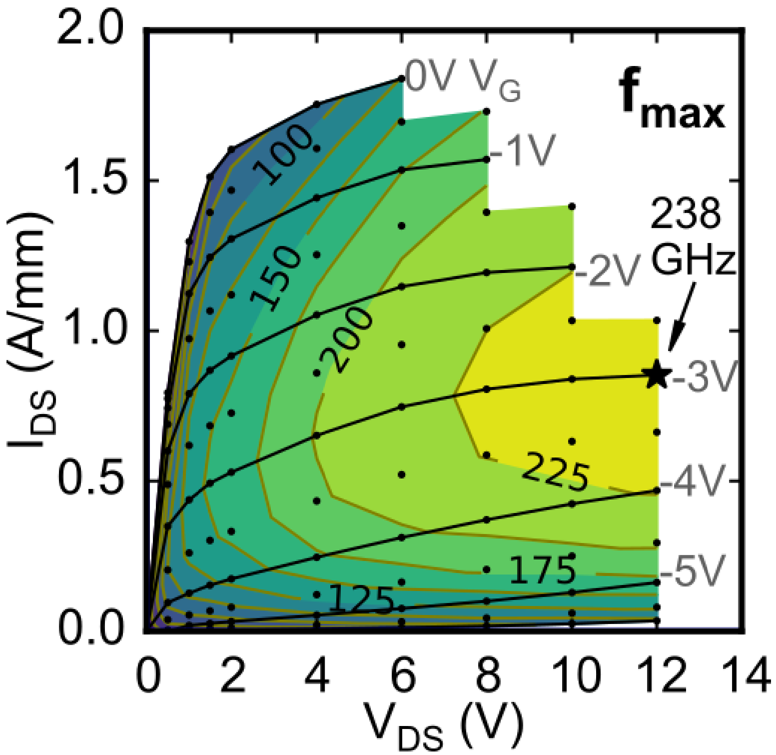
$R_{on}$ = 0.4 Ω-mm

Off-State Breakdown: 38 V



# Small Signal Gain



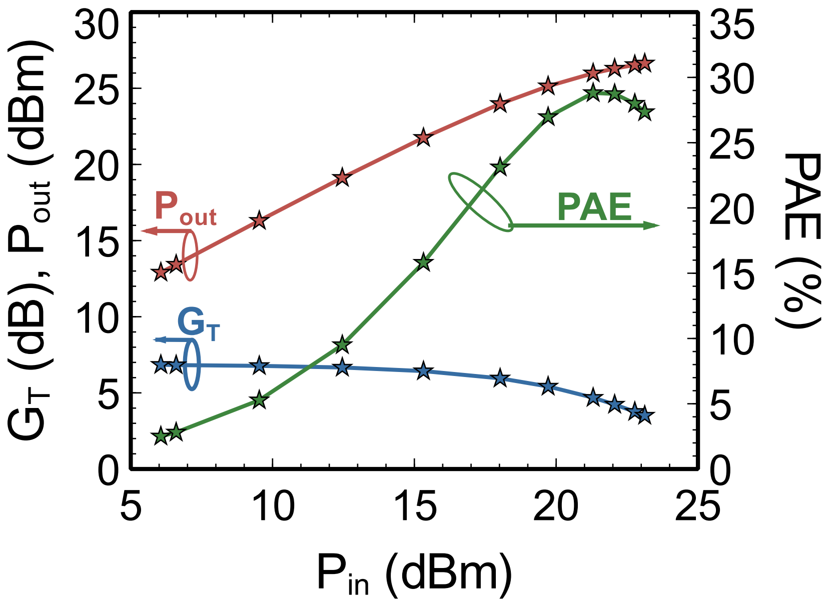


- 113 GHz peak $f_T$
- 238 GHz peak $f_{max}$

# Large Signal Device Evaluation: 94GHz Load Pull

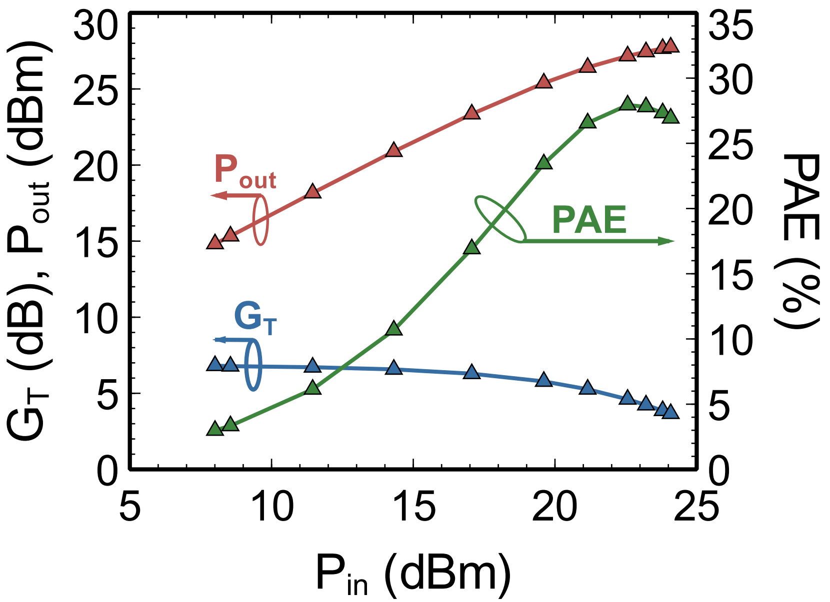
**16V $V_{DS,Q}$**

500 mA/mm (~25% $I_{DS,max}$)



**20V $V_{DS,Q}$**

500 mA/mm (~25% $I_{DS,max}$)



**28.8%** Peak PAE at 16V

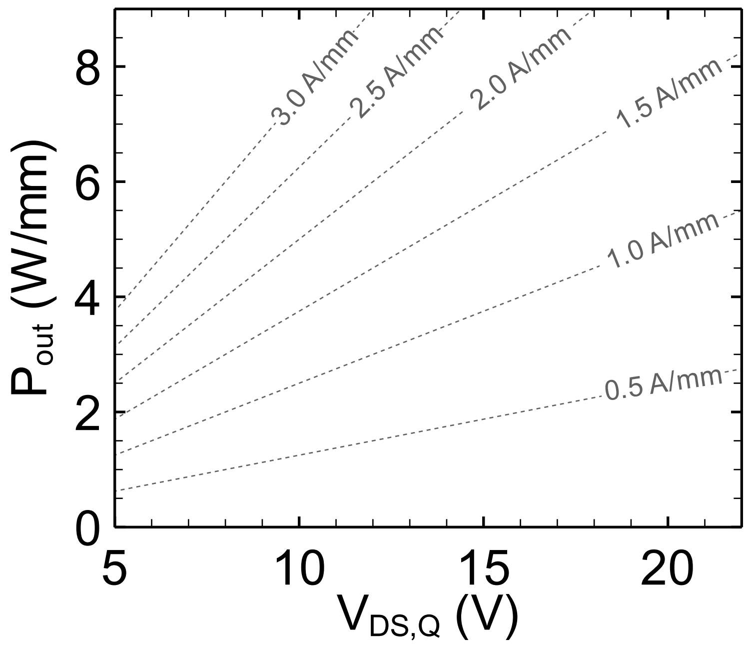
(5.3 W/mm $P_{out}$)

**7.94 W/mm** max $P_{out}$ at

20V (26.9% PAE)

Romanczyk et al. IEEE Trans. Electron Devices. Jan. 2018

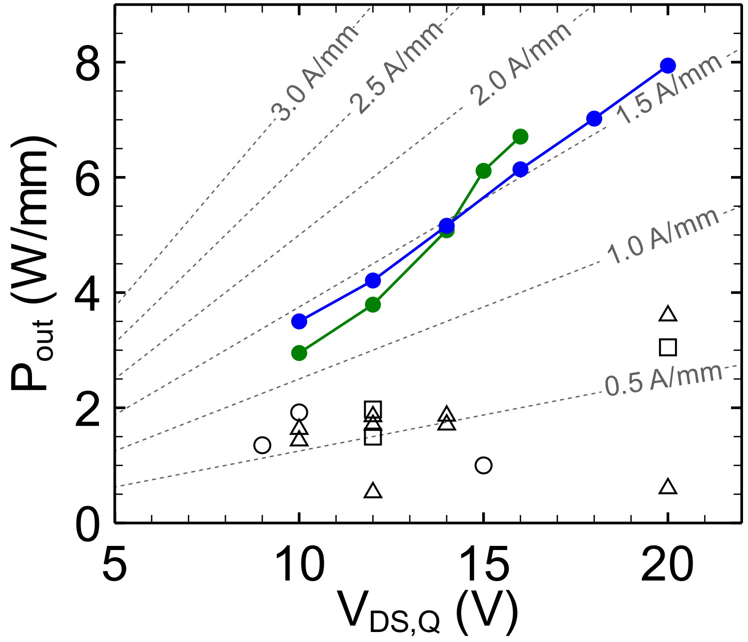
# Comparison with Literature

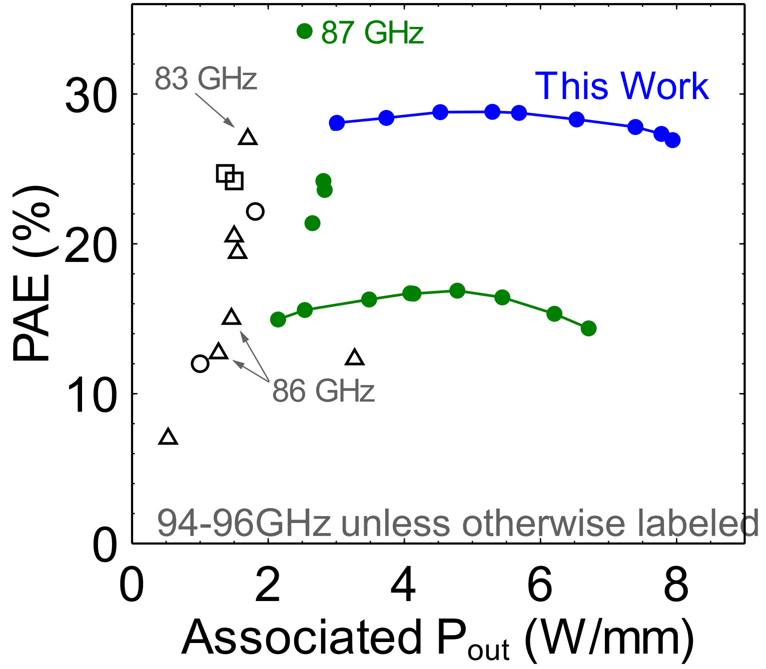


$$P_{out} = \frac{V_{swing} \times I_{swing}}{8} \leq \frac{2 \times V_{DS,Q} \times I_{max}}{8}$$

# N-Polar GaN: **Record W-Band Performance**

Closed Symbols: N-Polar (This Work) Open Symbols: Ga-Polar GaN

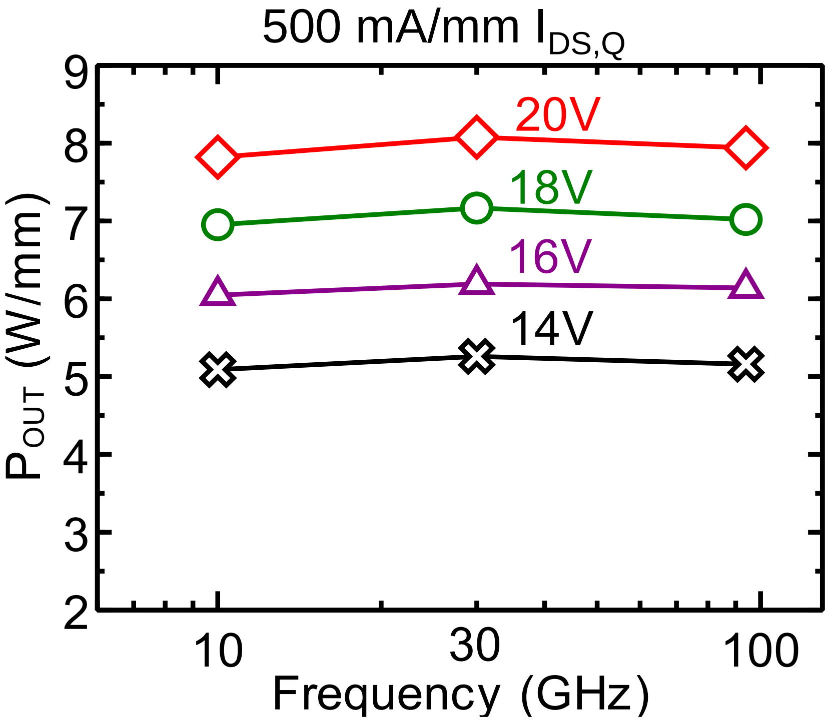




**N-Polar offers greater current density giving higher $P_{out}$**

**Record-high combination of PAE and Power Density**

# Constant 8 W/mm: 10 – 94 GHz



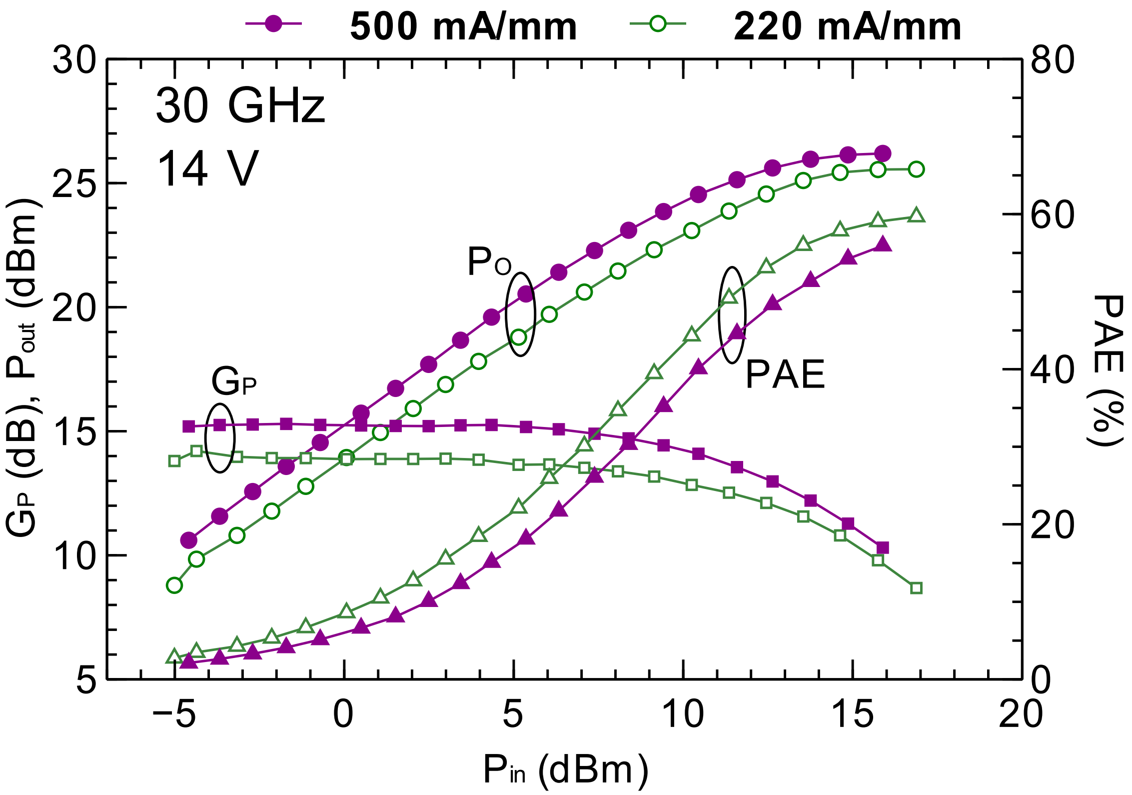
- 94 GHz: UCSB Passive Load pull
- 30 GHz: Maury Microwave MT2000 Active Load pull
- 10 GHz: UCSB Passive Load pull

**First Demonstration of Constant $P_{out}$ from 10 – 94 GHz**

(as expected from ideal FET operation)

Romanczyk et al. IEEE Trans. Electron Devices. Jan. 2018

# Ka-Band Performance (30GHz)

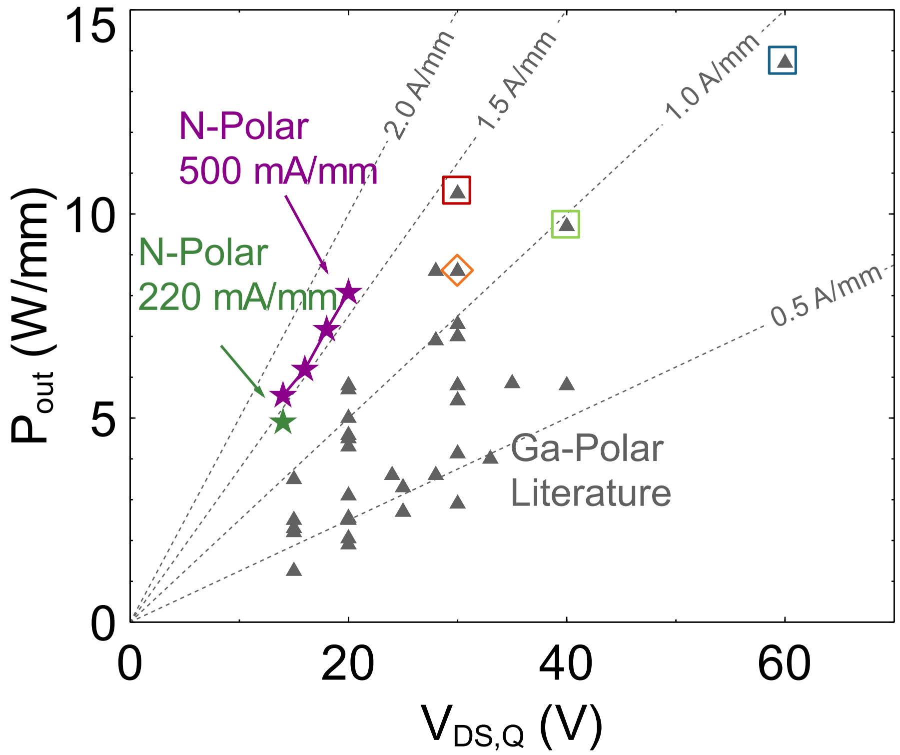


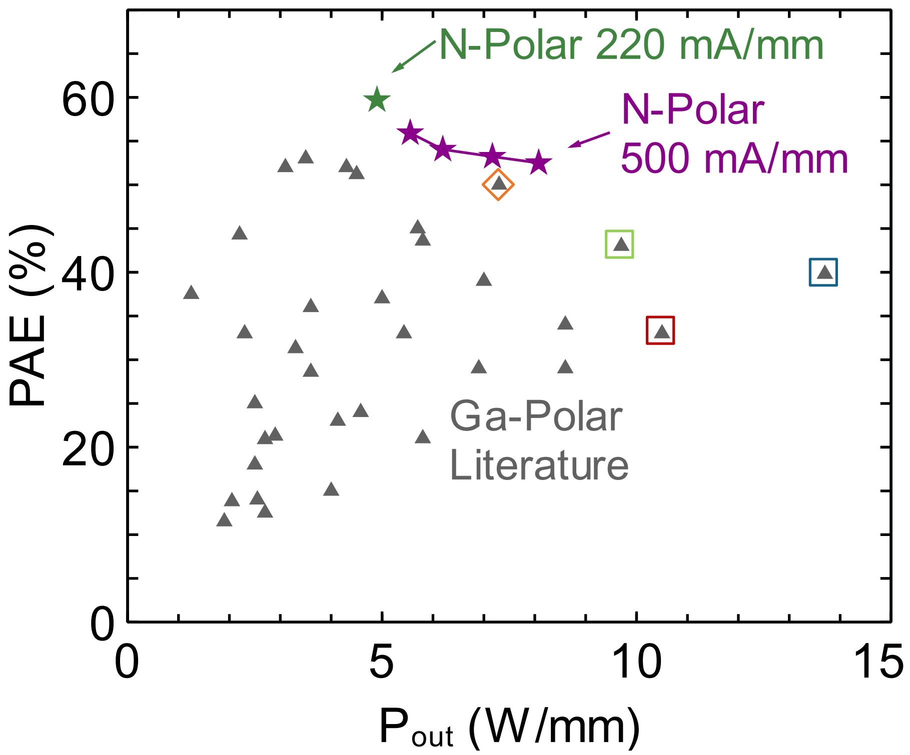
| 500 mA/mm | 220 mA/mm |
|---|---|
| ~25% $I_{DS,max}$ | ~11% $I_{DS,max}$ |
| 15.2 dB $G_{linear}$ | 13.8 dB $G_{linear}$ |
| 55.9% PAE | **59.8% PAE** |
| 5.6 W/mm | 4.9 W/mm |

At 30 GHz increased gain allows access to deeper Class AB operation

Romanczyk et al, GOMACTech 2018

# Ka-Band Load Pull of GaN Devices





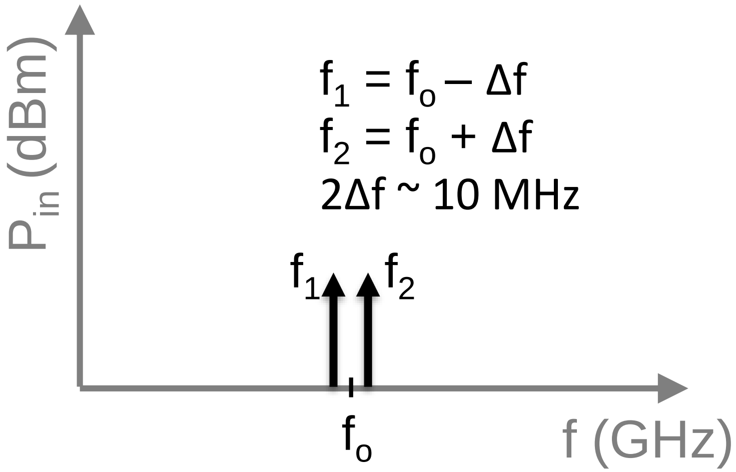
**N-Polar offers greater current density**

**Record-high combination of PAE and Power Density**

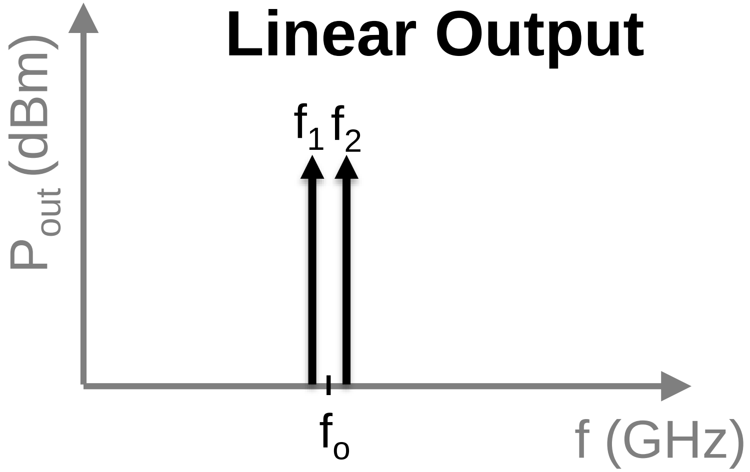
Romanczyk et al, GOMACTech 2018

# Two-Tone Linearity at 30 GHz

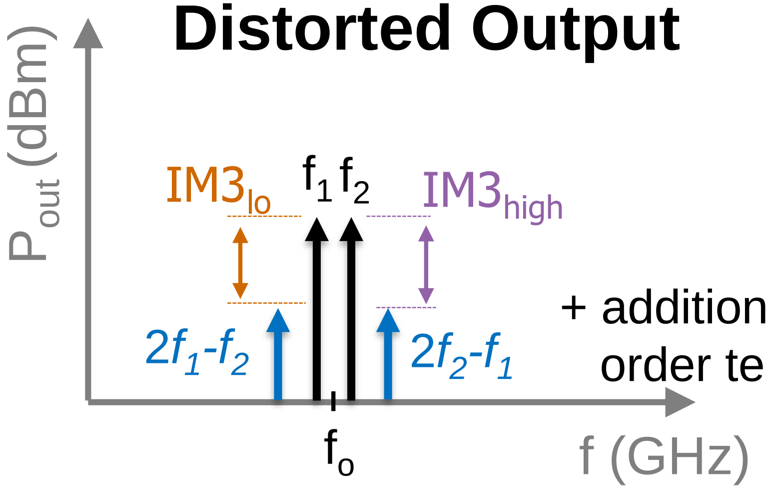
**Input**


$f_1 = f_o - \Delta f$
$f_2 = f_o + \Delta f$
$2\Delta f \sim 10$ MHz

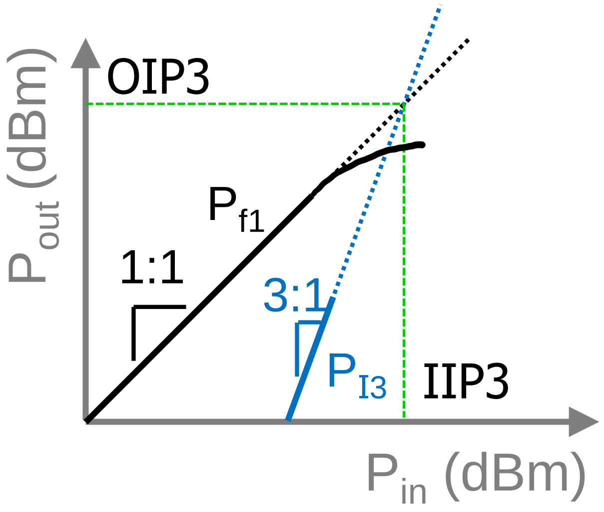
**Linear Output**



**Distorted Output**



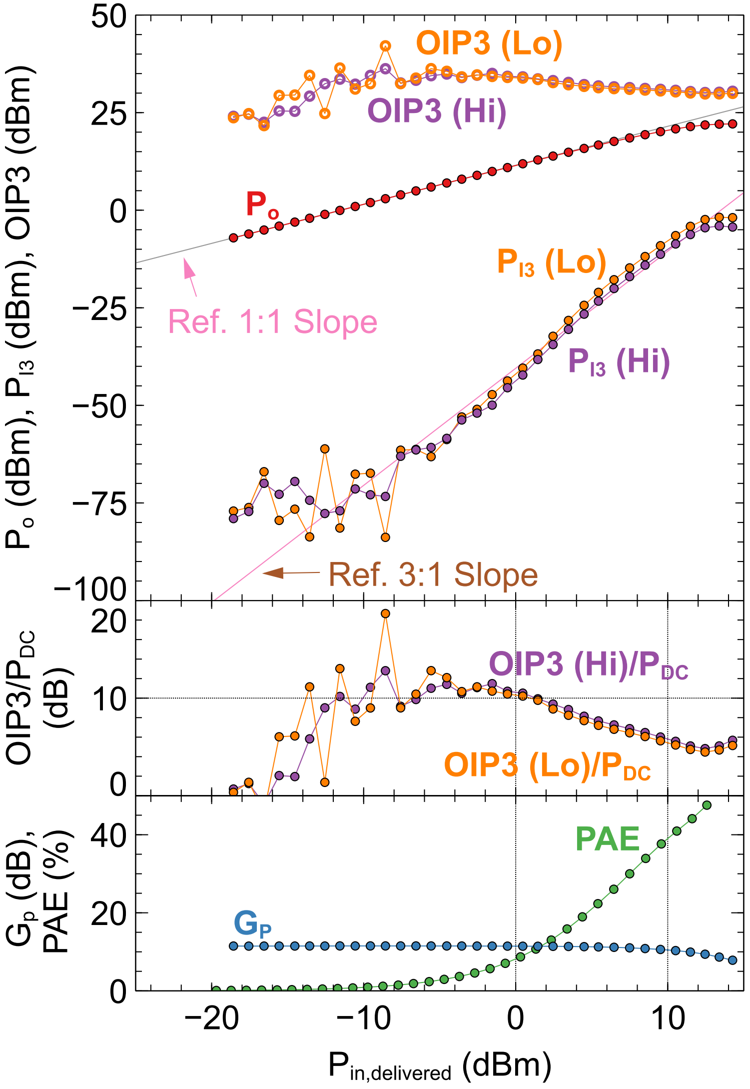
+ additional higher order terms



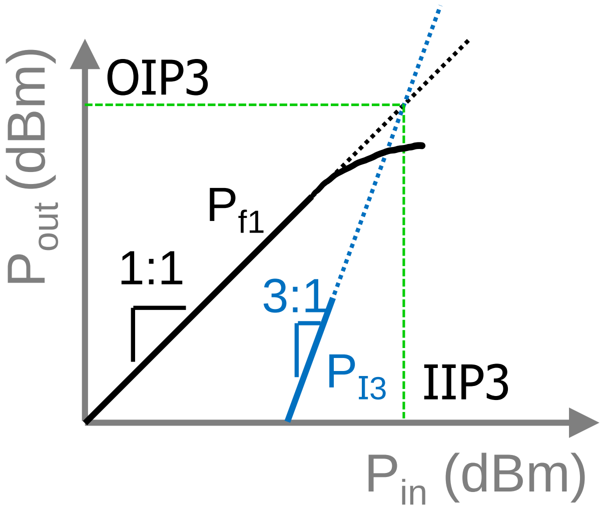
# Two-Tone Linearity at 30 GHz

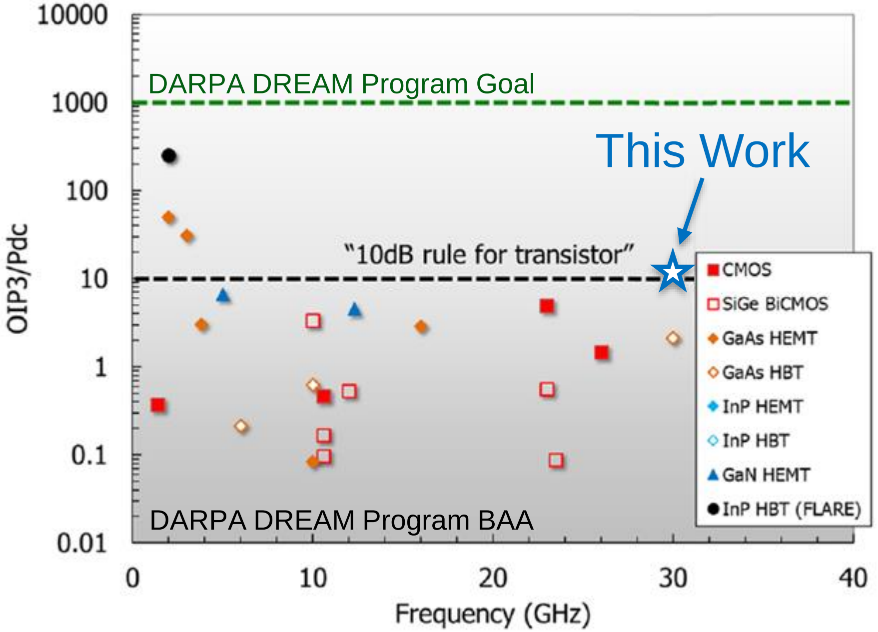
M. Guidry et al, EuMW 2019

**10V $V_D$, 300 mA/mm**



- $P_{I3}$ slope near 3:1
- 35 dBm OIP3
- **11dB OIP3/$P_{DC}$ Figure of Merit**





# Summary

## N-polar Deep Recess HEMT Advantage

- Inverted polarization fields enable the Deep Recess HEMT design
  - ✓ Enhanced Access Region Conductivity
  - ✓ Control of DC-RF Dispersion

## Large-Signal Performance

- **Frequency-Independent $P_{out}$**
- **94GHz:**
  - ✓ Record 8 W/mm $P_{out}$: 4x improvement over traditional Ga-Polar GaN HEMTs
  - ✓ 28.8% Peak PAE
- **30GHz:**
  - ✓ Record High GaN PAE: 59.8%
  - ✓ Record high combinations of PAE and $P_{out}$
  - ✓ 11 dB $OIP_3/P_{DC}$