# Demonstration of Record-High mm-Wave Power Performance using N-Polar Gallium Nitride HEMTs

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With support from ONR (Dr. Paul Maki) and DARPA (Dr. Dan Green)

# Outline

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

II. The N-Polar GaN Deep Recess HEMT
- N-polar vs. Ga-polar GaN HEMTs
- Enabling Features of the Device Structure

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

IV. Summary

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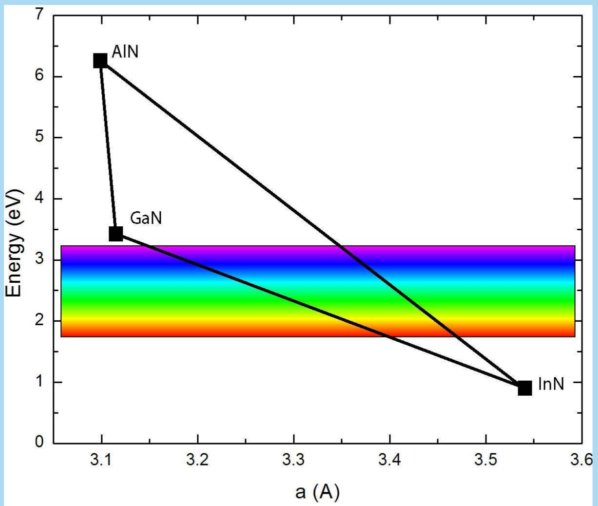
# Why use GaN? Exceptional Performance for Multiple Applications

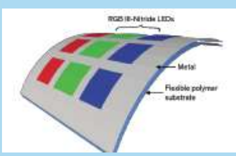
| **Opto-Electronics (LEDs & Lasers)** | Direct bandgap from UV to IR |
|---|---|

| **Analog & Power Electronics (FETs)** | Wide Bandgap (3.4 eV) | Polarization doping |
|---|---|---|
| | • High $V_{BR}$ | • High Mobility & $n_s$ |

LED Lighting




μLED Displays



UV-C LED

Li-Fi

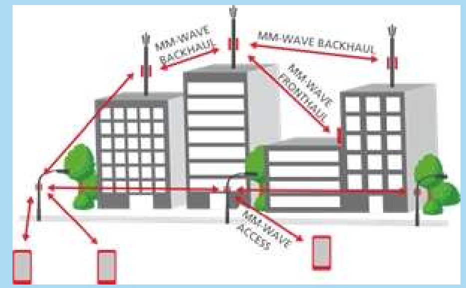

Laser Headlights

LED Horticulture

Laser-based Display


**RF & mm-wave Power Amplification**
(This Work)

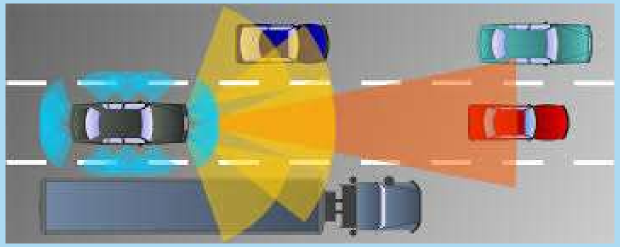
Communications




Radar Imaging

Cloud Radar

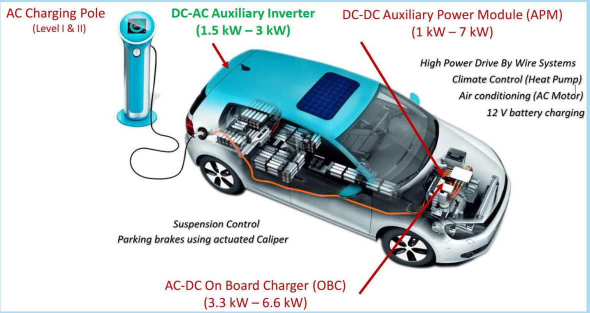
Automotive Radar



**Power Switching**

PV Inverters

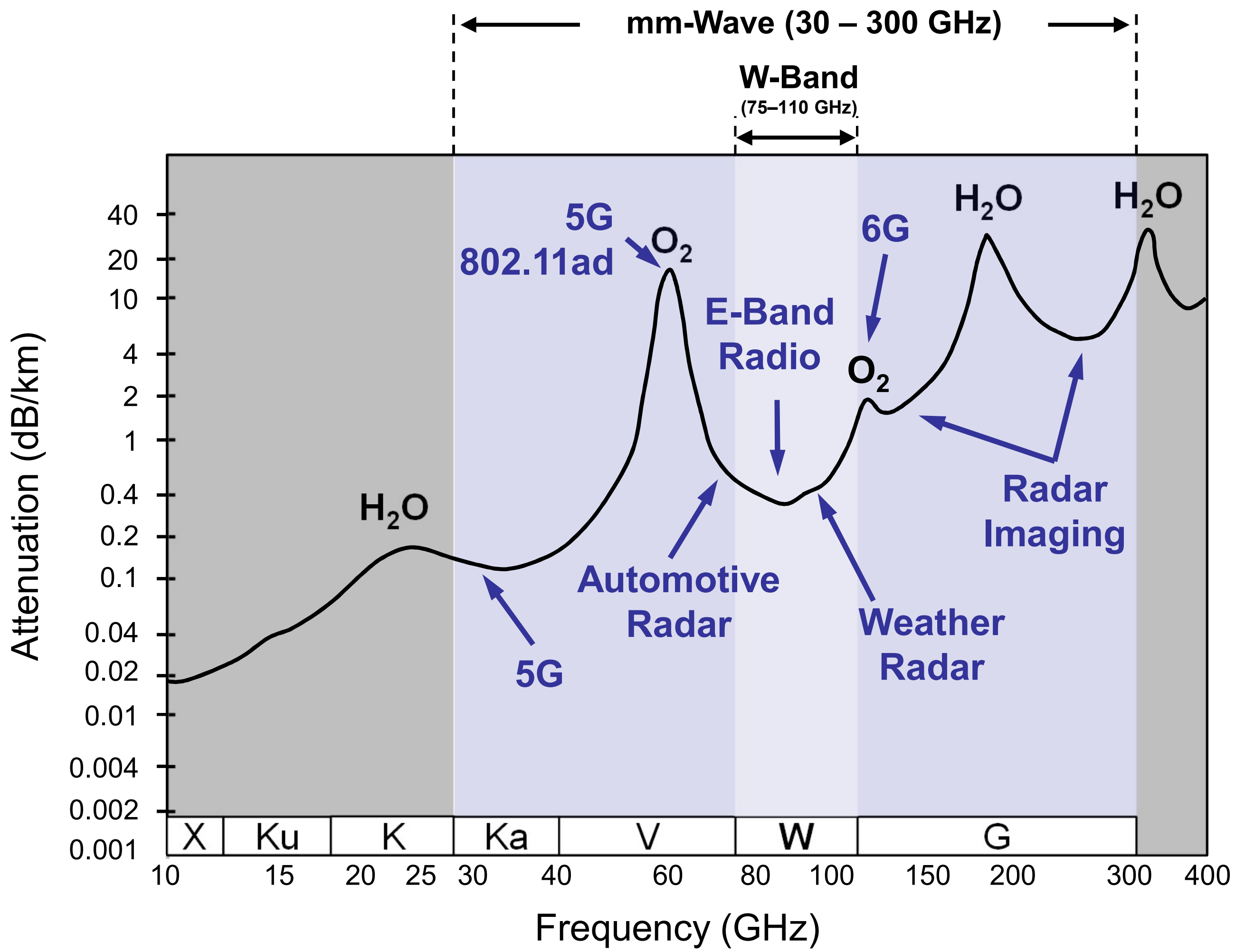
EV Charging & Drive



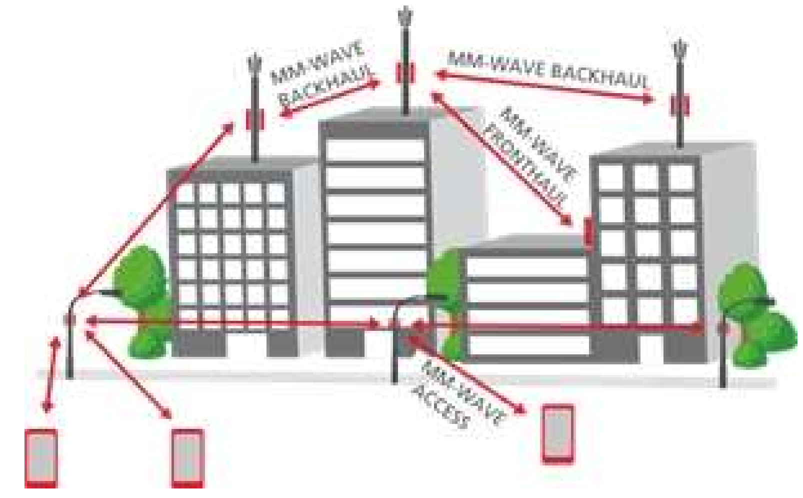

Servo Motor Drives

Power Supplies

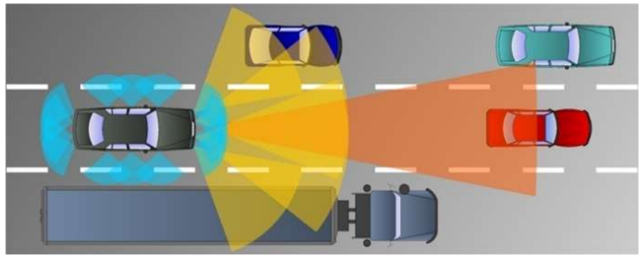
# mm-Wave Applications




5G & 6G Cell Communication

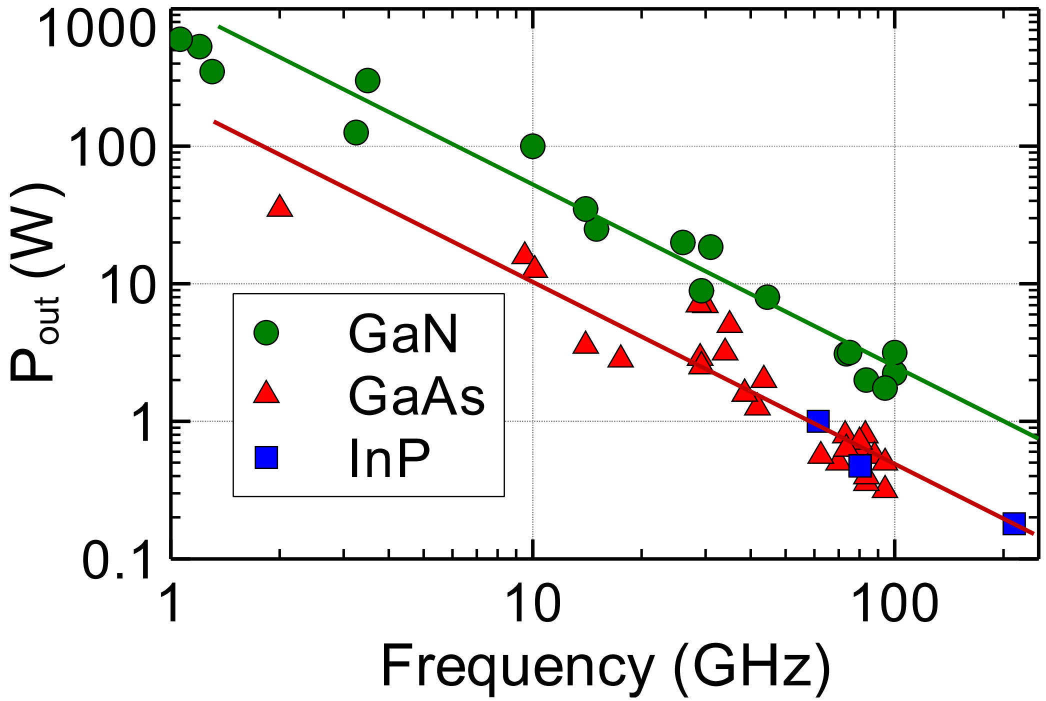



79 GHz: Automotive Radar / Collision Avoidance



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

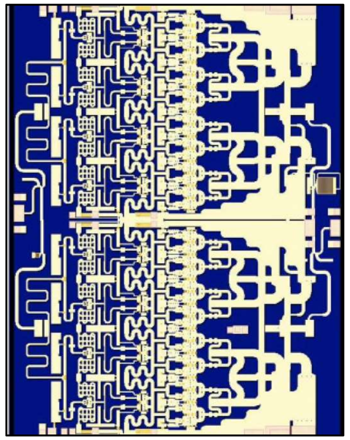
# GaN: Proven Material for Solid-State RF Power Generation




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

Qorvo TGA2575

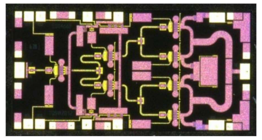
3W **GaAs** Ka-Band PA
5.4 x 4.1mm



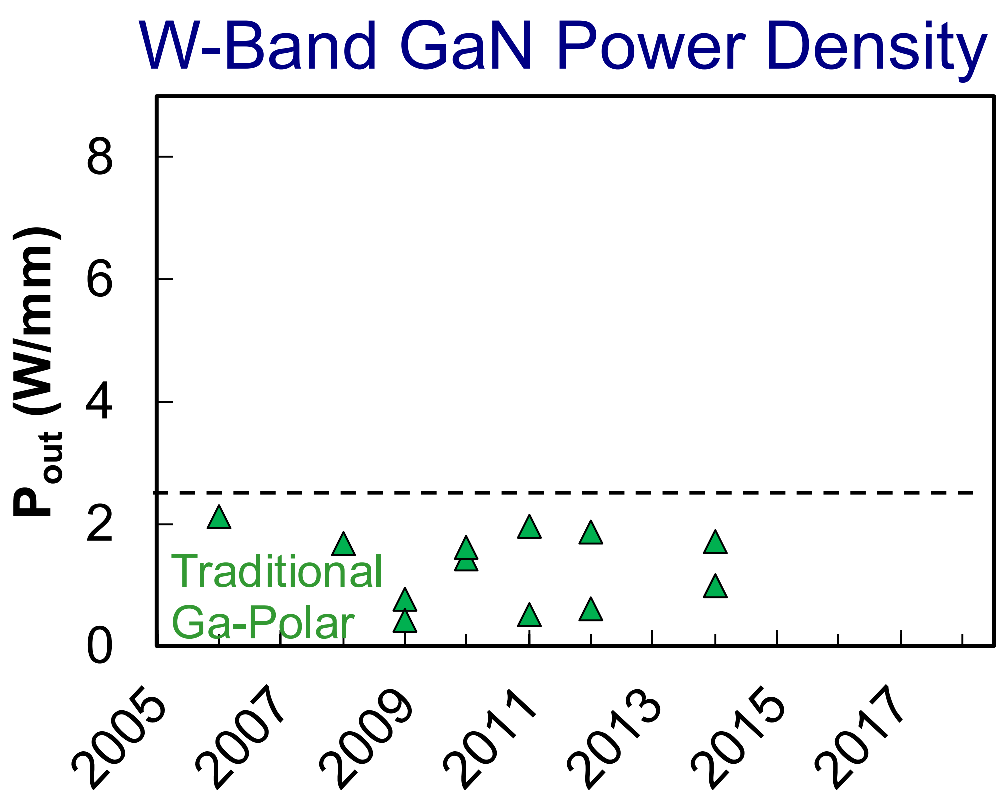
4x Smaller
5% More Efficient

Qorvo TGA2594

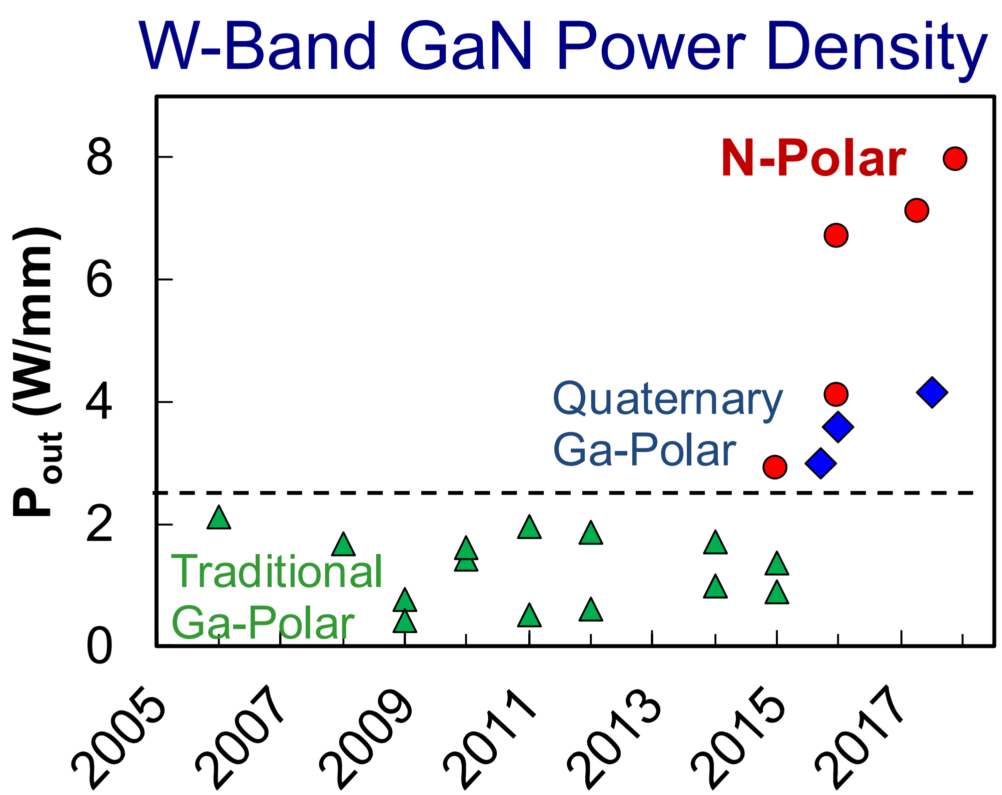
5W **GaN** Ka-Band PA
1.74 x 3.24 mm



# W-Band (75–110 GHz) GaN Power Density



# N-Polar GaN: **Record 8 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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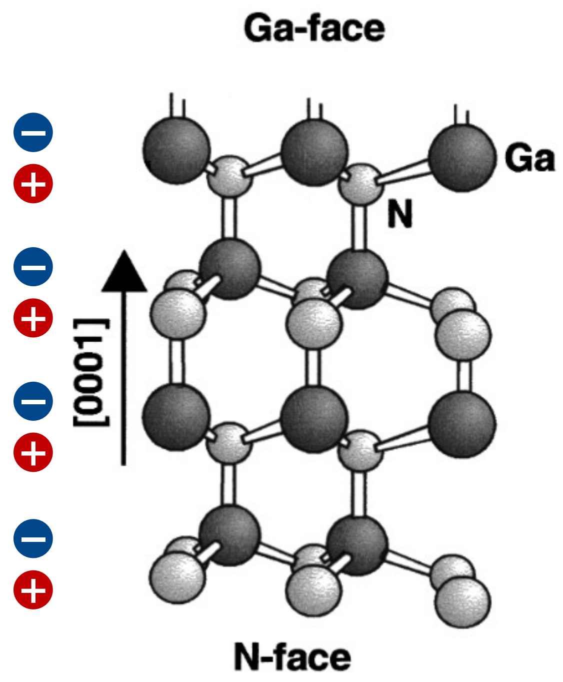
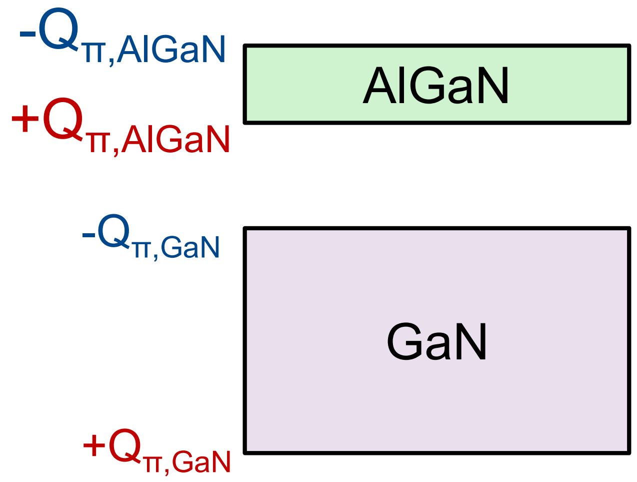
# GaN HEMT: Polarization Doping



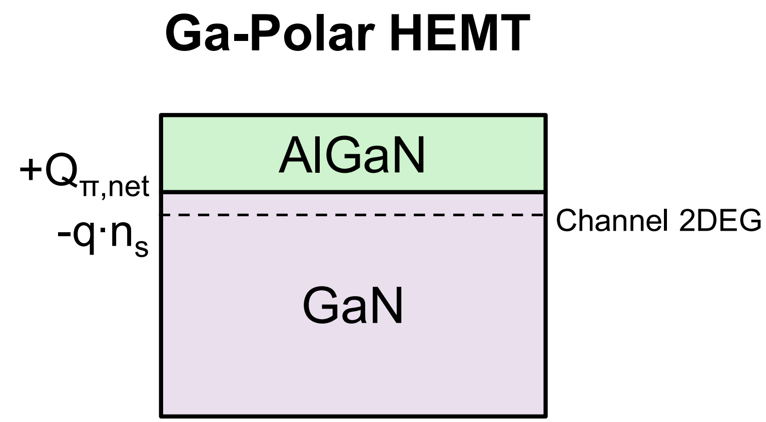

Wurtzite Crystal Structure

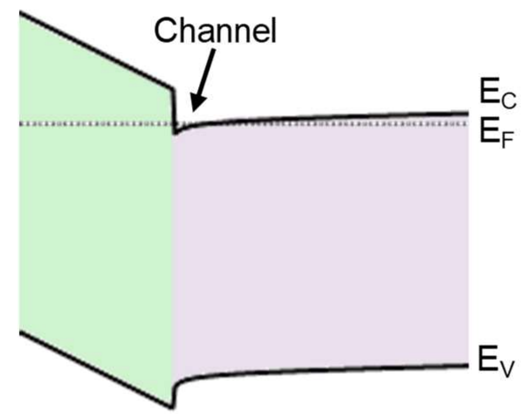
- Strongly polar in [0001] and [000-1] directions




Polarization is a function of Alloy Composition ($Al_xGa_yIn_zN$)

$Q_{\pi,AlGaN} > Q_{\pi,GaN}$

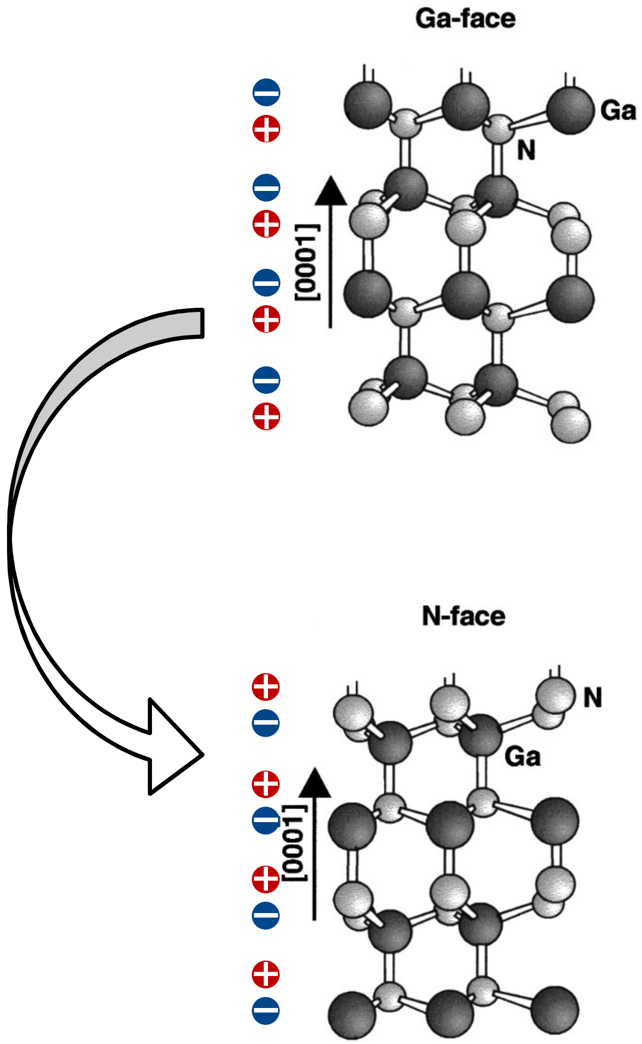


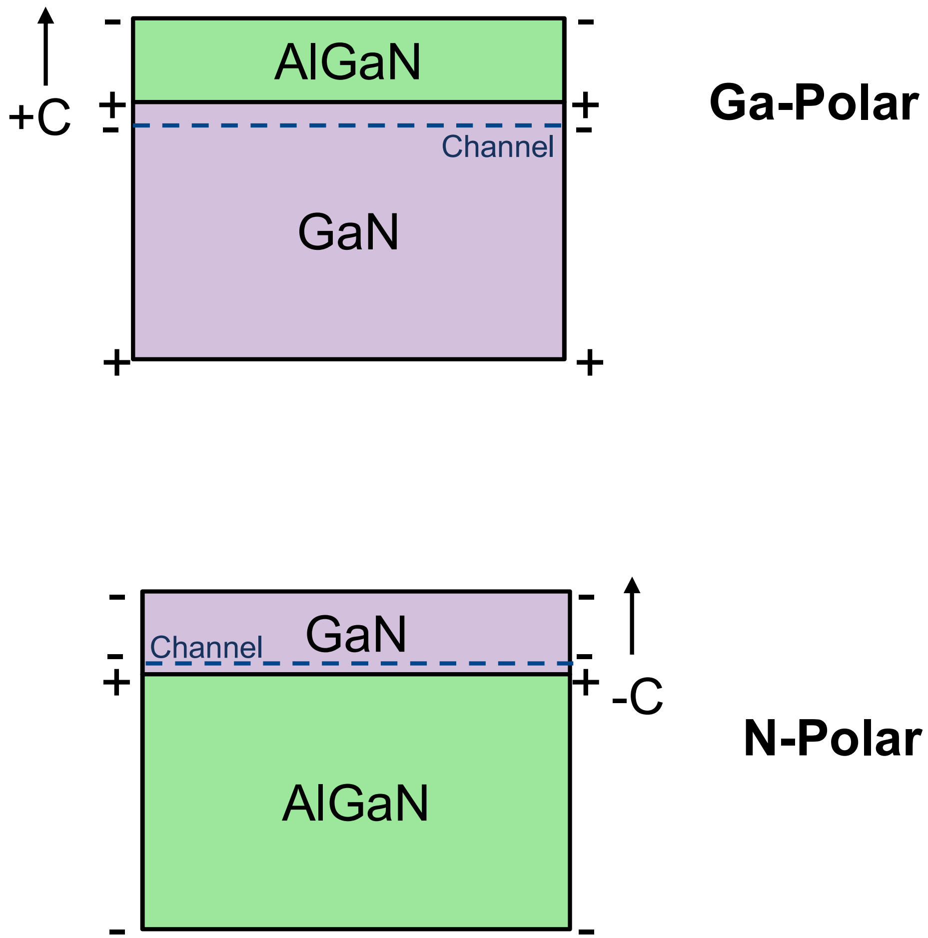



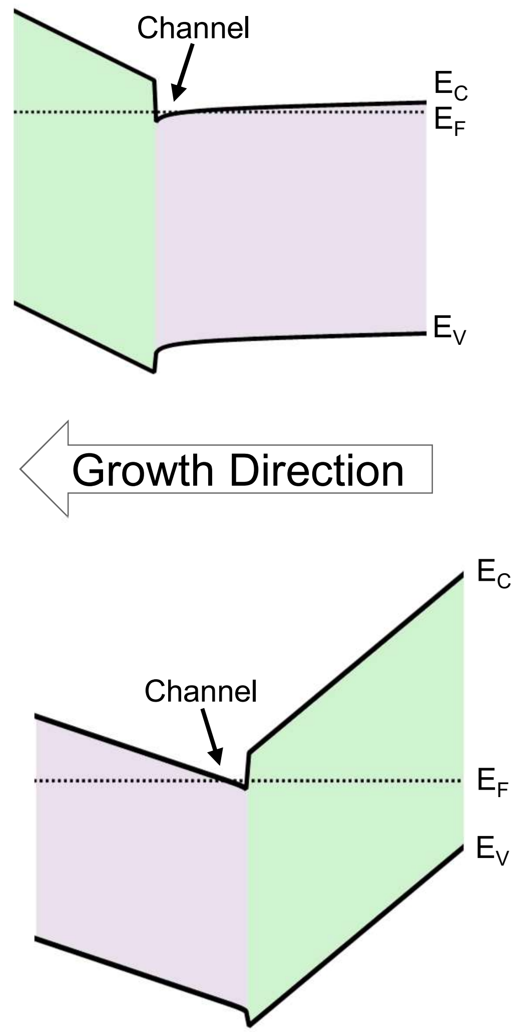

High density (>$10^{13}$ cm$^{-2}$) Channel formed **without impurity doping**

High Mobility & Channel Conductivity

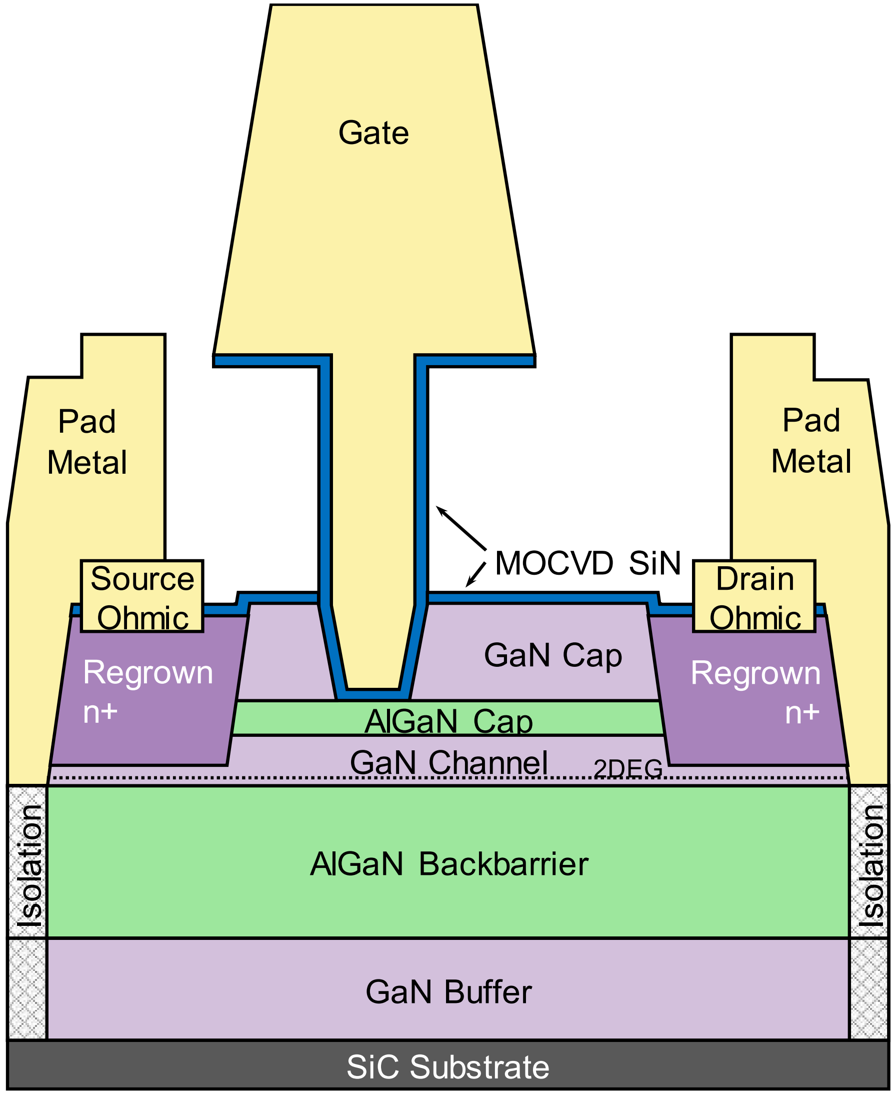
# N-Polar vs. Ga-Polar GaN: Inverted Polarization Fields



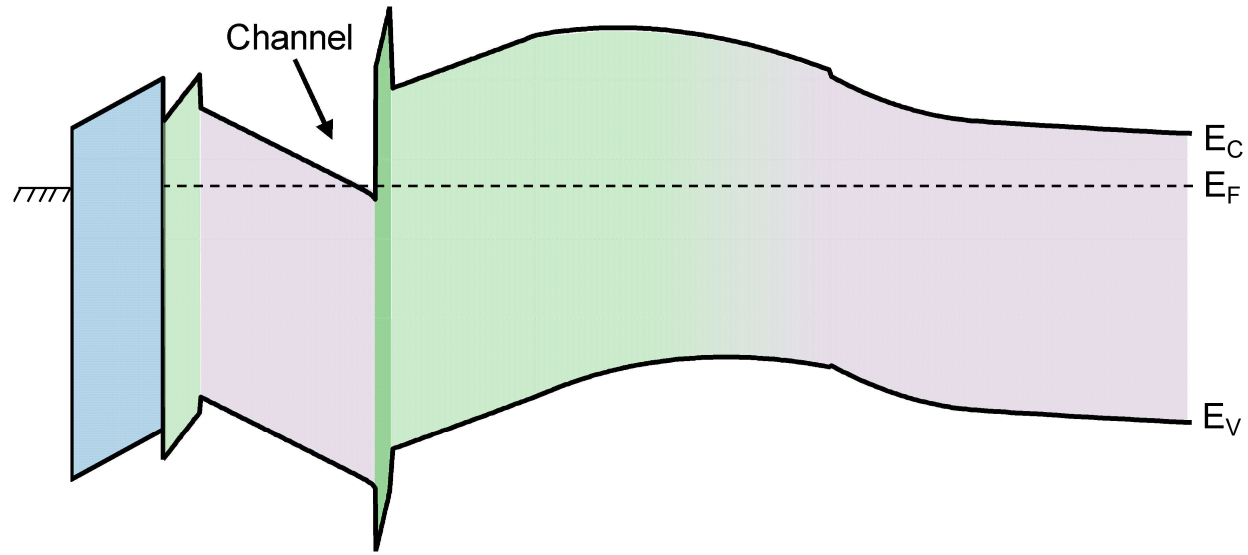



# The N-Polar GaN Deep Recess HEMT Structure

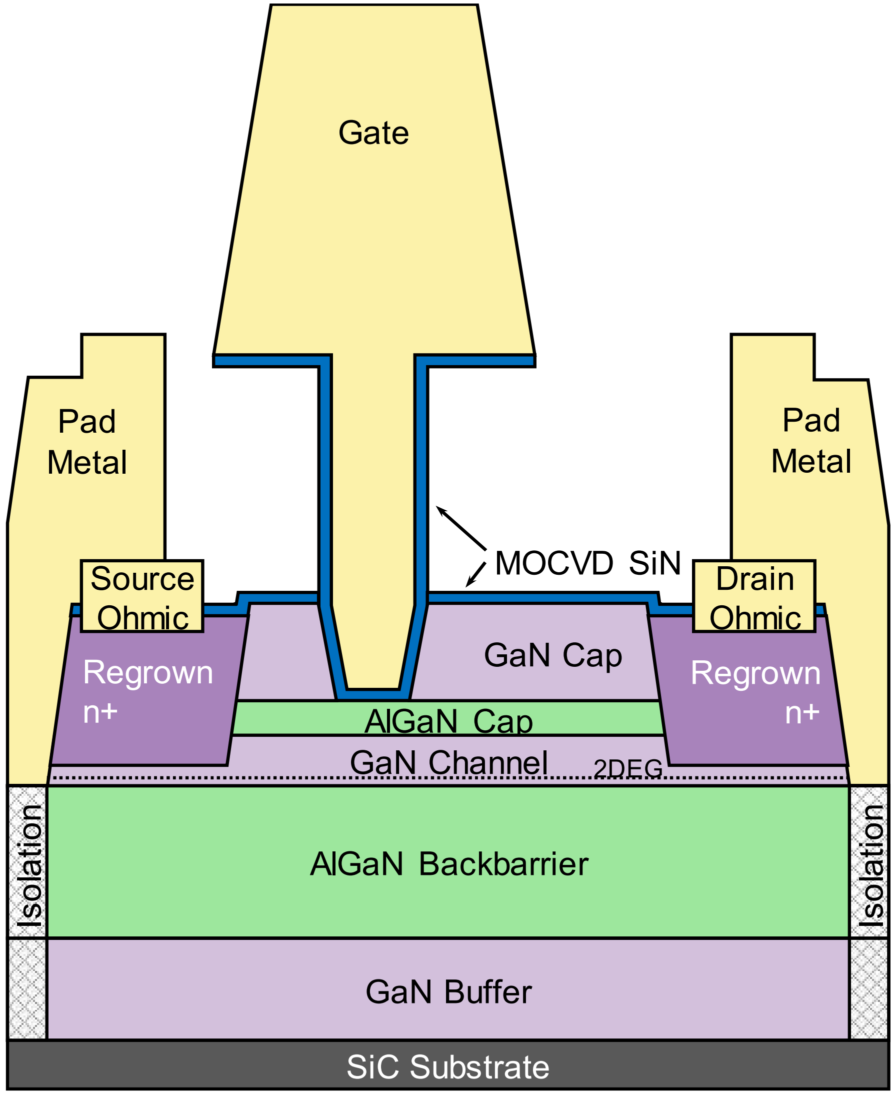



## N-Polar Deep Recess Structure

- ✓ 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

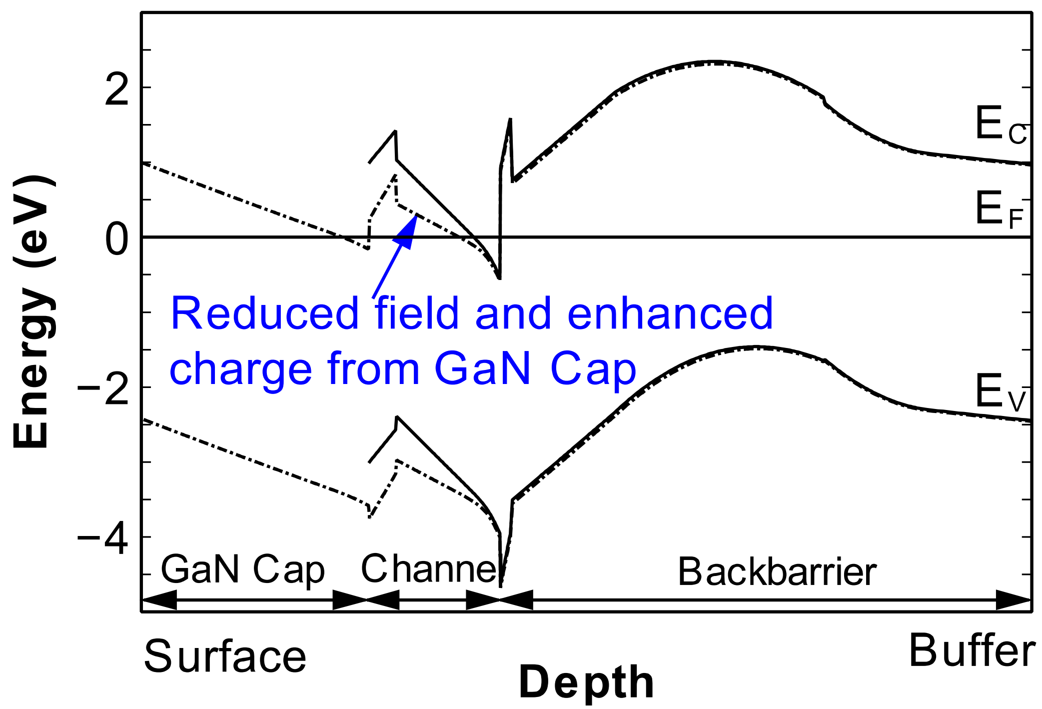


# N-Polar Deep Recess Design: **The GaN Cap**

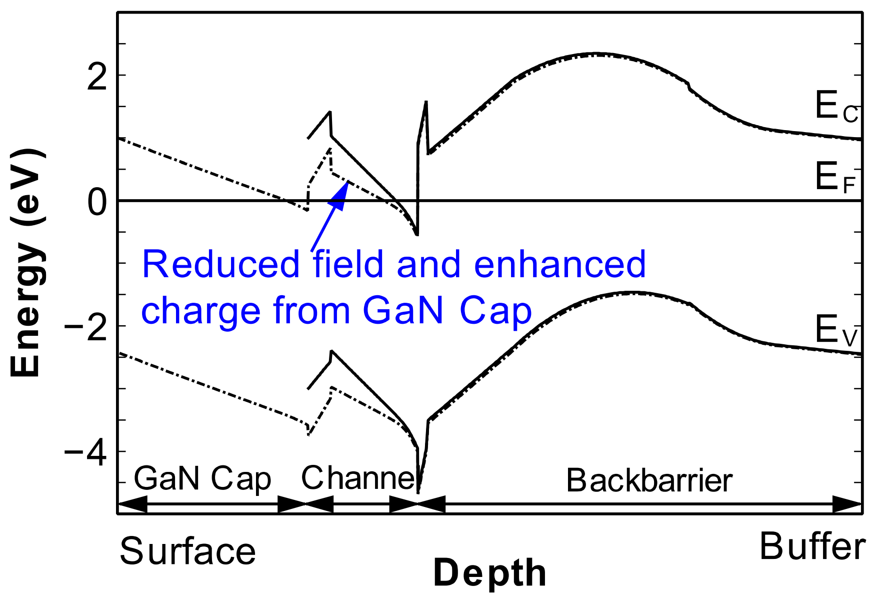


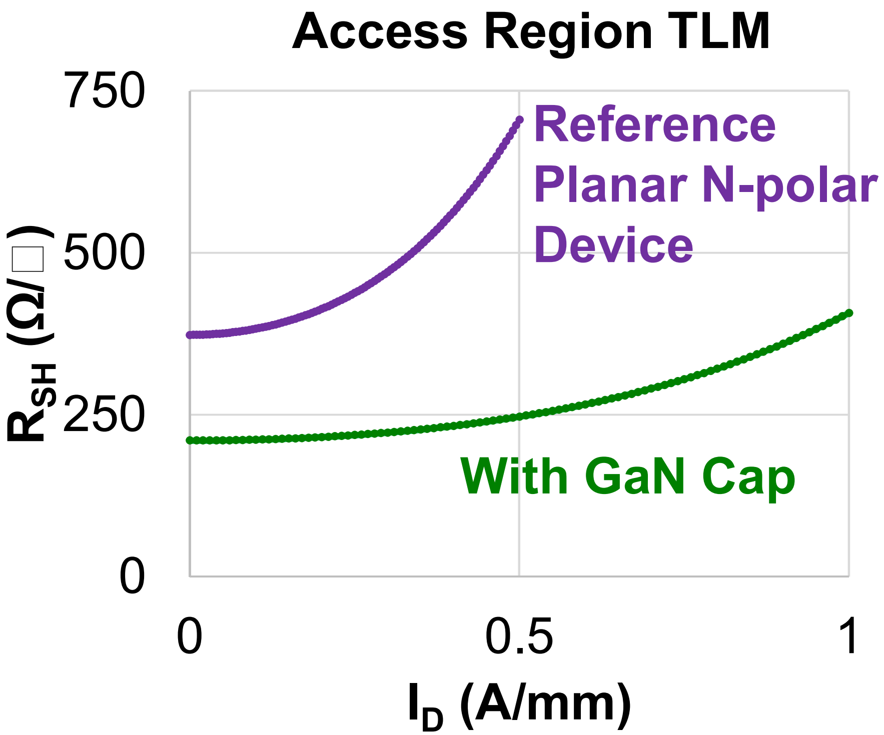

### Features of the GaN Cap in Access Regions

- Polarization **increases $n_s$** and **improves $\mu_n$**
  - **Enhanced Conductivity**: improves Gain & Power
  - **Dispersion Control**
- In-Situ Growth
- Highly selective recess etch: process well controlled



# GaN Cap Advantage #1: Access Region Conductivity

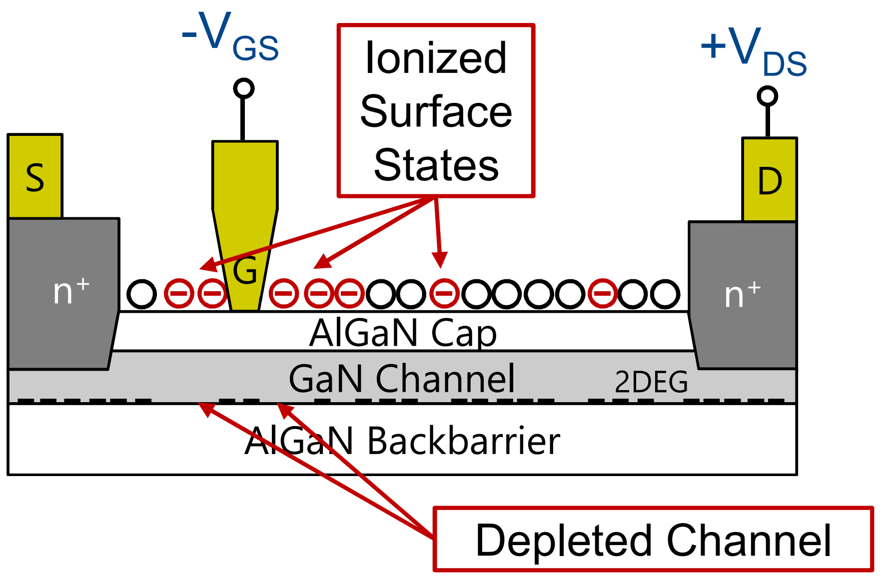


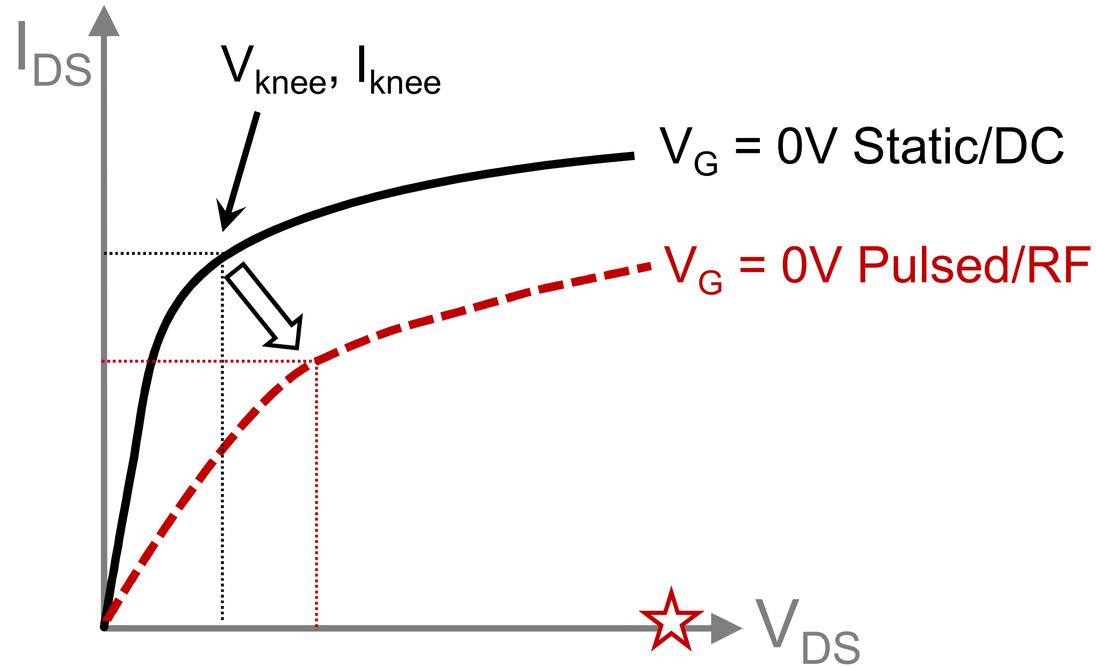




Polarization also reduces |E| in the GaN channel ⇨ improves mobility

- 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

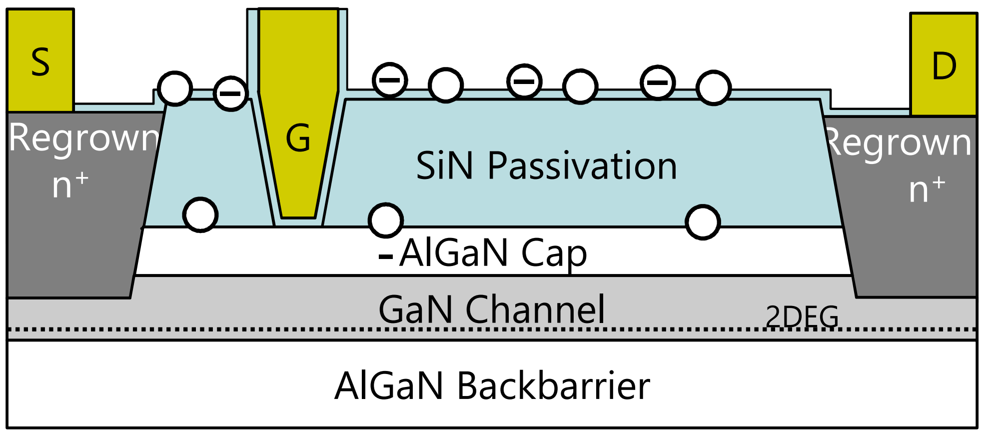
Charge state responds to DC bias

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

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

# Traditional Solutions to Dispersion

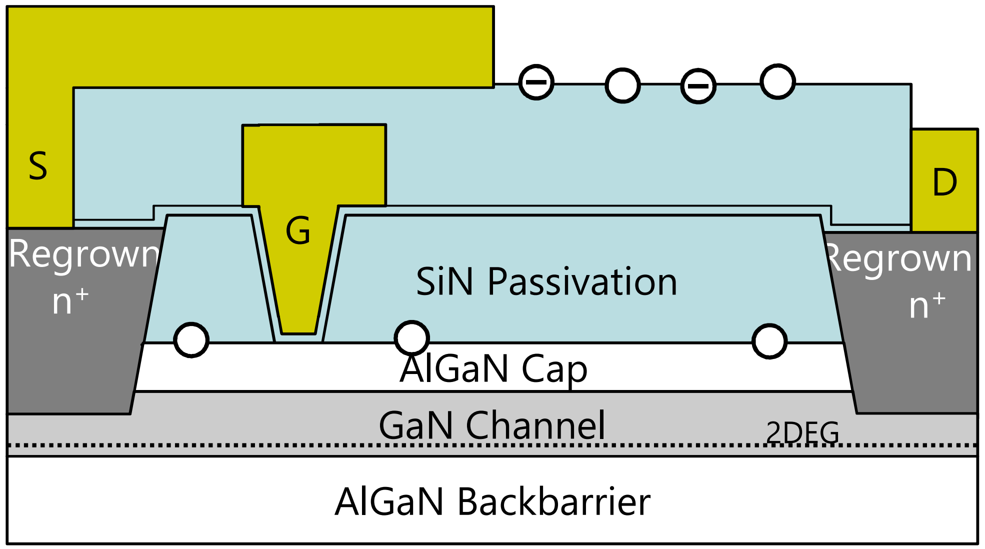
## SiN Passivation




SiN passivates surface states & moves external surface far from channel

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

## SiN + Field Plates

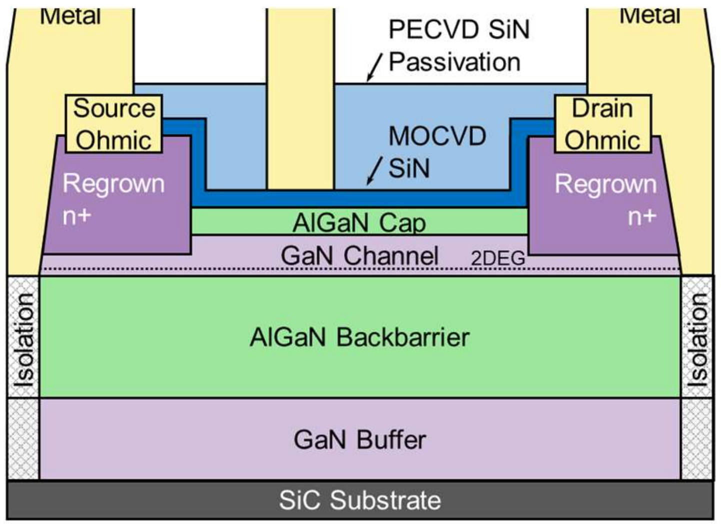



Reduced electric field prevent trap ionization

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

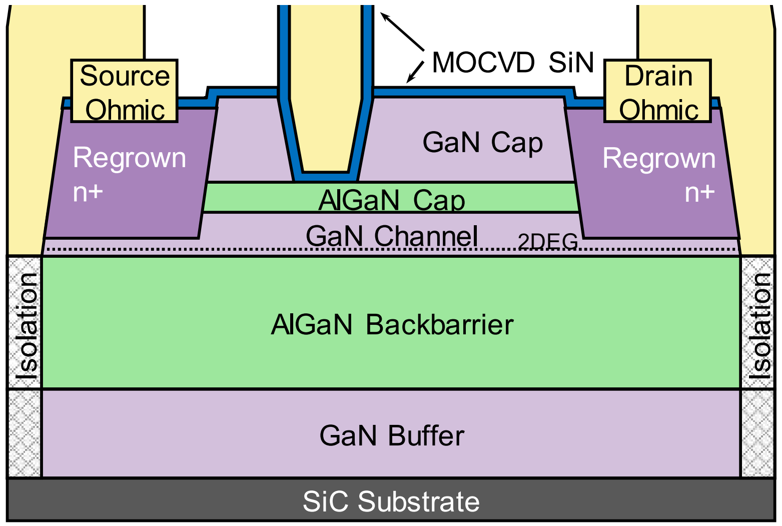
# GaN Cap Advantage #2: Dispersion Control

**Planar N-Polar HEMT**

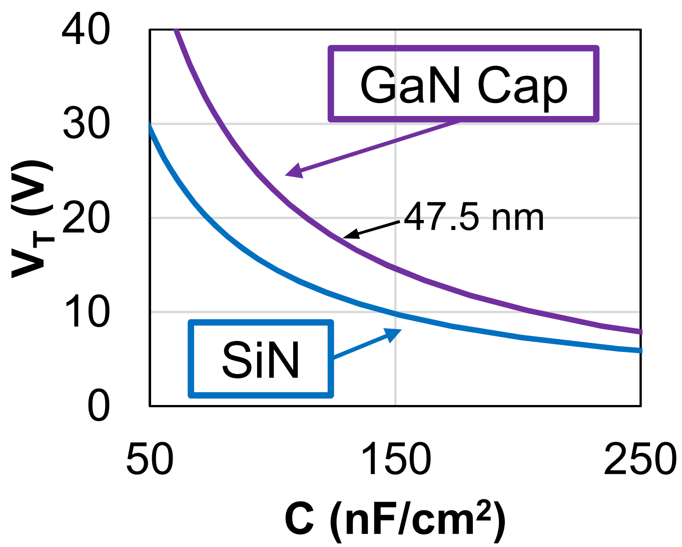



SiN passivation replaced by GaN cap

**Deep Recess N-Polar HEMT**

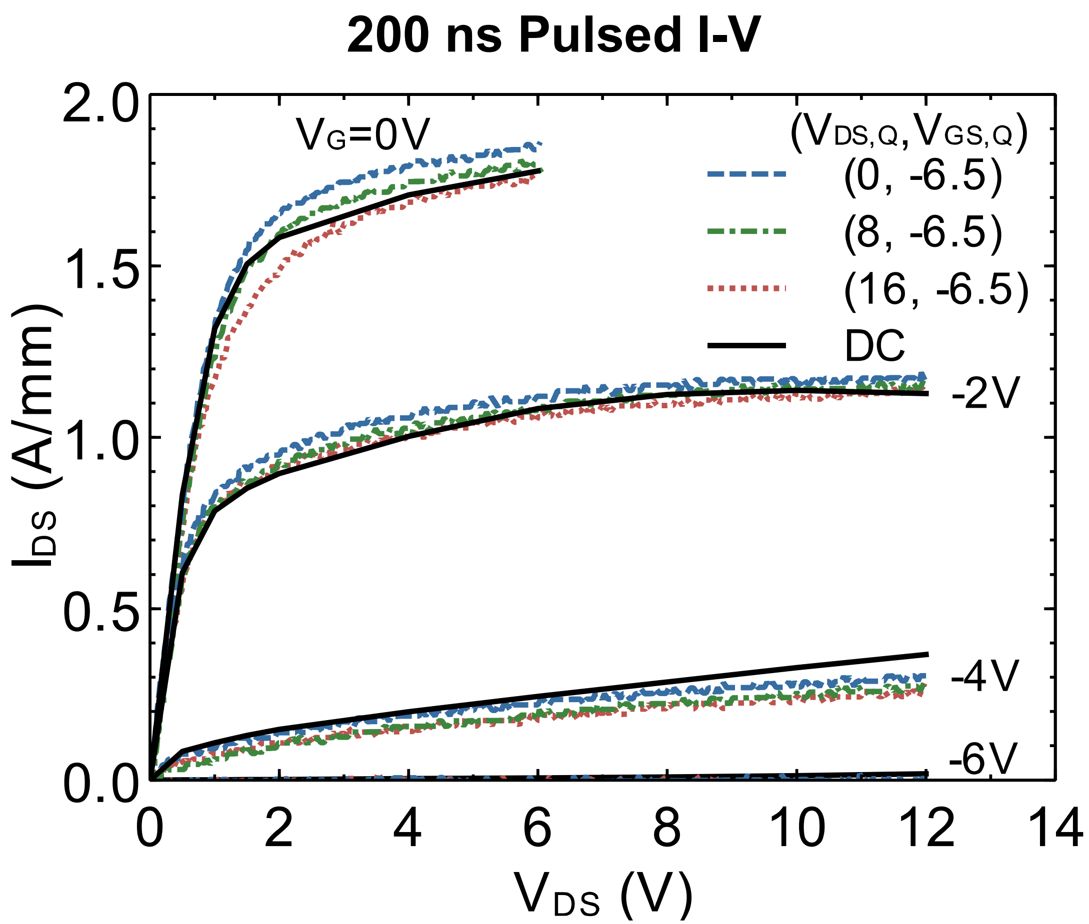



$$V_T = \frac{qn_s}{C}$$




- 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 $V_{DS,Q}$

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

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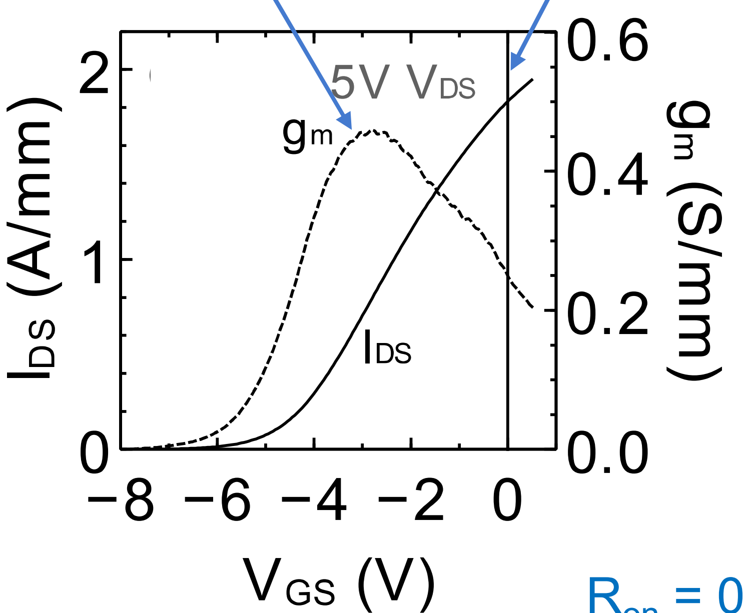
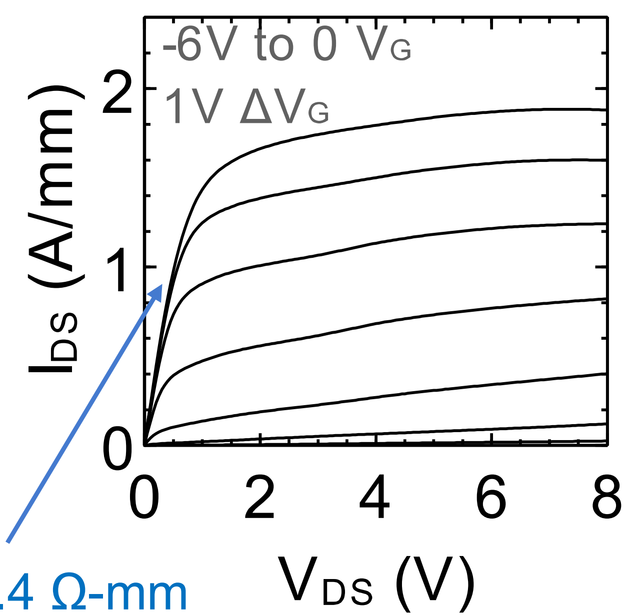
# N-Polar GaN Deep Recess Device Overview

| 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

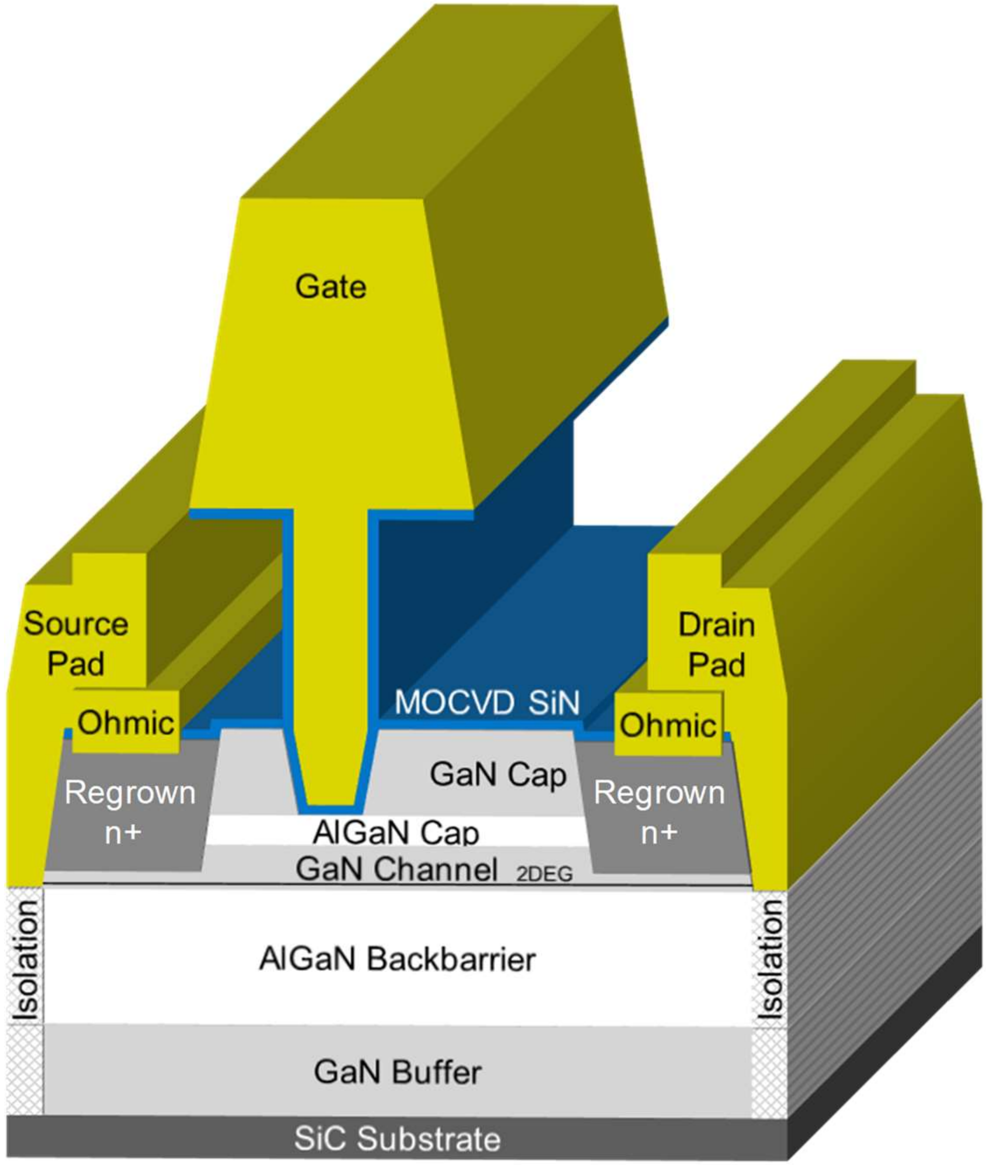
$I_D$ = 1.8 A/mm



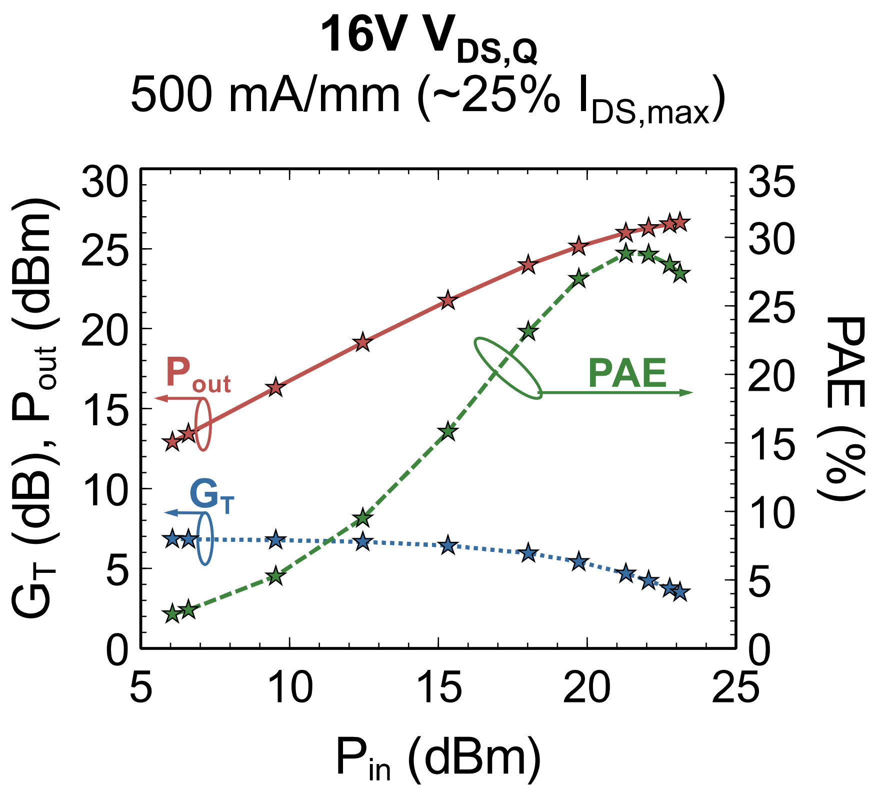



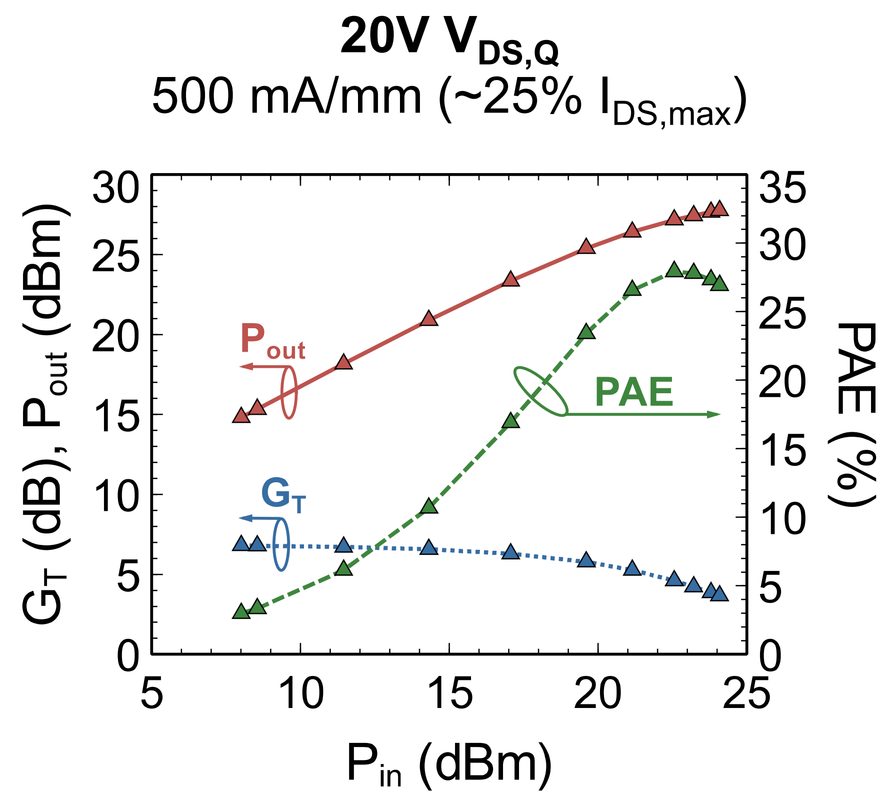

$R_{on}$ = 0.4 Ω-mm

Off-State Breakdown: 38 V



# Large Signal Device Evaluation: 94GHz Load Pull




**28.8%** Peak PAE at 16V

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

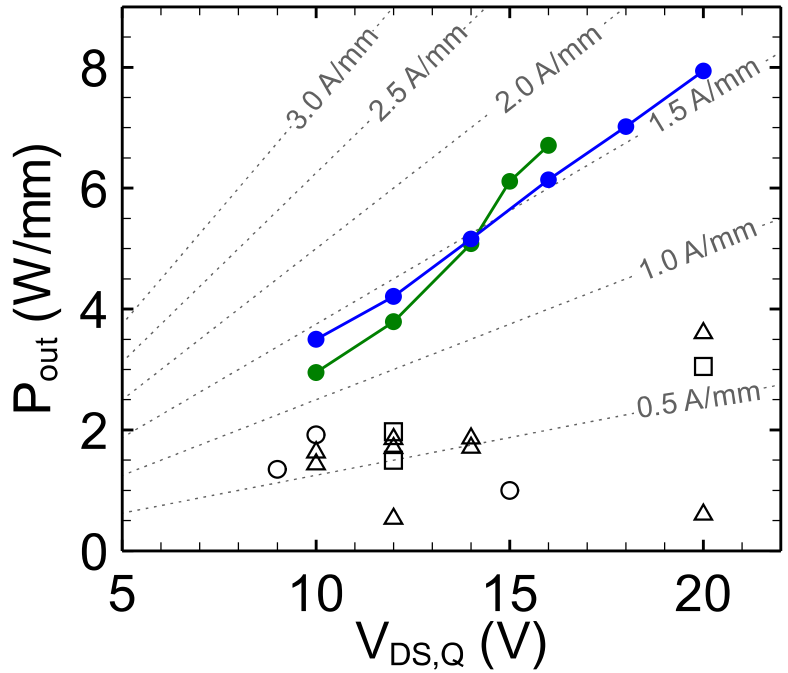
**7.94 W/mm** max $P_{out}$ at

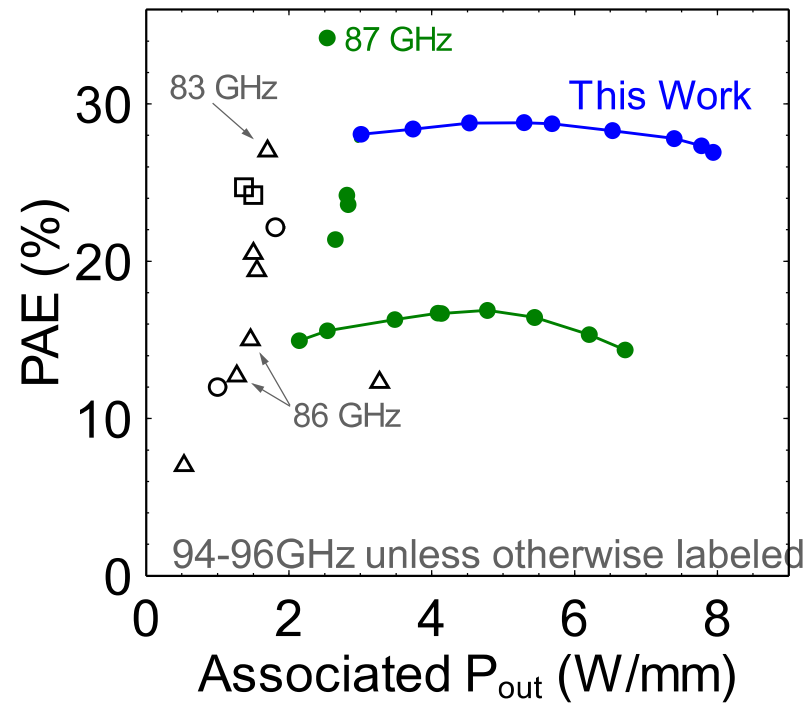
20V (26.9% PAE)

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

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

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



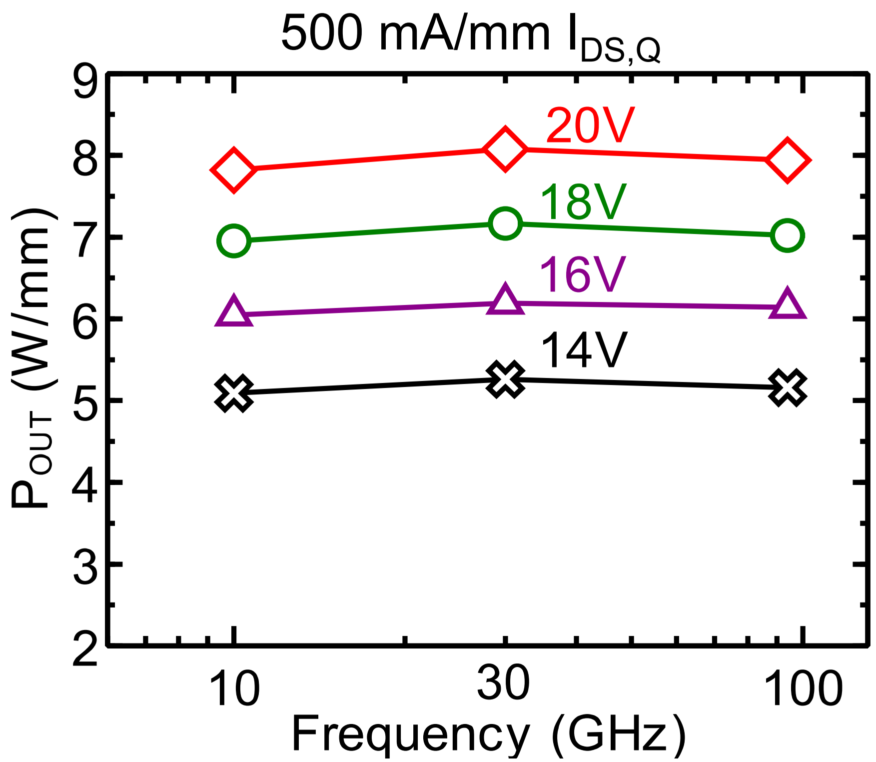




**N-Polar offers greater current density giving higher $P_{out}$**

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

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

# Constant 8 W/mm: 10 – 94 GHz



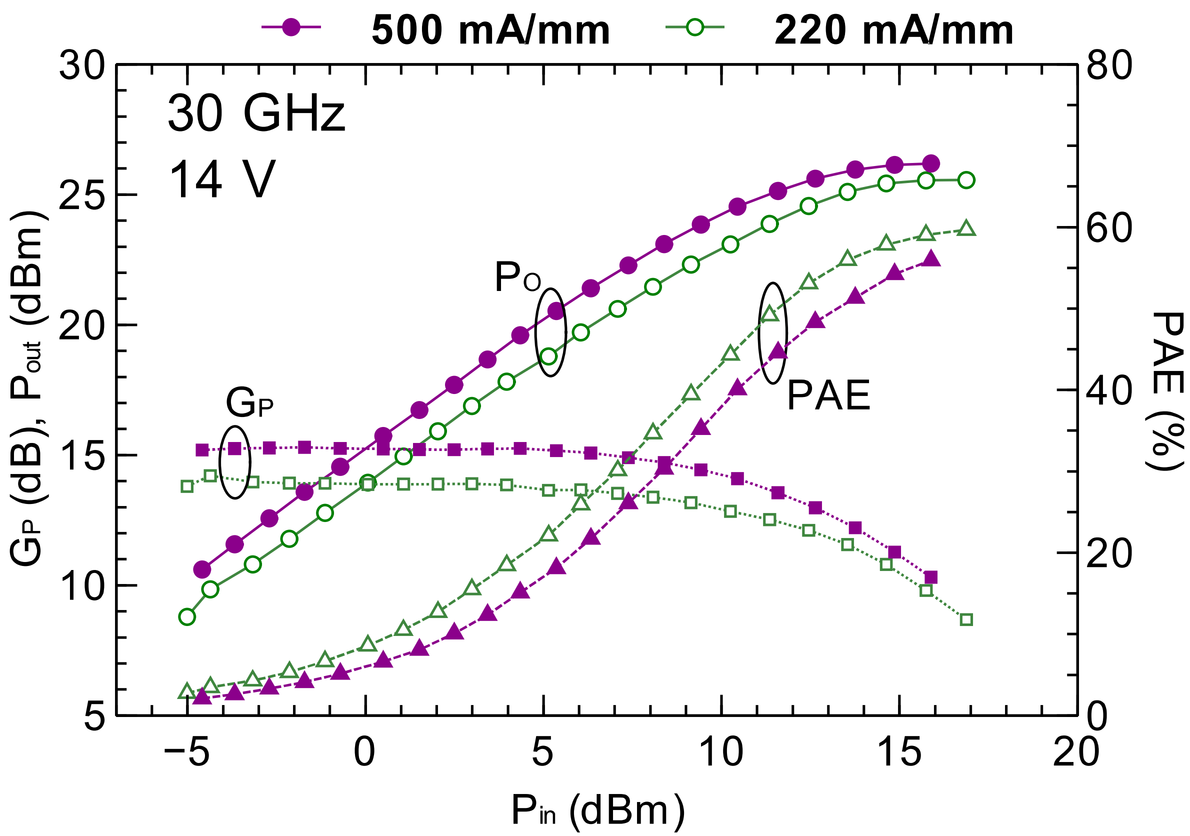

- 94 GHz: UCSB Passive Load pull
- 30 GHz: Maury Microwave MT2000 Active Load pull
- 10 GHz: UCSB Passive Load pull

**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)



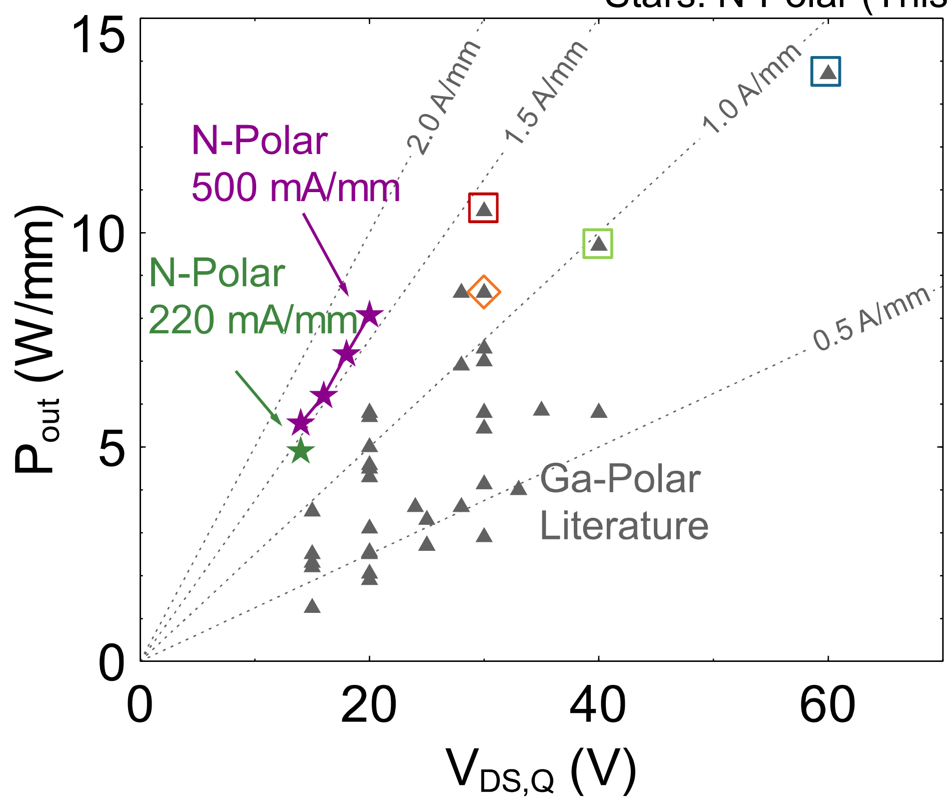

| 500 mA/mm | 220 mA/mm |
|---|---|
| ~25% $I_{DS,max}$ | ~11% $I_{DS,max}$ |
| 15.2 dB $G_{linear}$ | 13.8 dB $G_{linear}$ |
| 55.9% PAE | **59.8% PAE** |
| 5.6 W/mm | 4.9 W/mm |

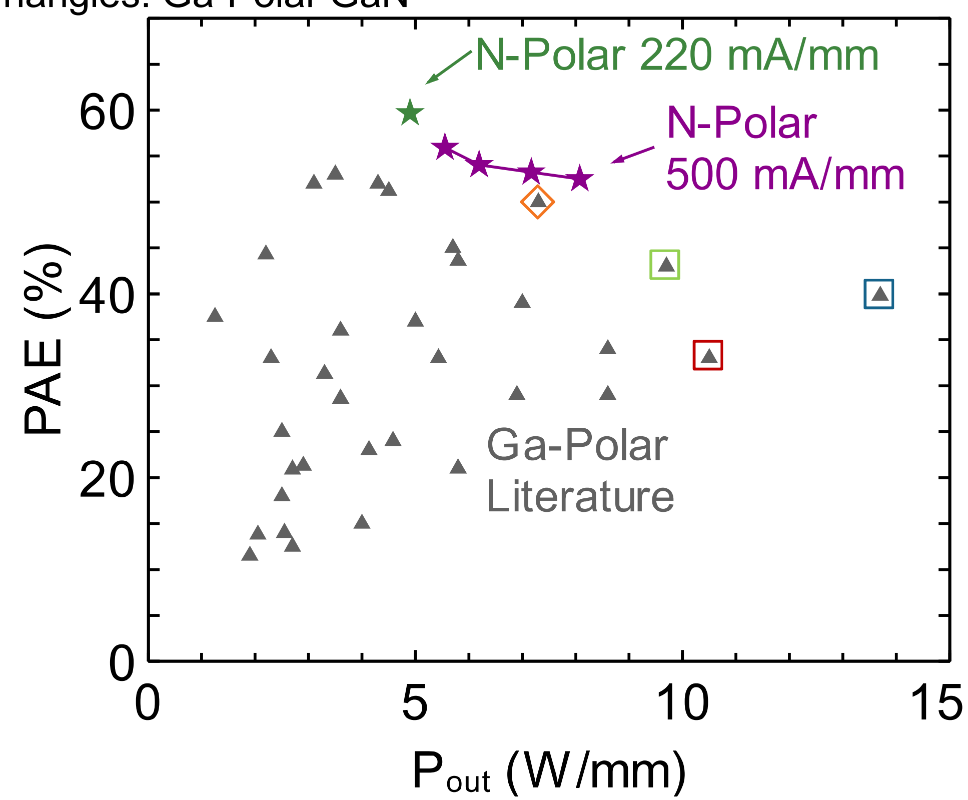
At 30 GHz increased gain allows access to deeper Class AB operation

Romanczyk et al, GOMACTech 2018

# Ka-Band Load Pull of GaN Devices

Stars: N-Polar (This Work)    Triangles: Ga-Polar GaN




**N-Polar offers greater current density**

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

Romanczyk et al, GOMACTech 2018

# 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
  - ✓ Recond 28.8% Peak PAE
- **30GHz:**
  - ✓ Record High GaN PAE: 59.8%
  - ✓ Record high combinations of PAE and $P_{out}$
  - ✓ 11 dB $OIP_3/P_{DC}$