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Sandia National Laboratories

AlGaN High Electron Mobility Transistors for Power Switches and High Temperature Logic

B.A. Klein, A.M. Armstrong, A.A. Allerman, C.D. Nordquist, J.C. Neely, S. Reza, E.A. Douglas, M. Van Heukelom, A. Rice, V. Patel, B. Matins, T.R. Fortune, M. Rosprim, L. Caravello, R. DeBerry, J.R. Pipkin, V.M. Abate, R.J. Kaplar

Lester Eastman Conference

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baklein@sandia.gov

U.S. DEPARTMENT OF ENERGY

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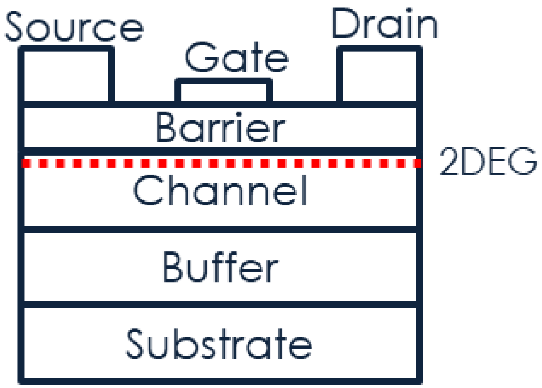
Outline

Goals: Al-rich AlGaN Channel E-mode power transistors and high temperature digital logic circuitry

1. Background / Motivation
2. Experiments
   - Threshold voltage – Enhancement Mode Power Switches
   - Epitaxial design – Mobility and Charge Density
   - Ohmic contacts
   - High temperature gate metals
3. High Temperature AlGaN HEMTs
4. Summary



Nomenclature

$Al_xGa_{1-x}N$ barrier / $Al_yGa_{1-y}N$ channel

=

X/Y HEMT

Why AlGaN HEMTs?

Estimated properties of wide band gap materials

Material	E_G (eV)	E_C (MV/cm)	Electron mobility (cm²/V s)	v_{sat} (10^7 cm/s)	Thermal conductivity (W/m·K)
SiC	3.3	2.5	1000	2.0	370
GaN	3.4	4.9	1000	1.4	253
AlN	6.0	15.4	426	1.3	319
$Al_xGa_{1-x}N$ (x>0.7)	5.0-6.0	13.5-15.4	~150-400	Interpolation	Interpolation
b-Ga_2O_3	4.9	10.3	180	1.1	11-27
Diamond	5.5	13.0	4500-7300	1.9-2.3	2290

High power

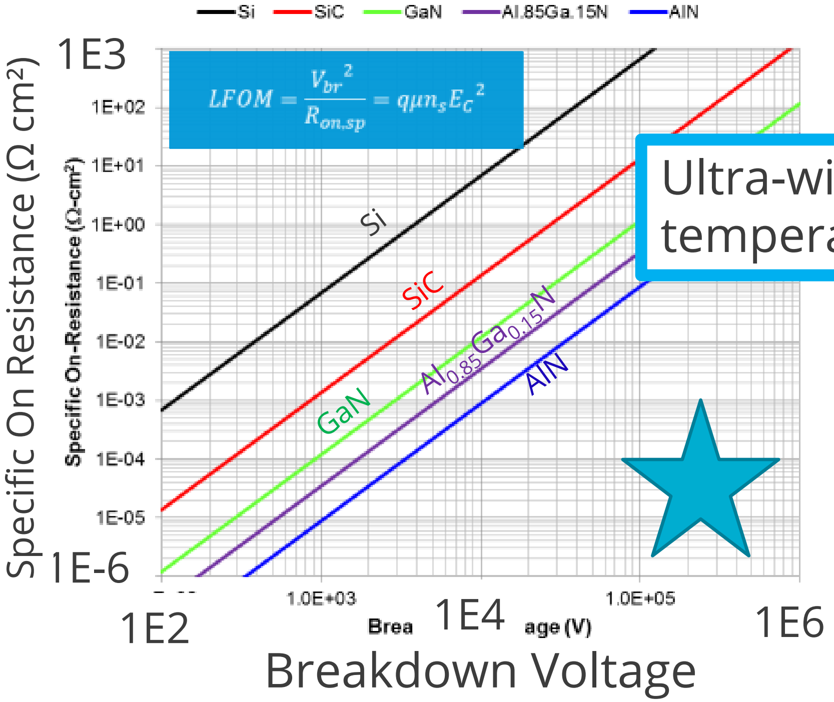
$$P_{max} = I_{max}V_{max}/8$$

$$J_{max} = q\mu n_s E_c \qquad J_{max} = q v_{sat} n_s$$

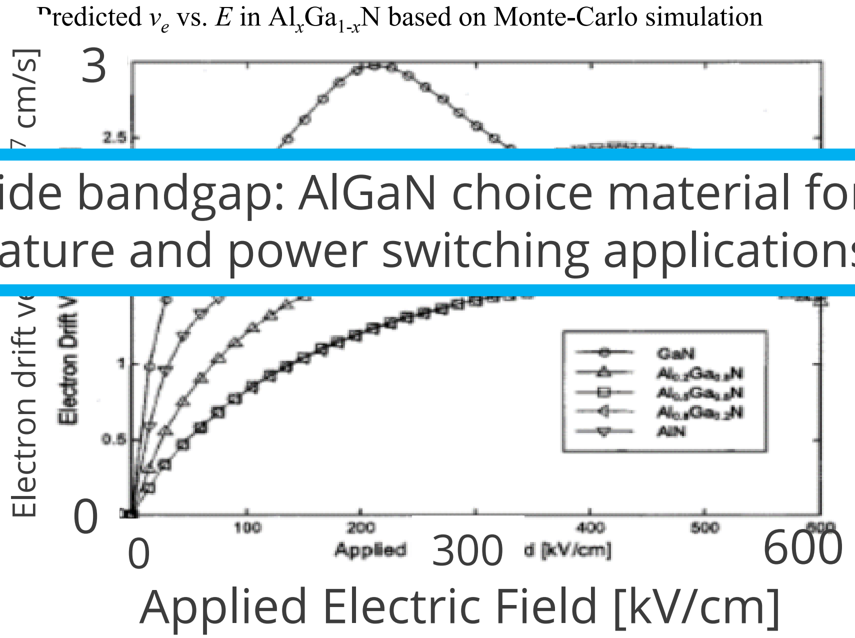
High temperature

- Wide band gaps suppress intrinsic carrier density effects and thermionic emission-induced leakage

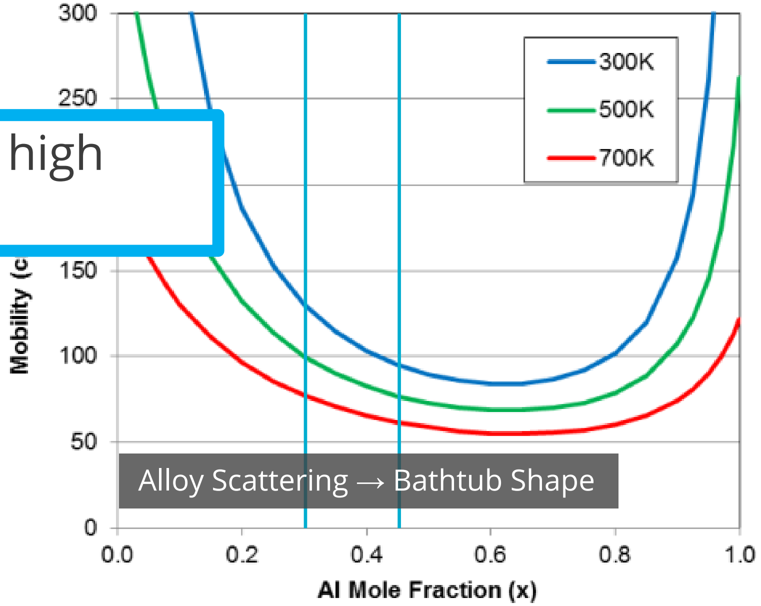
P. G. Neudeck, R. S. Okojie, and L.-Y. Chen, *Proceedings of the IEEE,* vol. 90, no. 6, pp. 1065 - 1076, 2002.



Ultra-wide bandgap: AlGaN choice material for high temperature and power switching applications



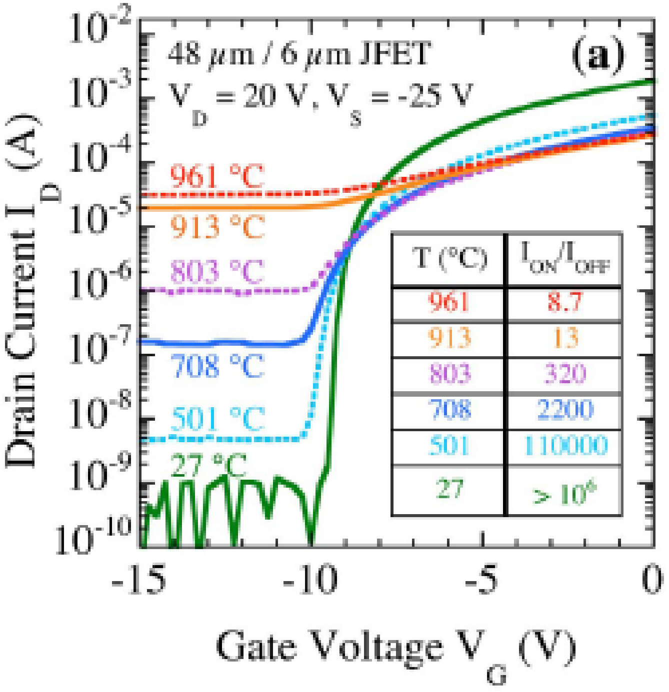
M. Farahmand *et al.,IEEE Transactions on Electron Devices,* vol. 48, no. 3, pp. 535-542, 2001.



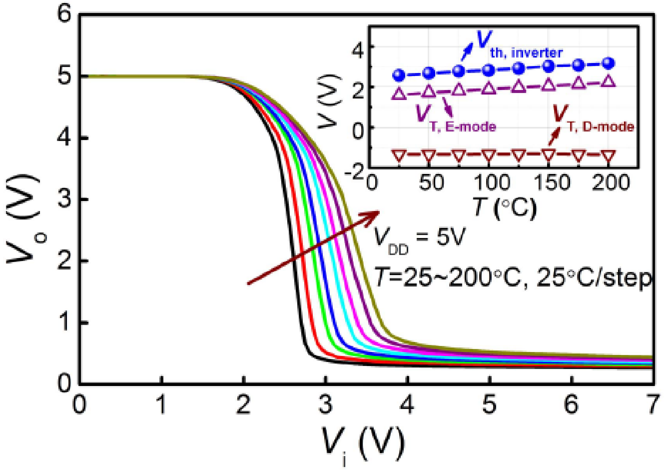
M. E. Coltrin and R. J. Kaplar, *Journal of Applied Physics,* vol. 121, no. 055706, 2017

High temperature device background

NASA: SiC JFET[1]
Characterized to 961°C

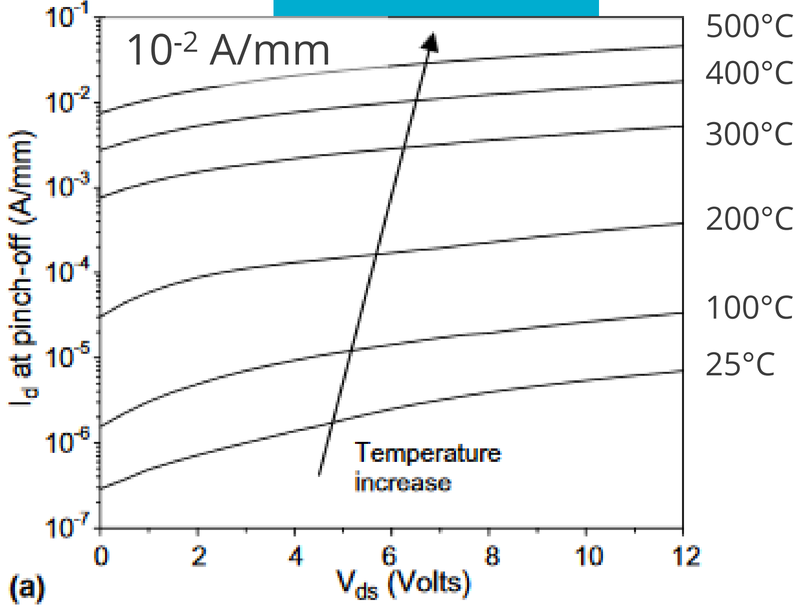


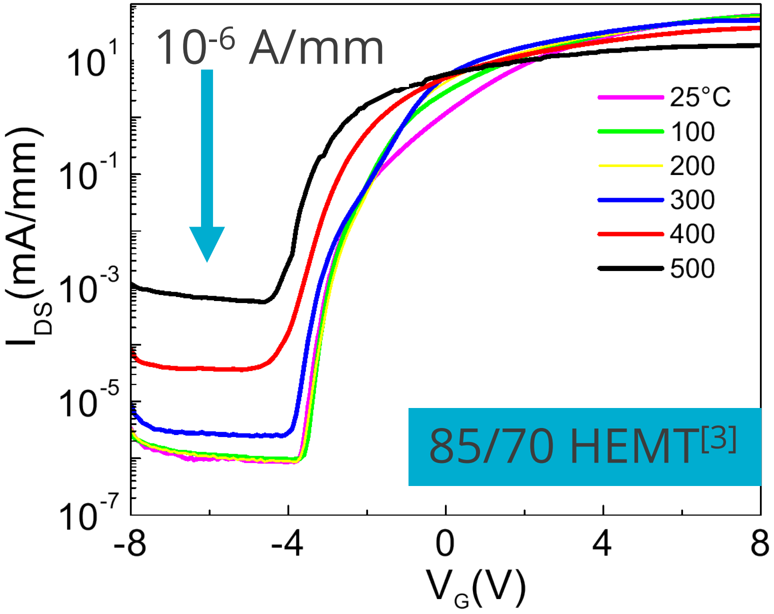
GaN HEMT inverter[2]
25 – 200°C



Low off-state leakage for high temperatures:
10^{-6} A/mm for $Al_{0.85}GaN/Al_{0.7}Ga_{0.3}N$ HEMTs (Sandia),
compared to
10^{-2} A/mm for $Al_{0.25}Ga_{0.75}N/GaN$ HEMTs (1)

25/0 HEMT[4]





85/70 HEMT[3]

[1] P. G. Neudeck, *IEEE Electron Device Letters,* vol. 38, no. 8, (2017).
[2] G. Tang, *IEEE Electron Device Letters,* vol. 38, no. 9, pp. 1282-1285 (2017).
[3] P. H. Carey, *Journal of the Electron Devices Society,* vol. 7, pp. 444-452, 2019.
[4] W. S. Tan, *Solid-State Electronics* **50**: 511-513 (2006).

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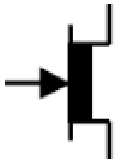
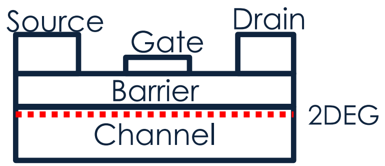
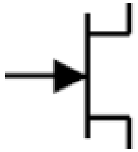
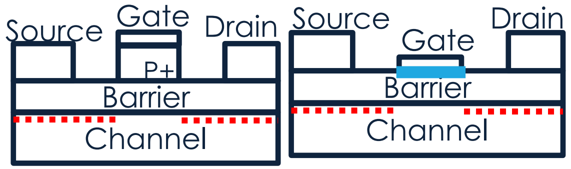
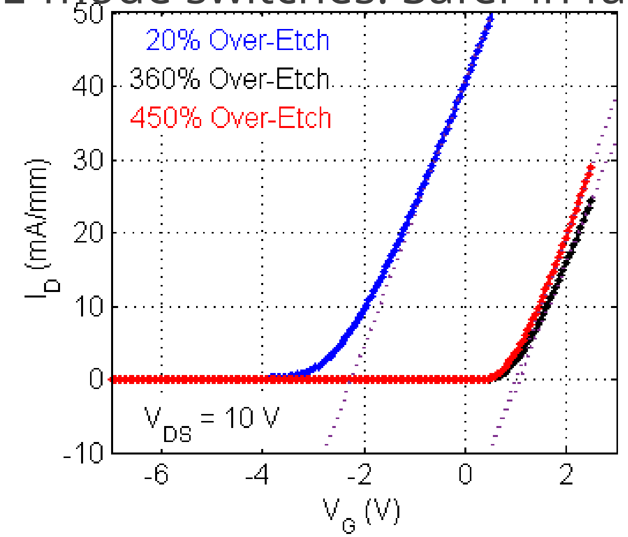
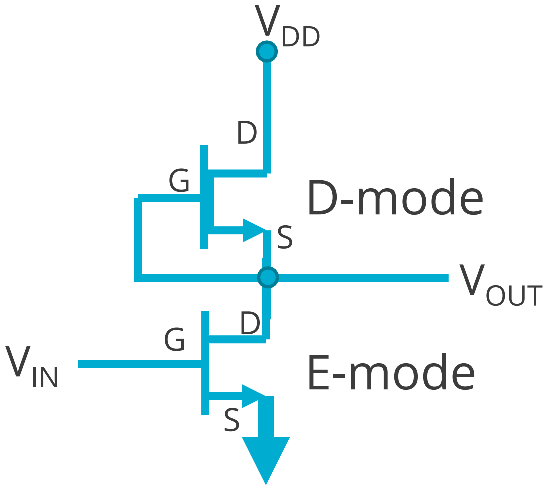
Enhancement-Mode AlGaN-channel HEMTs

Depletion-Mode (normally on)			AlGaN HEMTs are innately D-mode
Enhancement-Mode (normally off)		 P-Gate Recess + F⁻ ions	Two approaches for E-mode already successfully implemented at Sandia

E-mode switches: Safer in failures



Currently complimentary pFET and nFET not practical
→Combine e-mode and d-mode for logic

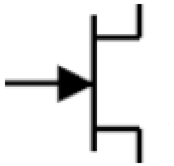


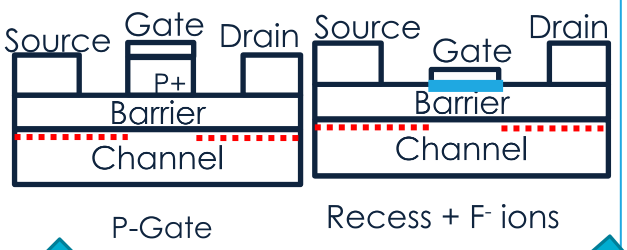
Depletion-mode load inverter

Masahito Kanamura, et al. (2010). IEEE Electron Device Letters **31**(3): 189-191.
Hilt, O., et al. (2010). Proceedings of the 22nd International Symposium on Power Semiconductor Devices & ICs, Hiroshima, Japan, IEEE.
Yong Cai, et al. (2006). IEEE Transactions on Electron Devices **53**(9): 2207-2215.

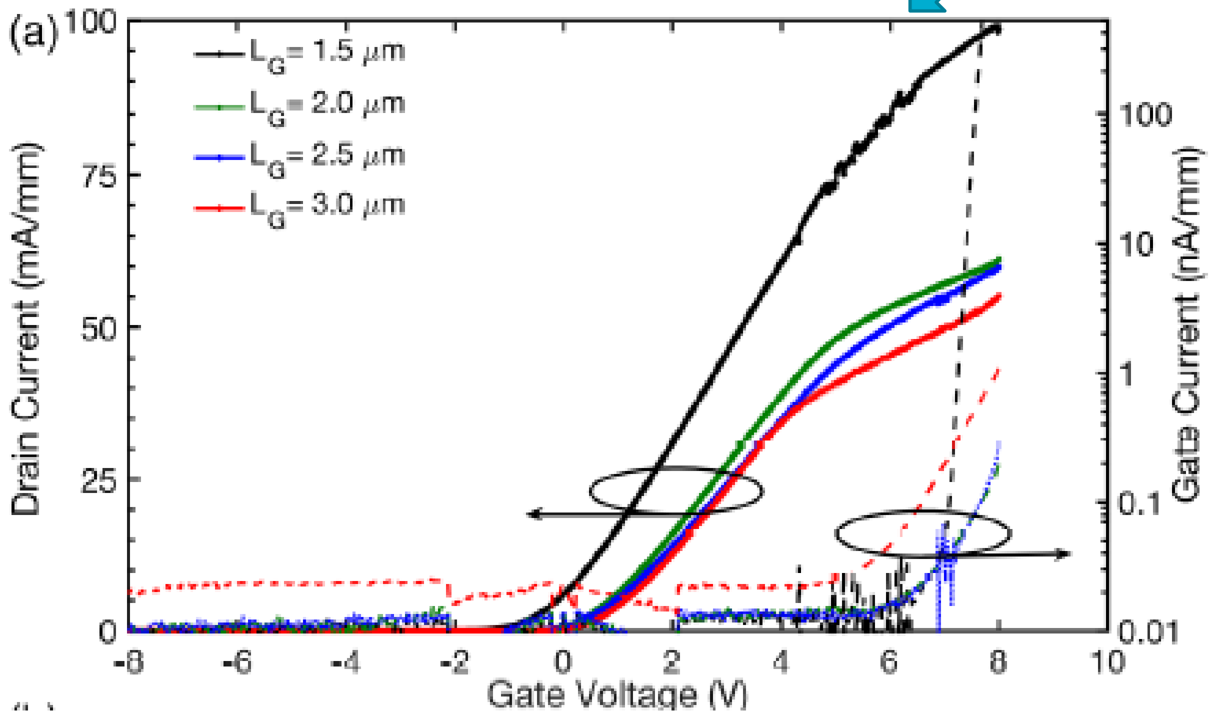
Enhancement-Mode AlGaN-channel HEMTs

Enhancement-Mode (normally off)



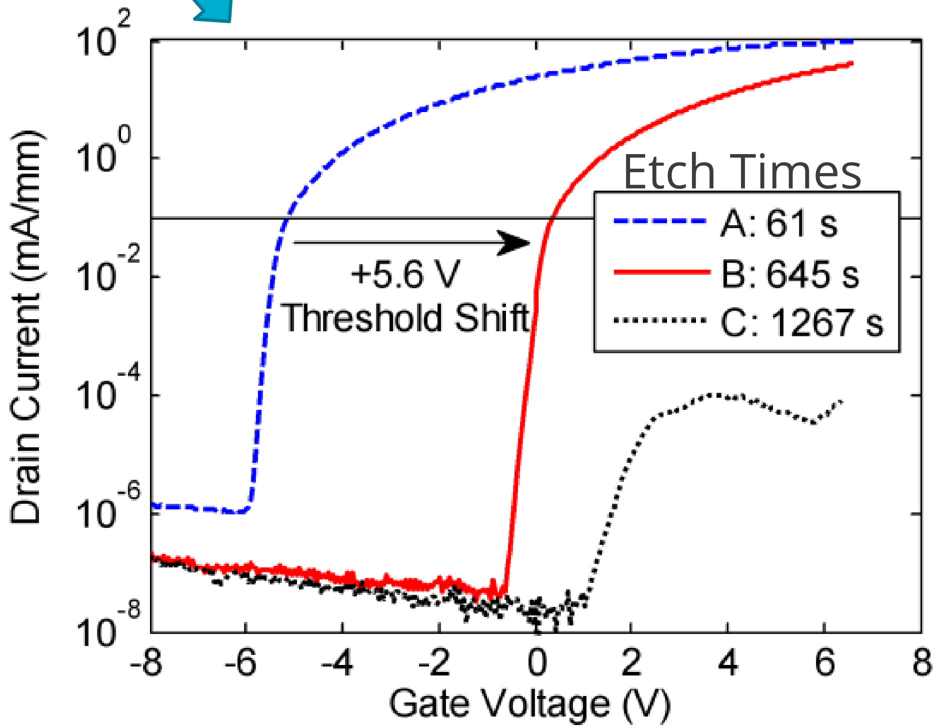


Two approaches for E-mode successfully implemented at Sandia



JVSTB, vol. 37, no. 021208, 2019.

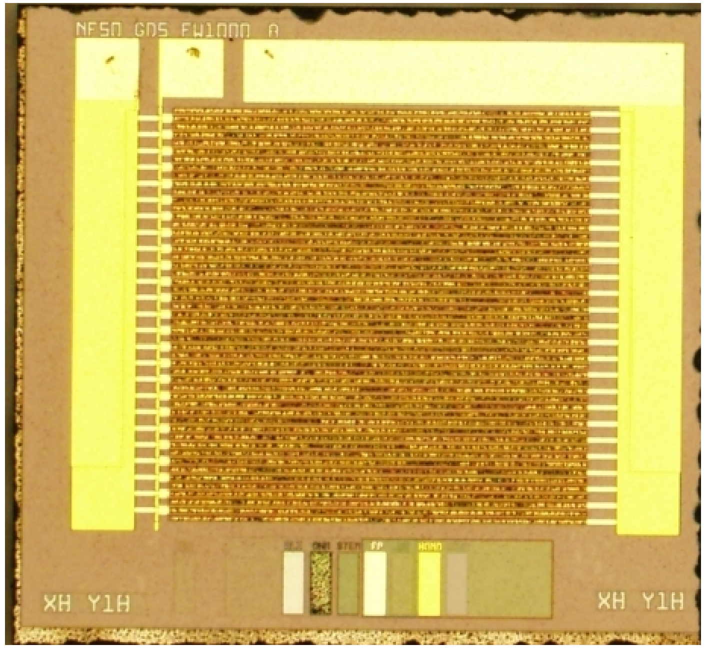
45/30 HEMT + p-AlGaN cap

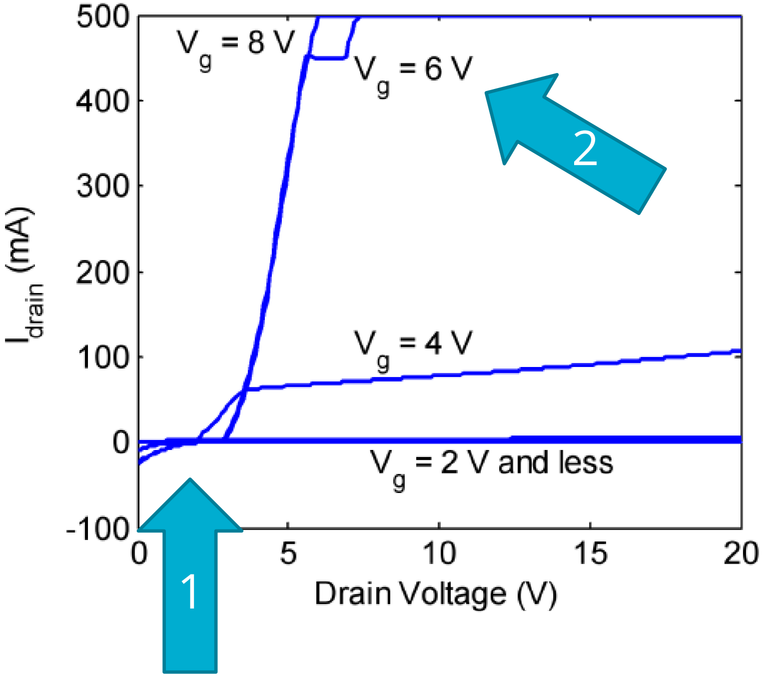


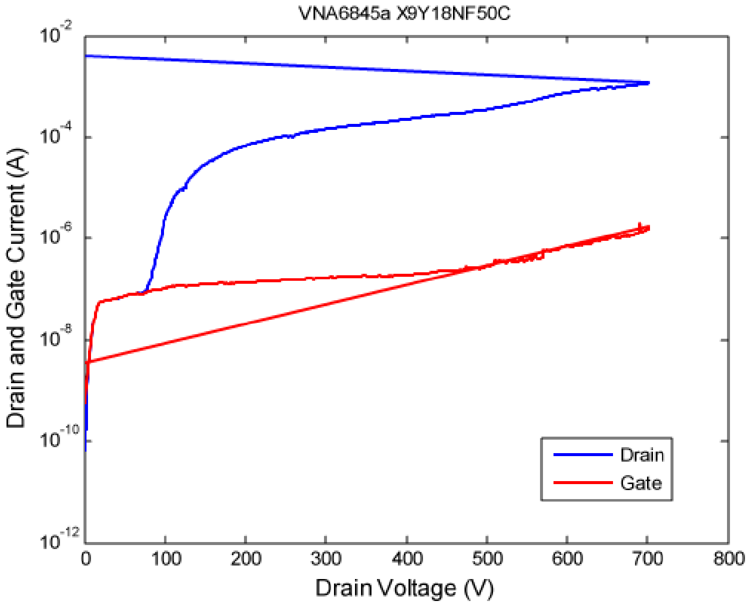
Appl. Phys. Lett. **114**, 112104 (2019)

85/70 HEMT: Recess + F^- ions

Enhancement-Mode AlGaN-channel HEMTs







Threshold voltage = 1.5 V
Drain Current = 500 mA (DC), 1.5 A (pulsed)
Breakdown voltage = ~650 V

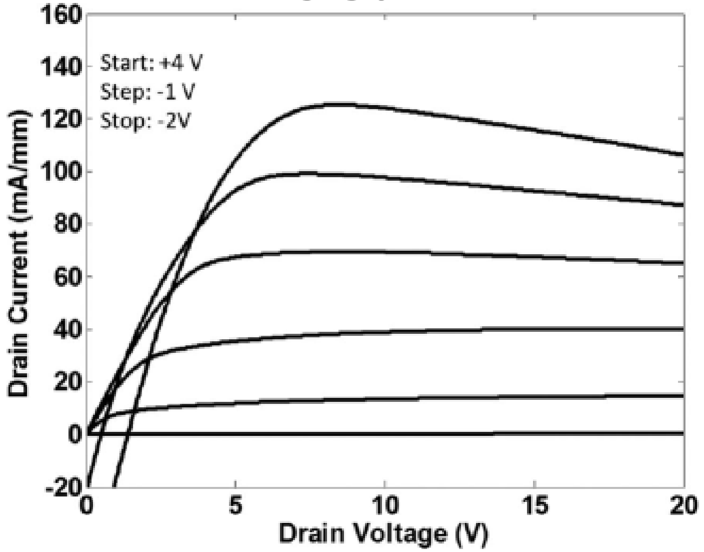
What needs more work?

1. Offset voltage
2. High gate bias

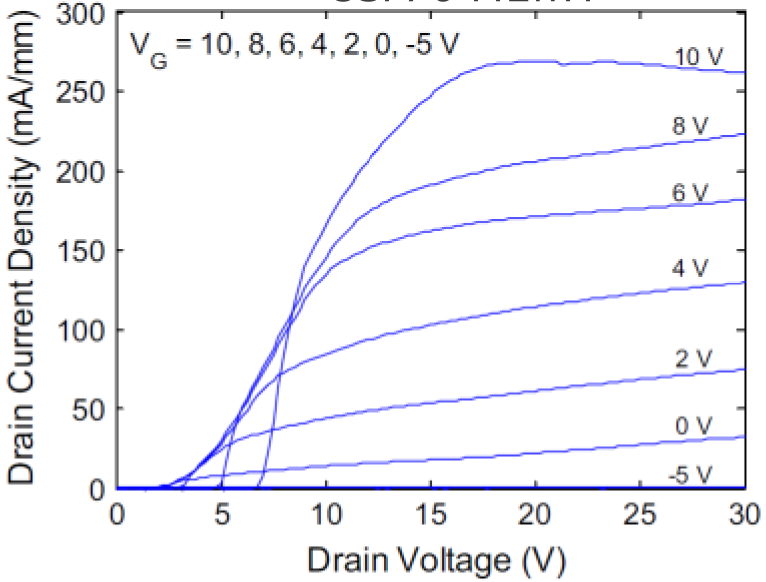
Need to change epitaxy design
Ohmic contact needs improvement

Epitaxial Design

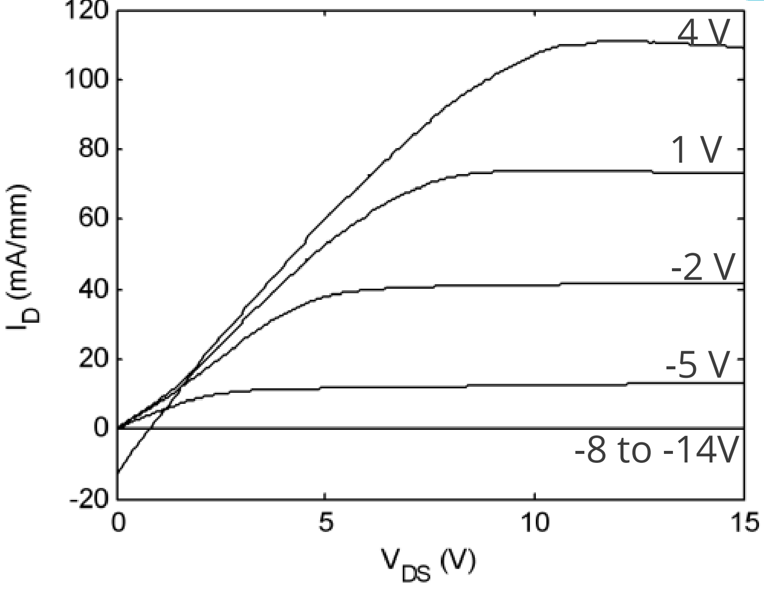
45/30 HEMT [1]



85/70 HEMT[2]



100/60 HEMT



- Could repeatably make good contacts to a 45/30 HEMT
- For a long time we worked off the assumption that the high barrier composition was limiting our ohmic contacts
- ...Until we observed Ohmic contacts on a 100/60 HEMT → Channel composition dependence → What was going on?

Motivated transport study[3]

45/30 HEMT
$Al_{0.45}Ga_{0.55}N$ (50 nm)
$Al_{0.3}Ga_{0.7}N$ (270 nm)
$Al_{0.3}Ga_{0.7}N$ (3.9 µm)
AlN (1.6 µm)
Sapphire Substrate

100/60 HEMT
AlN (30 nm)
$Al_{0.6}Ga_{0.4}N$ (150 nm)
$Al_{0.73\rightarrow0.6}Ga_{0.27\rightarrow0.4}N$ (10 nm)
$Al_{0.73}Ga_{0.27}N$ (50 nm)
$Al_{1\rightarrow0.73}Ga_{0\rightarrow0.27}N$ (50 nm)
AlN (1.6 µm)
Sapphire Substrate

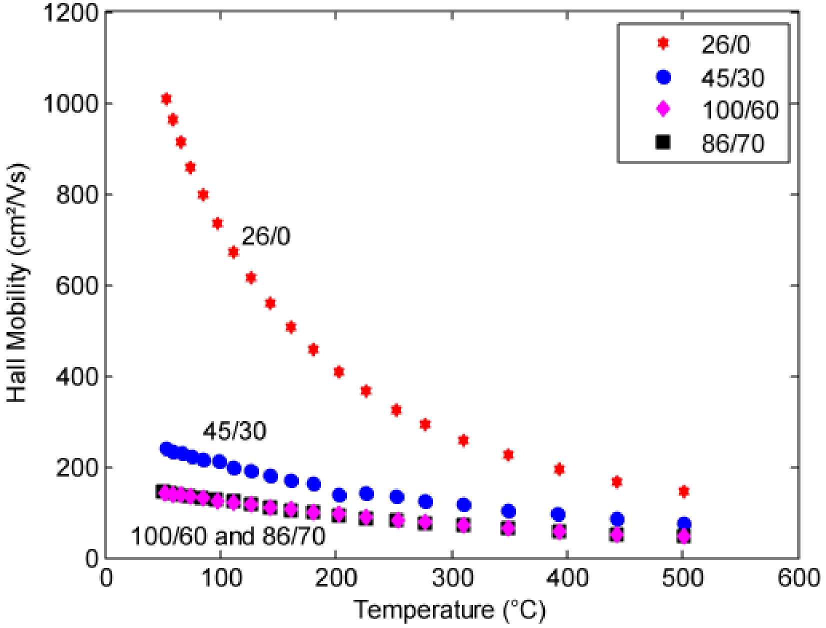
86/70 HEMT
$Al_{0.86}Ga_{0.14}N$ (30 nm), 2.5×10^{18} Si
$Al_{0.7}Ga_{0.3}N$ (500 nm)
$Al_{1\rightarrow0.7}Ga_{0\rightarrow0.3}N$ (10 nm)
AlN (2.5 µm)
Sapphire Substrate

26/0 HEMT
$Al_{0.26}Ga_{0.74}N$ (20 nm)
GaN (50 nm)
GaN:C (1.7 µm), 1×10^{18} C
AlN nucleation
SiC substrate

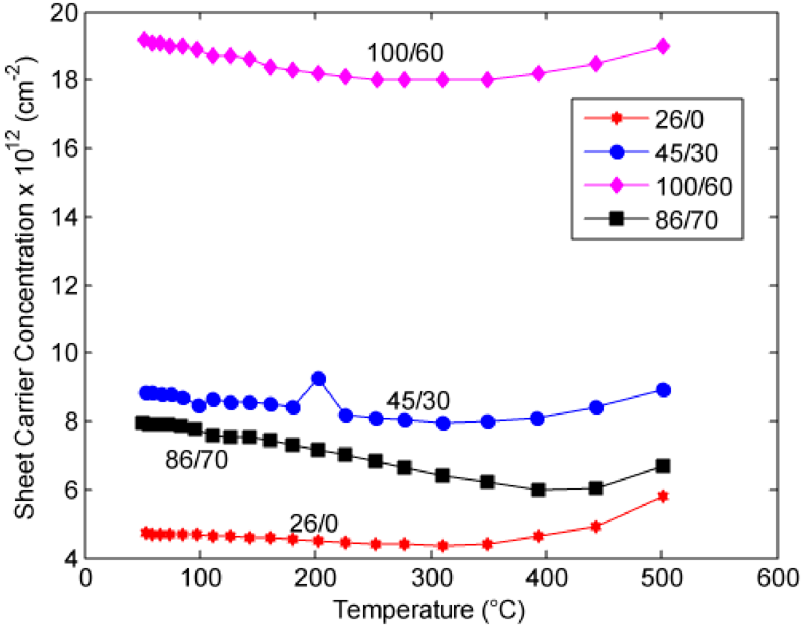
[1] *ECS Journal of Solid State Science and Technology*, vol. 6, no. 11, pp. S3010-S3013, 2017.
[2] *Journal of Electronic Materials*, vol. 48, pp. 5581–5585, 2019.
[3] B. A. Klein, *Journal of Applied Physics (submitted).*

Epitaxial Design

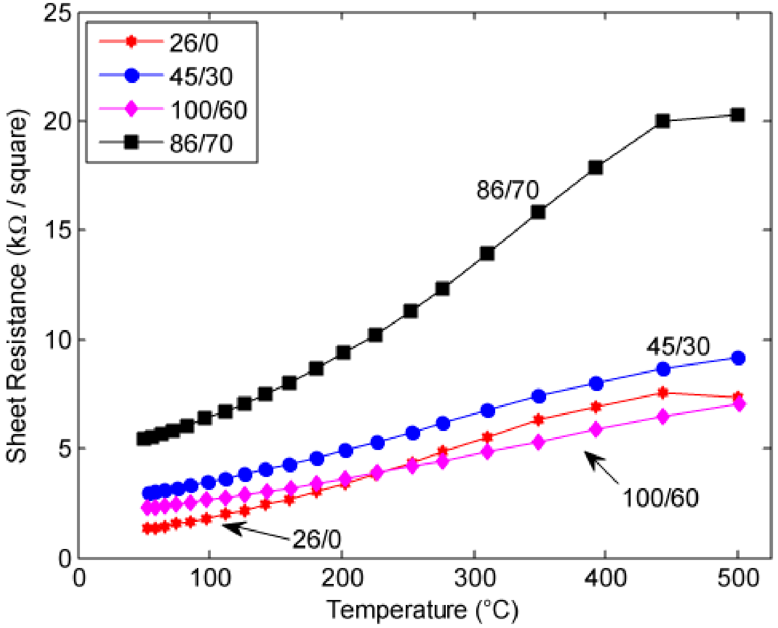
Hall Mobility



Sheet Carrier Concentration



Sheet Resistance



$$\mu \; * \; n_s \; = 1/qR_{SH}$$

- Lower Al% channel = higher mobility
- Mobility less variable over temperature compared to GaN HEMTs
- Over the 500°C range
  - AlGaN channels: 3.1x reduction
  - GaN channel: 6.9 x reduction
- ➢ Improved stability over T

- High barrier/channel Al contrast increases carrier concentration

Good combination for high temperature epitaxy:

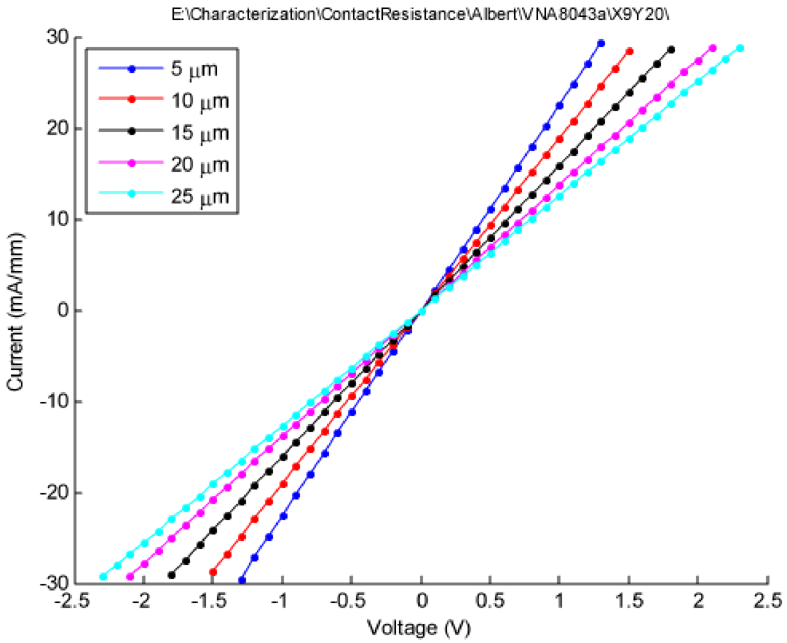
1. Low mobility variation
2. High carrier concentration

Guidelines
Reduced channel Al% → higher mobility
Increased Barrier/Channel Al% contrast → higher n_s

B. A. Klein, *Journal of Applied Physics (submitted).*

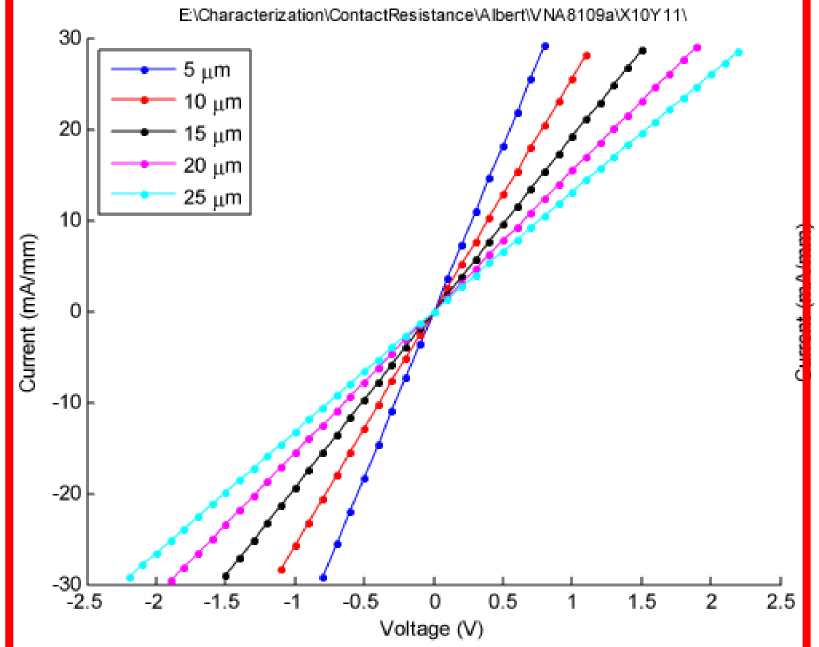
Epitaxial Design → Ohmic Contacts

100/40/100
VNA8043a



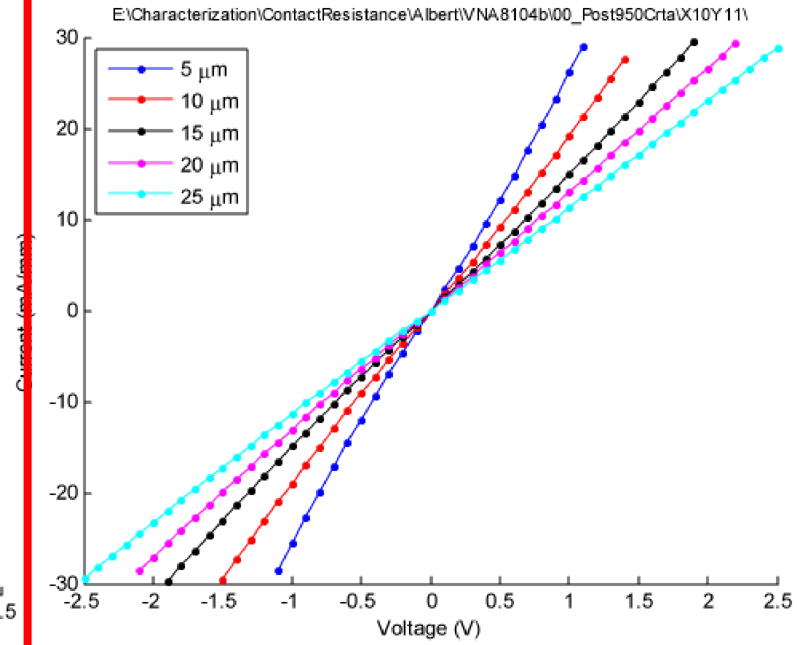
9e-04 Ωcm²

85/50/100
VNA8109



1.1e-04 Ωcm²

72/40/100
VNA8104

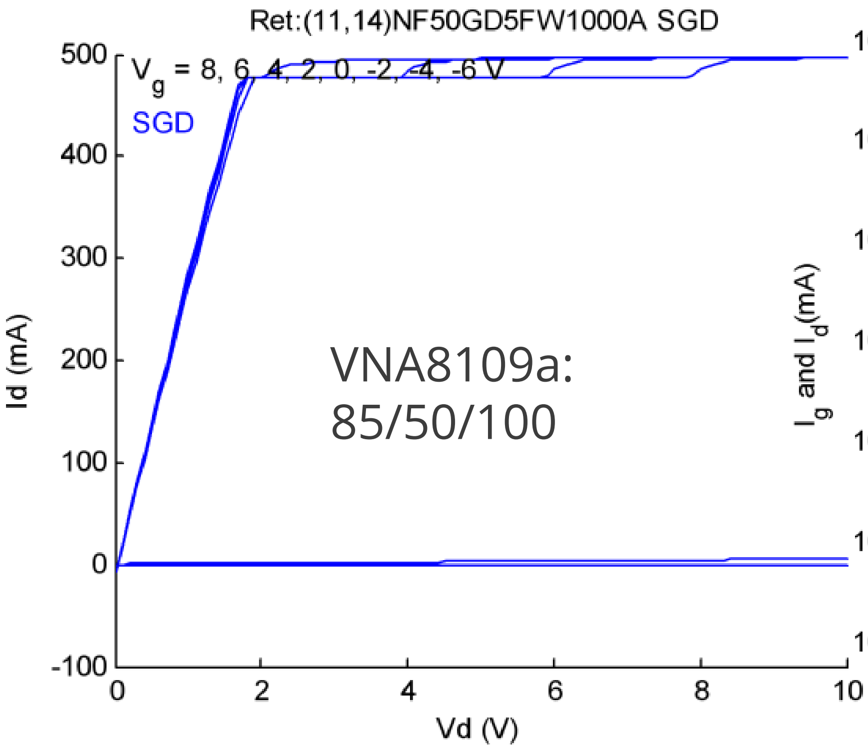


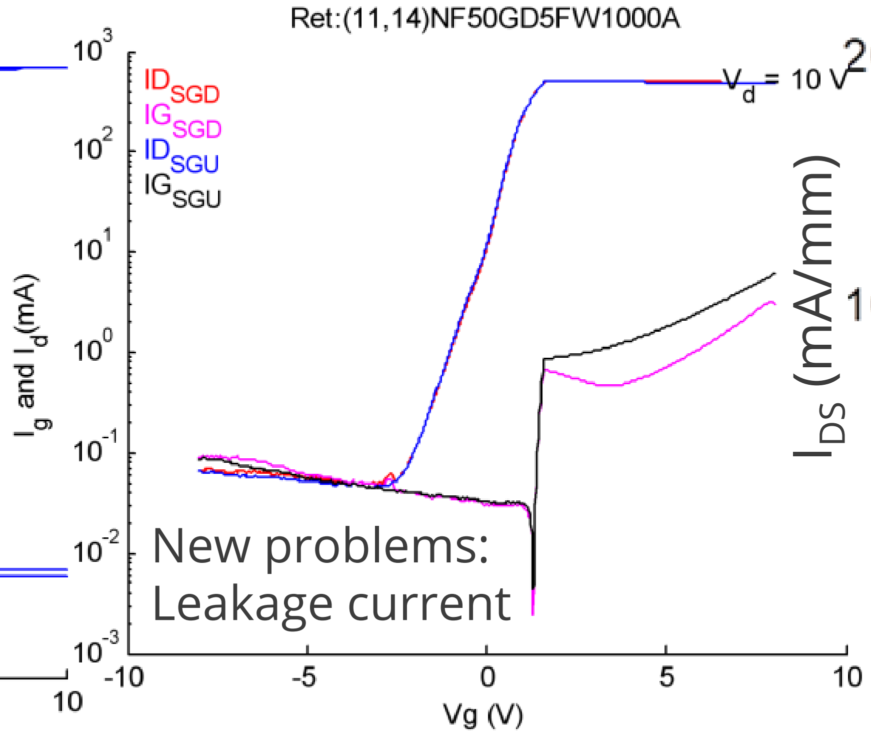
3.3 e-04 Ωcm²

Design Principles

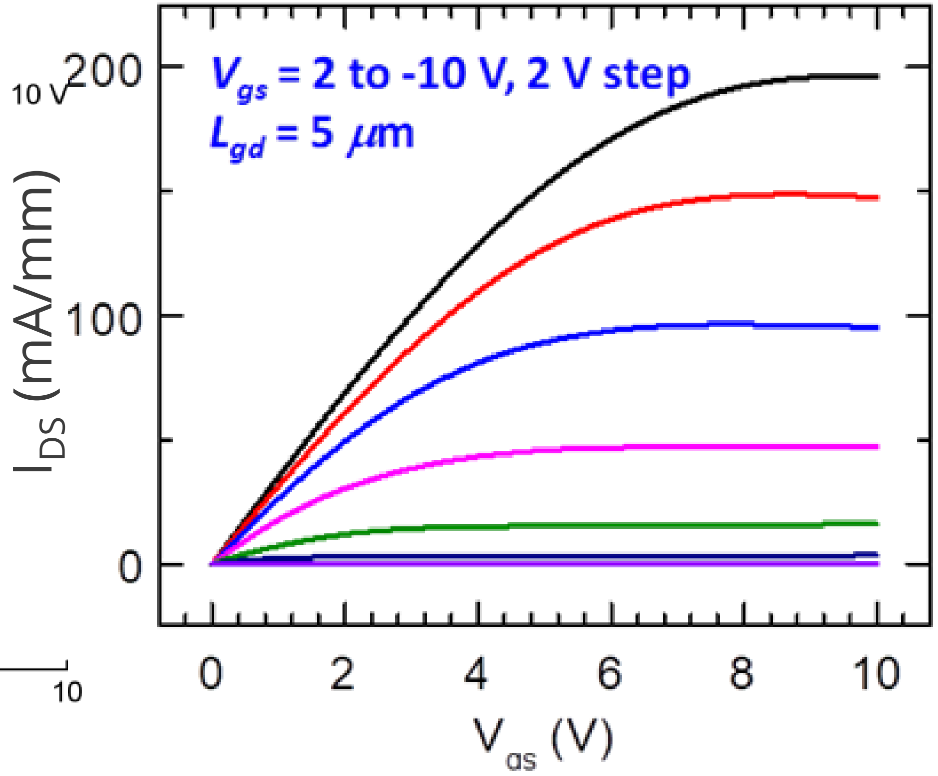
1. Keep the Al-rich barrier – Want to keep for benefits in power and high temperature
2. Increase the Al contrast between barrier and channel – Reduce sheet resistance

Epitaxial Design → Ohmic Contacts





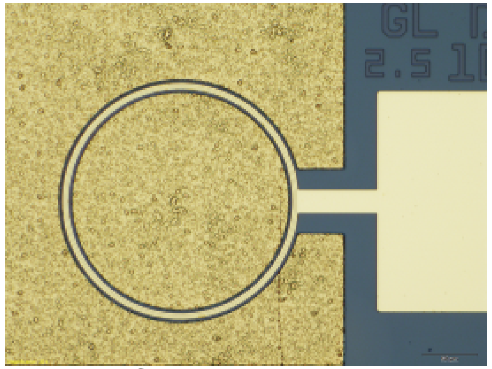
Planar Ohmic contacts
85/50 HEMT



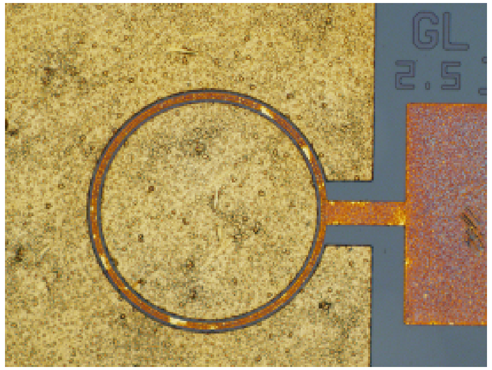
- ➢ Reduced specific contact resistance by 2×:
  5×10^{-3} to 1×10^{-4} Ωcm²
- ➢ Reduced sheet resistance by over half:
  4.7 kΩ/sq to 1.7 kΩ/sq
- ➢ Increased current density by over 6×:
  30 mA/mm to 200 mA/mm (long channel devices)

- ✓ Threshold voltage control
- ✓ Epitaxial design
- ✓ Ohmic contacts
- **High temperature gate metals**

High Temperature Gates



Before >300°C



After >300°C

"Standard" Gate: 200 Å Ni / 4500 Å Au
- Nickel metal migration
- Changes to electrical properties
- Metal pads don't survive
- ➢ Need high temperature gate metal

Properties of Candidate Metals

Metal	Resistivity, ~25°C (Ωm)	Melting Point (K)	Thermal Expansion (x10^6) (cm^{-1})
Au	2.35	1337	14.2
Mo	5.34	2896	5
W	**5.6**	**3695**	**4.5** ⬅
Ni	6.84	1726	13
Pt	**10.6**	**2042**	**9** ⬅
Ta	12.4	3293	6.5
Nb	12.5	2742	7
Cr	12.9	2130	6
Pd	**20**	**1825**	⬅
V	25	2163	8
Zr	40	2128	5.7

Pattern standard Ohmic contacts
- 85/70 HEMT
- 250 Å Ti / 1000 Å Al / 150 Å Ni / 500 Å Au
- Anneal: 1100°C, 30s, ~1mT nitrogen

➡

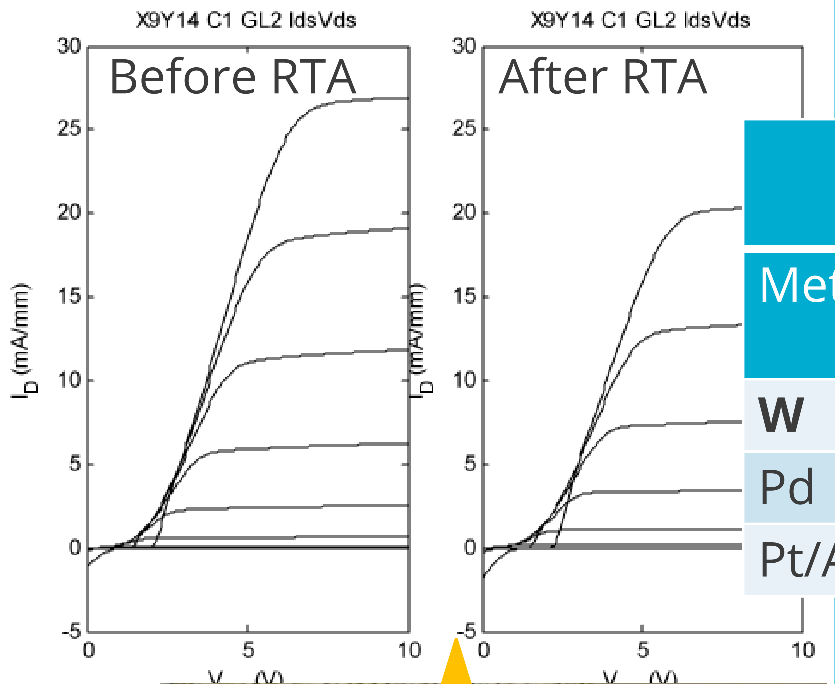
Gate Metal Experiment
1. 2000 Å W (sputter)
2. 2000 Å Pd (evap)
3. 200 Å Pt / 2000 Å Au (evap)

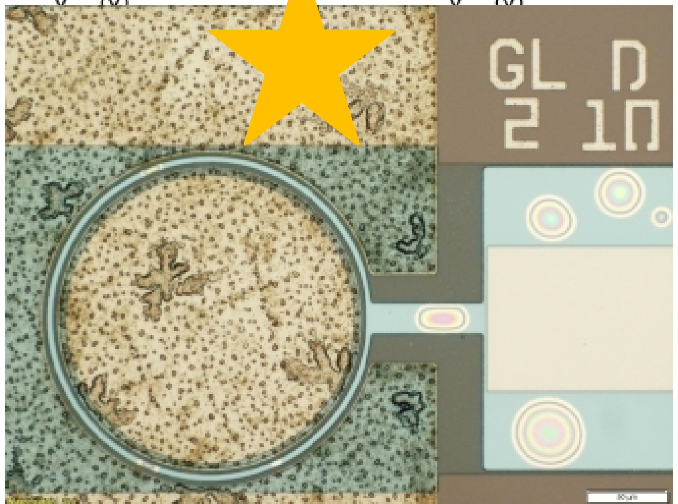
➡

Characterization
1. Pre-high temperature I-V sweeps
2. Multiple Cycles: Anneal at 500°C → I-V sweeps

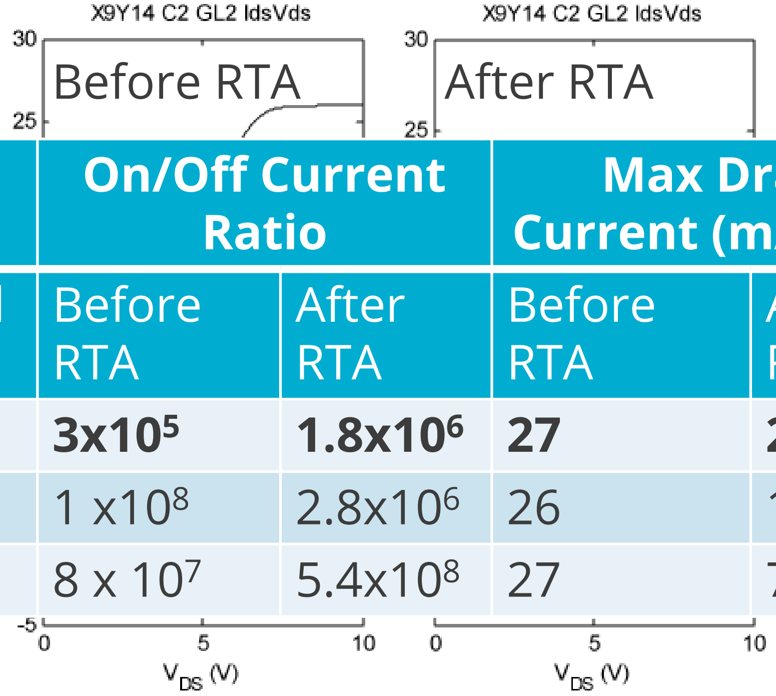
High Temperature Gates

W Gate

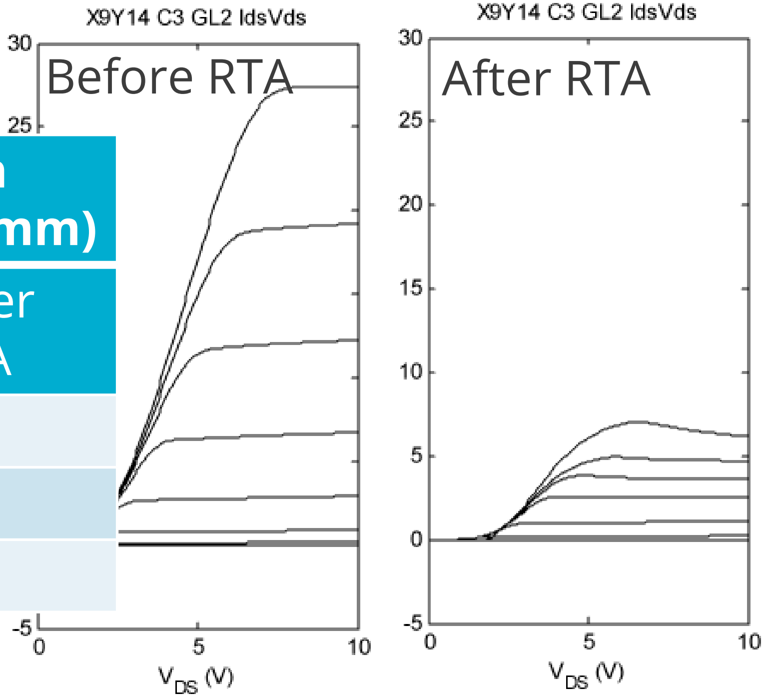


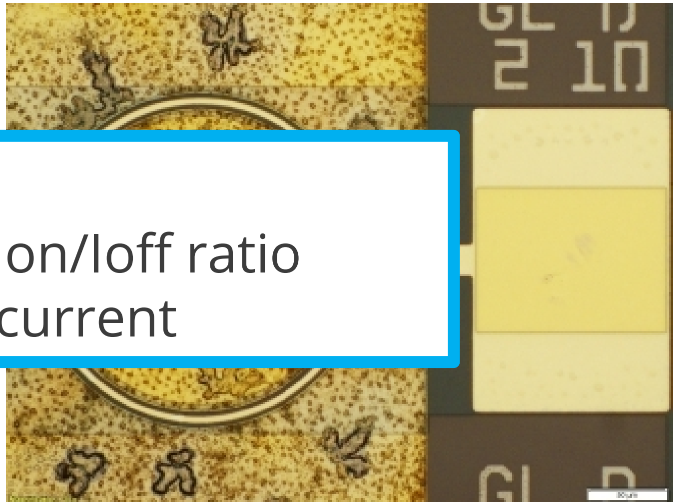


Pd Gate



Pt/Au Gate





	On/Off Current Ratio		Max Drain Current (mA/mm)	
Metal	Before RTA	After RTA	Before RTA	After RTA
W	**$3x10^5$**	**$1.8x10^6$**	**27**	**21**
Pd	$1 x10^8$	$2.8x10^6$	26	13
Pt/Au	$8 x 10^7$	$5.4x10^8$	27	7

Best Results: W gate

- Burn-in for improved Ion/Ioff ratio
- Maintains good drain current

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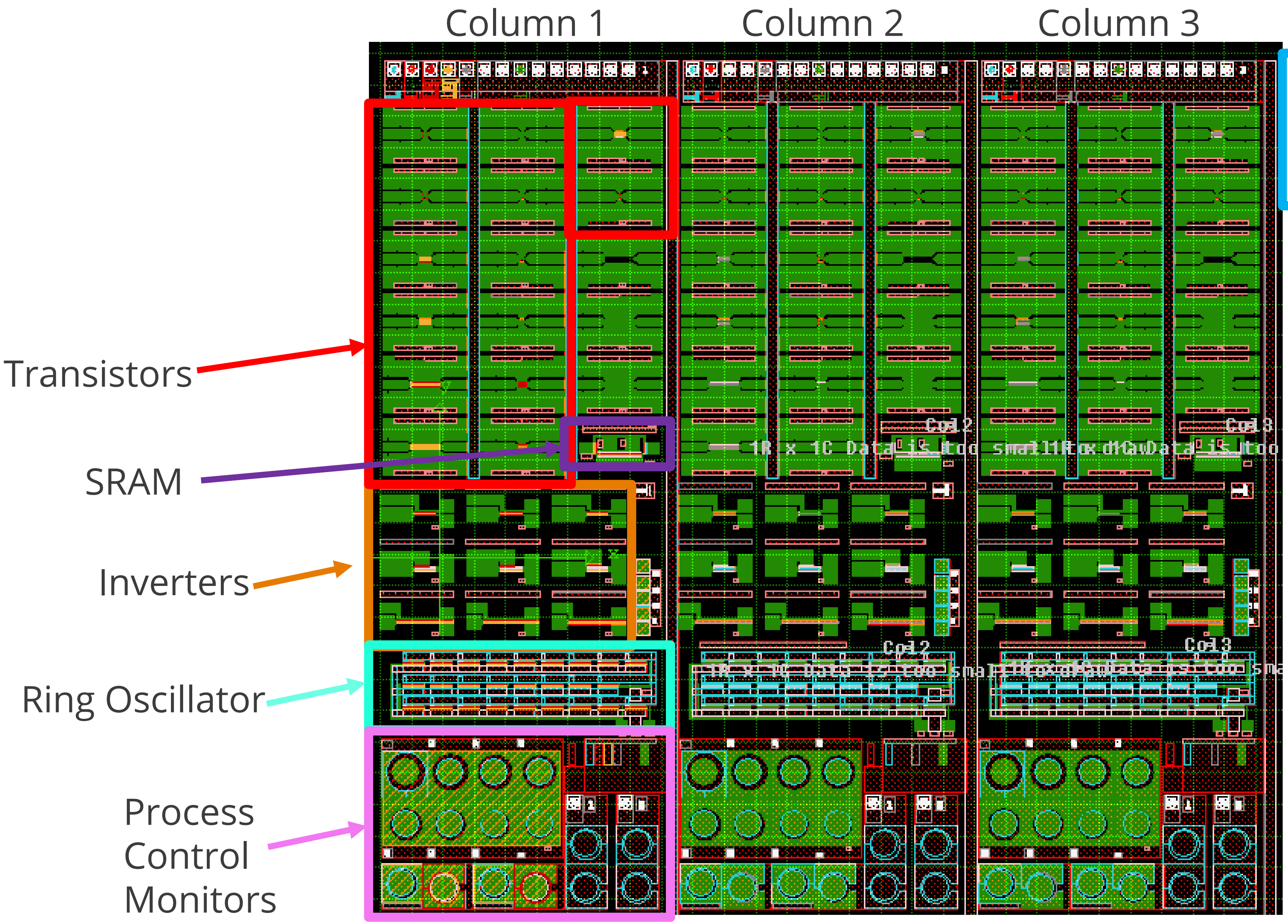
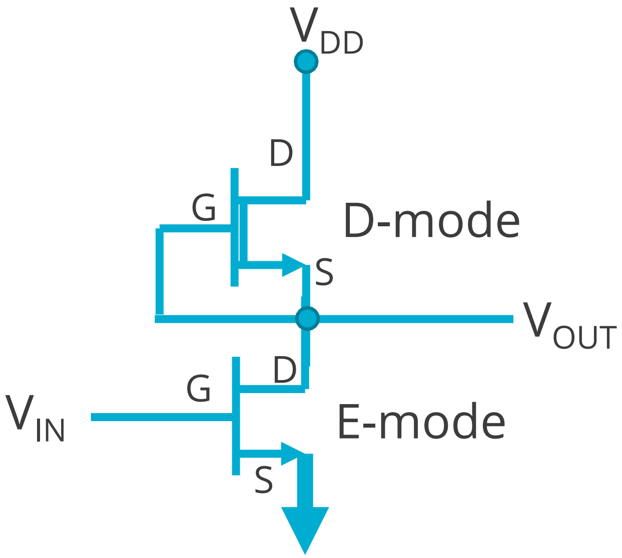
High Temperature Mask Set

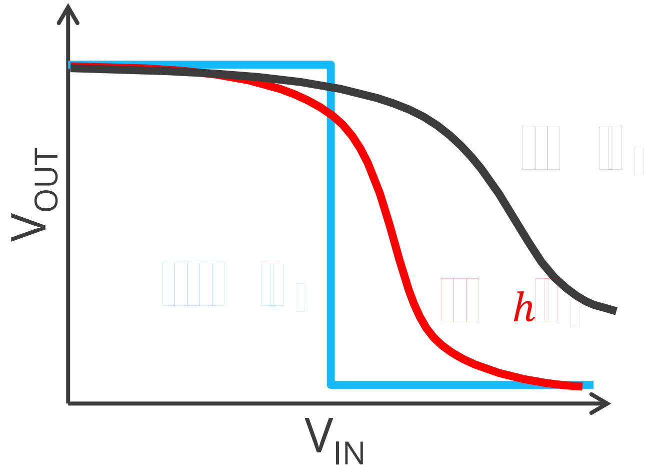


3 Columns
Use for 3 different barrier etches
OR
Use for 3 different p-(Al)GaN etches

High Temperature Mask Set: Inverter design



Inverter Characteristic Plot



See for example: J. Uyemura, *Fundamentals of MOS Digital Integrated Circuits* (1988).

Column 1			Column 2			Column 3		
Vary β_R (driver-load ratio) by E/D gate width ratio. Vary gate length.			**Vary β_R (driver-load ratio) by E/D gate width ratio. Vary gate length.**			**Vary β_R (driver-load ratio) by E/D gate width ratio. Vary gate length.**		
GL 1.5 µm	**GL 2.5 µm**	**GL 5 µm**	**GL 1.5 µm**	**GL 2.5 µm**	**GL 5 µm**	**GL 1.5 µm**	**GL 2.5 µm**	**GL 5 µm**
β_R = 1.5	β_R = 1.5	β_R = 1.5	β_R = 1.5	β_R = 1.5	β_R = 1.5	β_R = 1.5	β_R = 1.5	β_R = 1.5
β_R = 6	β_R = 6	β_R = 6	β_R = 6	β_R = 6	β_R = 6	β_R = 6	β_R = 6	β_R = 6
β_R = 16	β_R = 16	β_R = 16	β_R = 16	β_R = 16	β_R = 16	β_R = 16	β_R = 16	β_R = 16

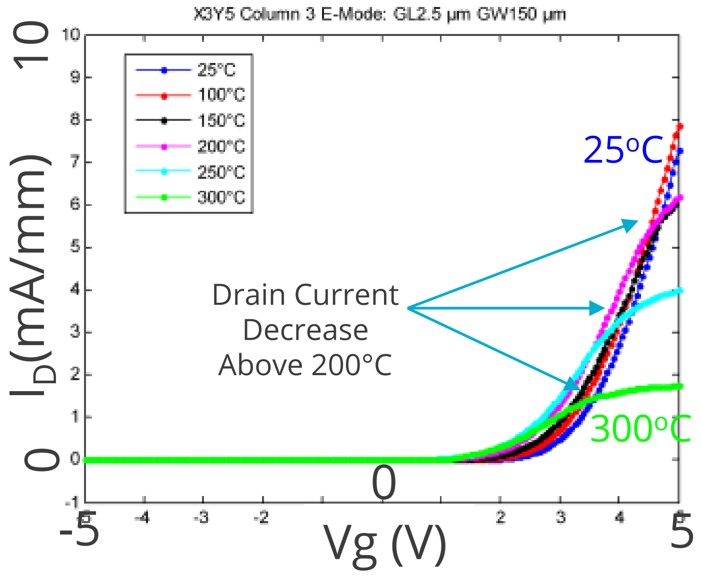
$$\beta_R = \frac{W_{Emode}/L_{Emode}}{W_{Dmode}/L_{Dmode}}$$

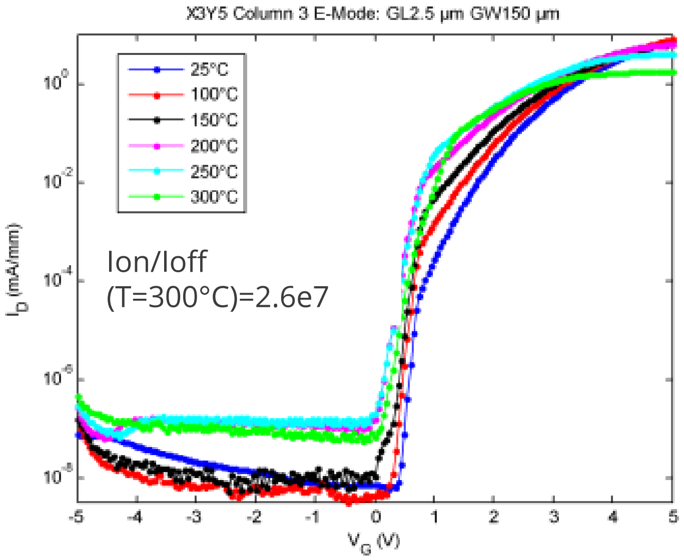
Mask Features

- Increasing β_R → Increasingly abrupt transition
- Multiple columns → Vary recess etch time

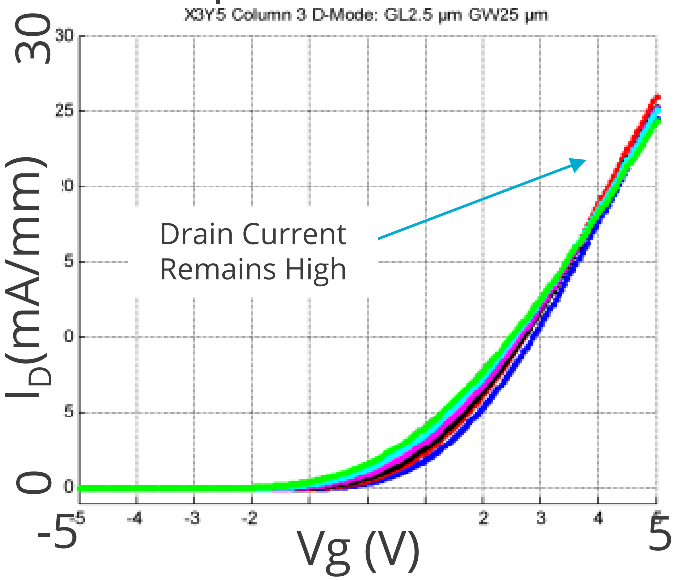
High Temperature Devices: Transistor

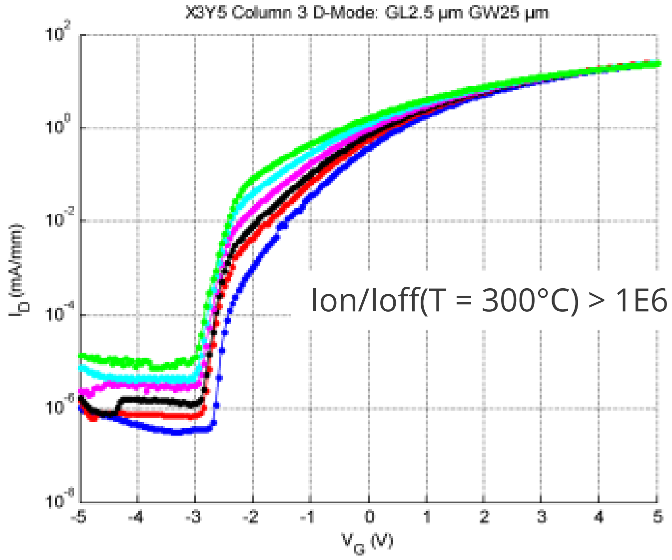
Enhancement Mode





Depletion Mode





D-mode: drain current stable 25-300°C
E-mode: drain current decreases >200°C

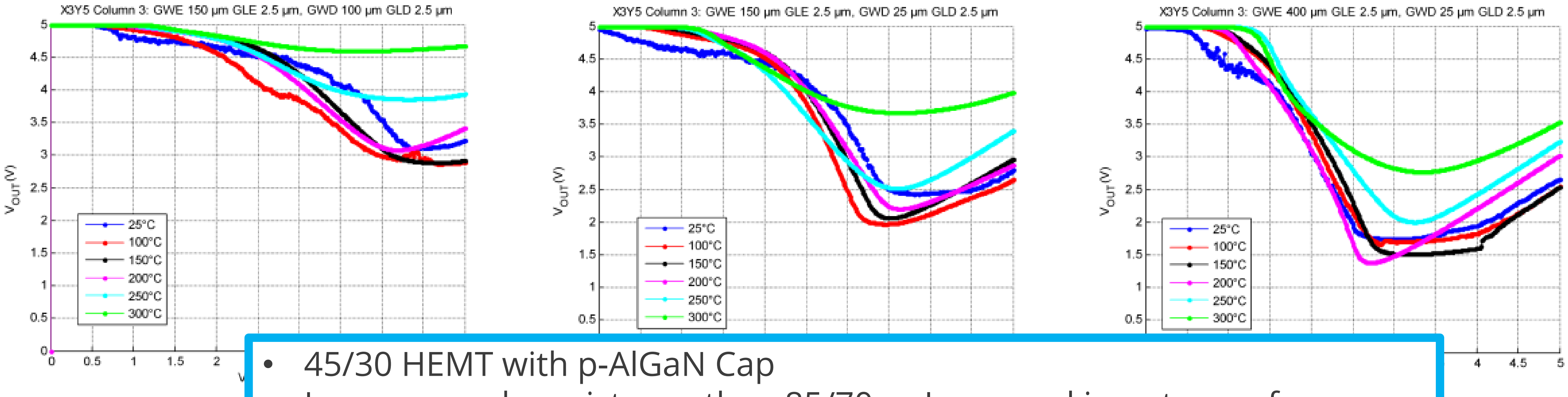
E-mode resistance increases → inverter $V_{out,Low}$ rises

On/Off ratio stable 25-300°C for both e- and d-mode transistors

High Temperature Devices: Inverter Results

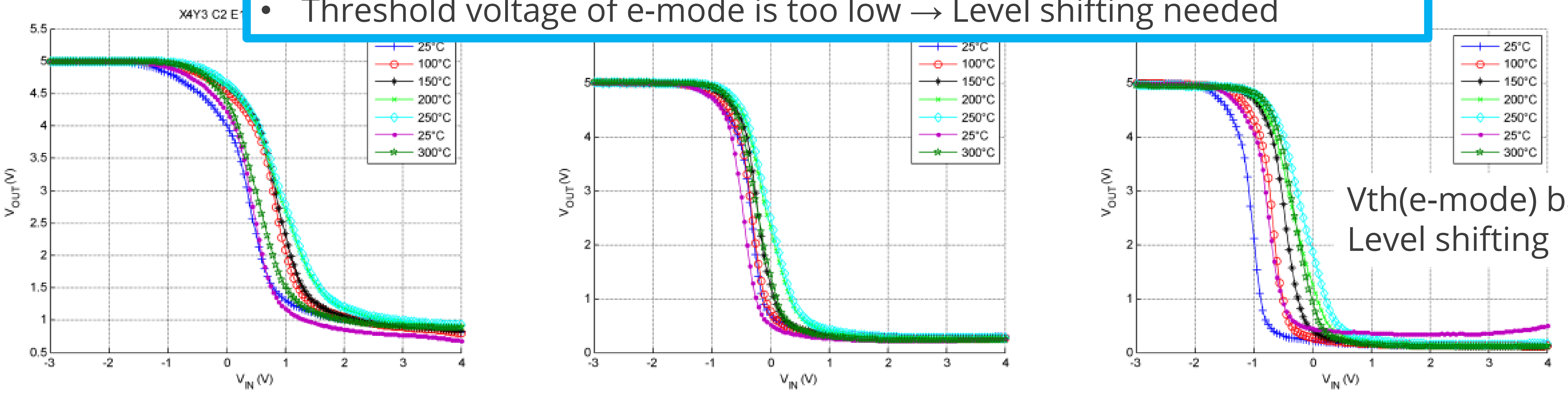
$\beta_R = 1.5$ | $\beta_R = 6$ | $\beta_R = 16$

85/70 HEMT

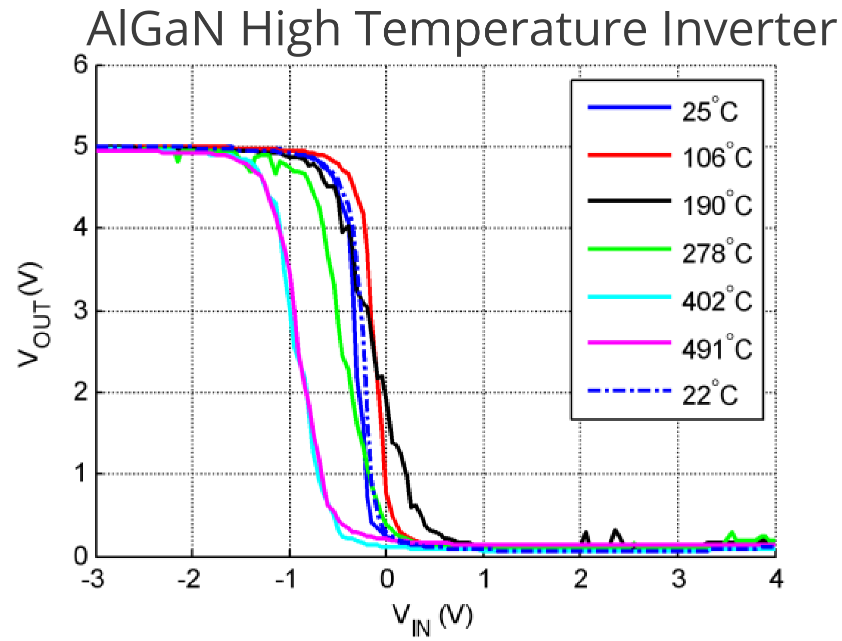


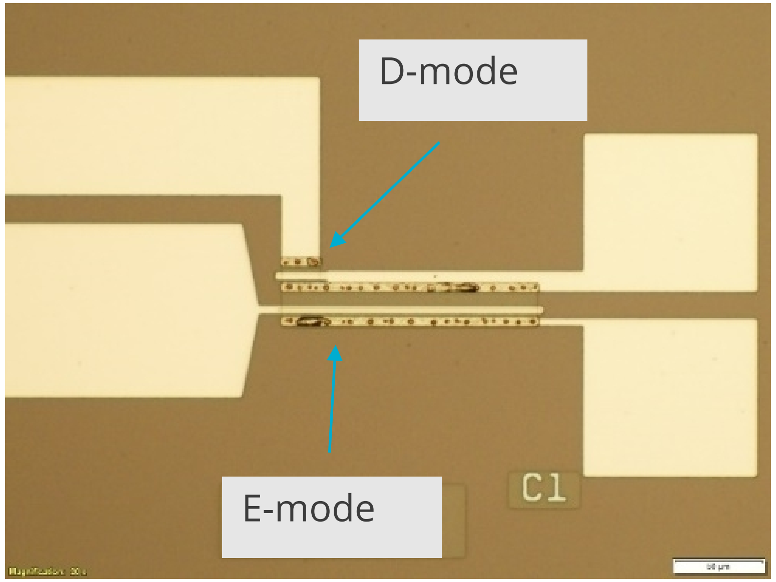
- 45/30 HEMT with p-AlGaN Cap
- Lower e-mode resistance than 85/70 → Improved inverter performance
- Threshold voltage of e-mode is too low → Level shifting needed

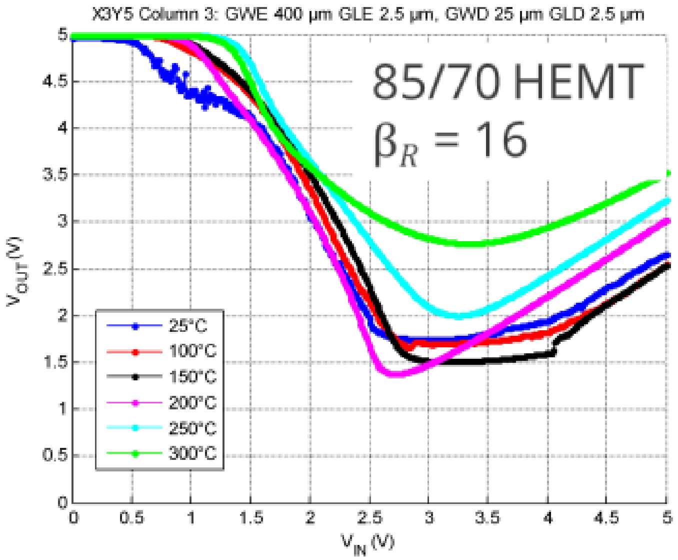
45/30 HEMT

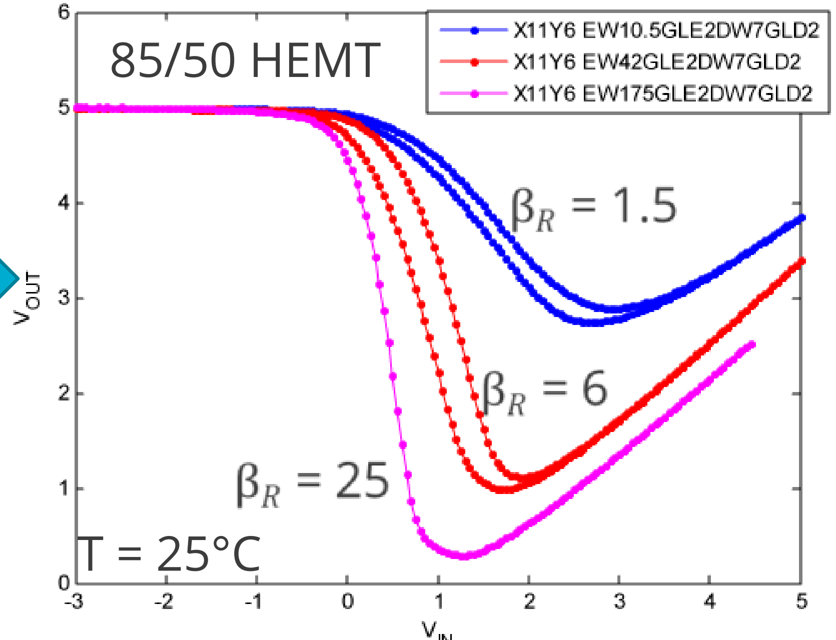


High Temperature Devices: Inverter Results









45/30 HEMT + p-AlGaN gate cap
- Operation up to 491°C
- Requires level shifting
- E-mode threshold wasn't shifted positive enough

85/70 HEMT
- Increasing resistance of e-mode → Degradation of inverter characteristics with increasing temperature

85/50 HEMT
- Room T performance improvements from reduced sheet resistance.
- Needs testing over T
- Need to minimize leakage for high V_{in}

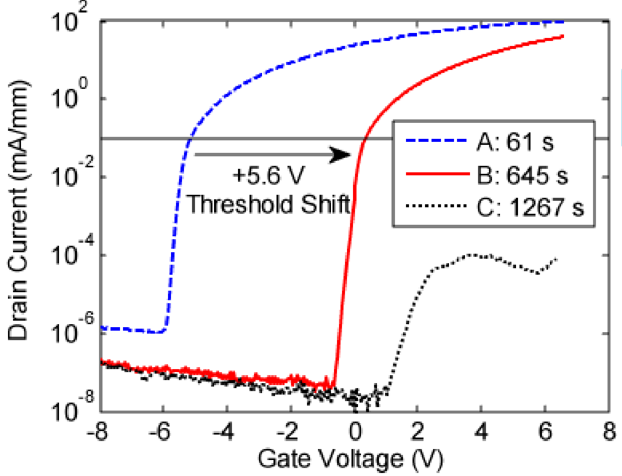
Summary

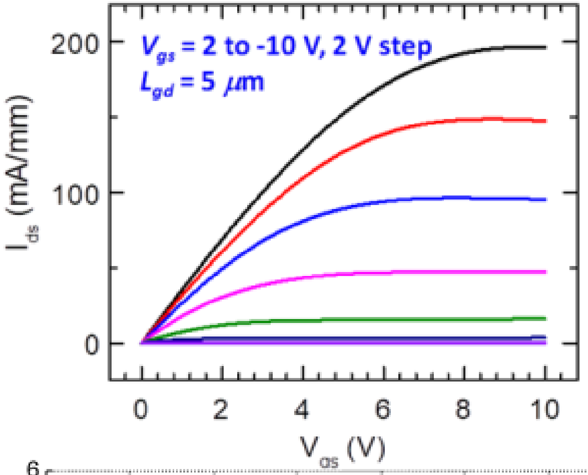
Ultra-wide bandgap: AlGaN choice material for high temperature and power switching applications

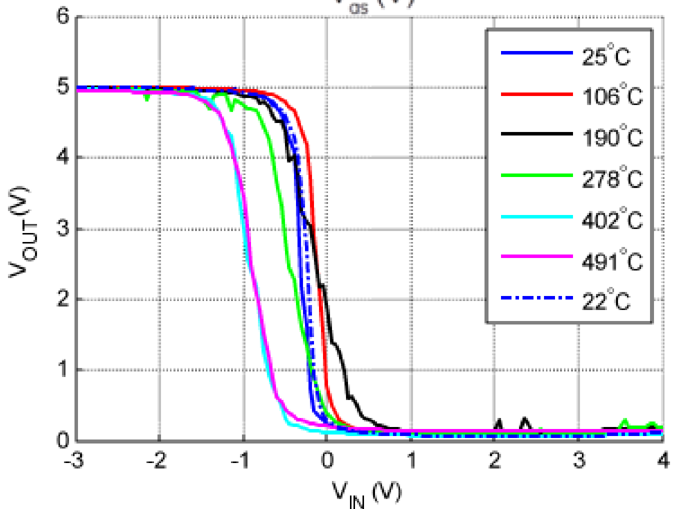
- E-mode: Two approaches for threshold voltage control
- Transport study: Needed high barrier/channel Al contrast
- Ohmic contacts: Improved by modifying epitaxy 85/70 HEMT → 85/50 HEMT
- High temperature Gate Metals: Tungsten (2000 Å)

High Temperature Devices

- E-mode/D-mode logic gates
- 45/30 HEMT Inverter tested up to ~500°C







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B.A. Klein, A.M. Armstrong, A.A. Allerman, C.D. Nordquist, J.C. Neely, S. Reza, E.A. Douglas, M. Van Heukelom, A. Rice, V. Patel, B. Matins, T.R. Fortune, M. Rosprim, L. Caravello, R. DeBerry, J.R. Pipkin, V.M. Abate, R.J. Kaplar

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baklein@sandia.gov

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