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Addressing Challenges in AlGaN-Channel High Electron Mobility Transistors

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2024 MRS Spring Meeting

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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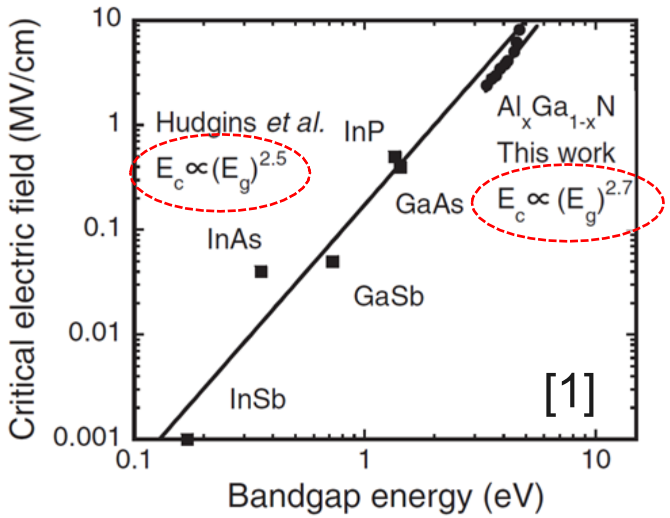
Why Al-rich AlGaN-Channel HEMTs?

1. Electrical power density scales *dramatically* with band gap
2. Large bandgaps enable high operating temperatures

Material	E_G (eV)	E_C (MV/cm)	Electron mobility (cm²/V s)
SiC	3.3	2.5	1000
GaN	3.4	4.9	1000
$Al_xGa_{1-x}N$	>3.4 - 6.0	4.9-15.4	~150-400
AlN	6.0	15.4	426
β-Ga_2O_3	4.9	10.3	180
Diamond	5.5	13.0	4500-7300

- Band gap energy (E_g) is the fundamental material property driving size, weight, power, and cooling (SWaP-C) at the device-, circuit-, and system-levels
- Wide band gaps suppress intrinsic carrier density effects and thermionic emission-induced leakage[2]



- Electrical power density of GaN >1000x Si
- Electrical power density of AlN potentially >20x GaN

$$R_{on,sp} = \frac{4V_{br}^2}{\epsilon \mu E_{crit}^3}$$

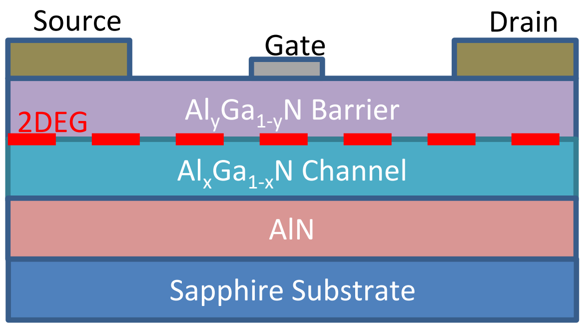
$$Power\ density \sim 1/R_{on,sp} \sim \epsilon \mu E_g^8$$

$$V_{br} \sim E_g^{5.5}$$

[1] Nishikawa, *et al.*, JJAP 46, 2316 (2007).
[2] P. G. Neudeck, R. S. Okojie, and L.-Y. Chen, *Proceedings of the IEEE,* vol. 90, no. 6, pp. 1065 - 1076, 2002.

OUTLINE

- Ohmic contacts to Al-rich AlGaN HEMTs (Power Transistors)
  - Barrier / Channel Al composition
  - Regrown gates
  - Regrown contacts
- High operating temperature AlGaN HEMTs (Logic)



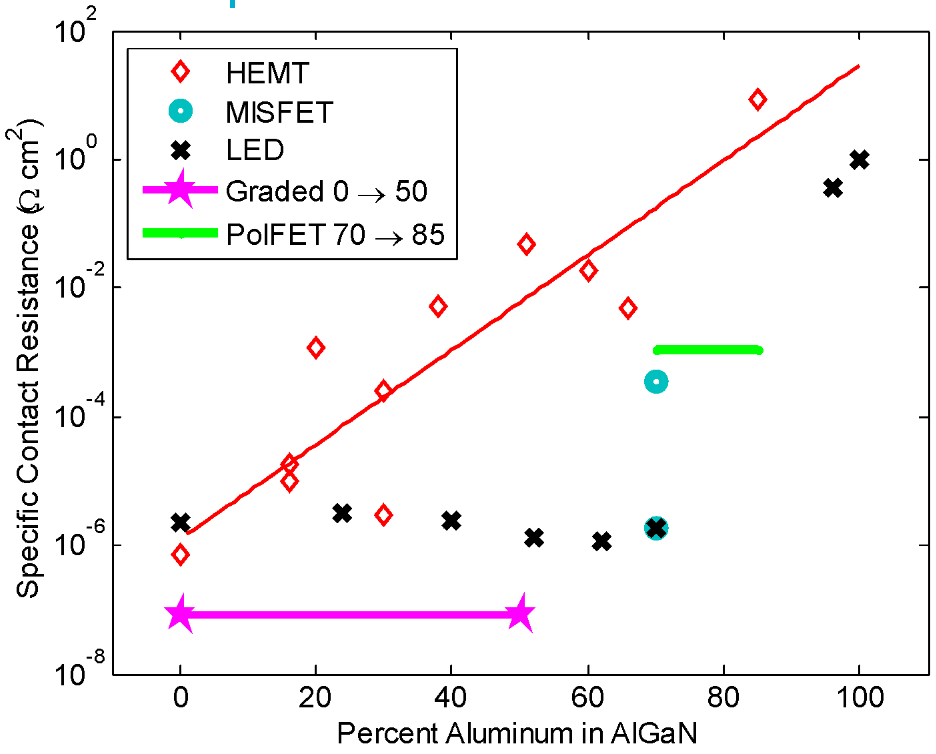
Nomenclature: Y/X HEMT

HEMT = High Electron Mobility Transistor

Ohmic Contacts to Al-rich AlGaN HEMTs

Literature Review: Ohmic Contacts to AlGaN

Contact Resistance vs. Channel Composition



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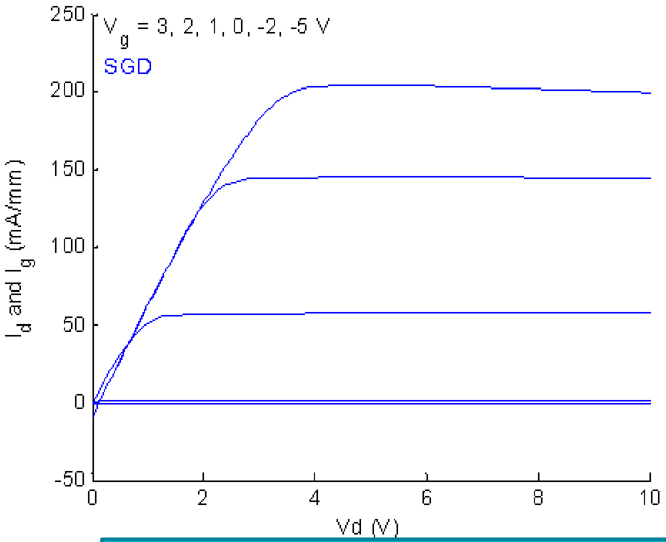
E. A. Douglas, Physica Status Solidi A, vol. 214, no. 8, 2017.
B. A. Klein, ECS Journal of Solid State Science and Technology, vol. 6, no. 11, pp. S3067-S3071, 2017.

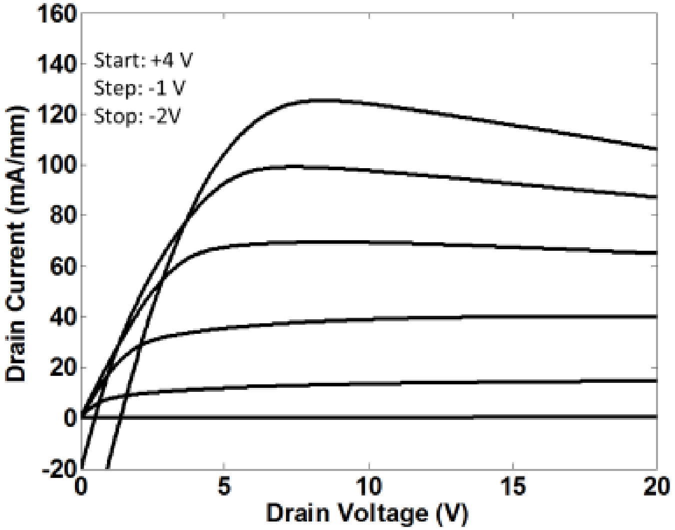
Which matters: Barrier composition or channel composition?
Increasing Al composition increases specific contact resistance

Contacts to increasing Al content

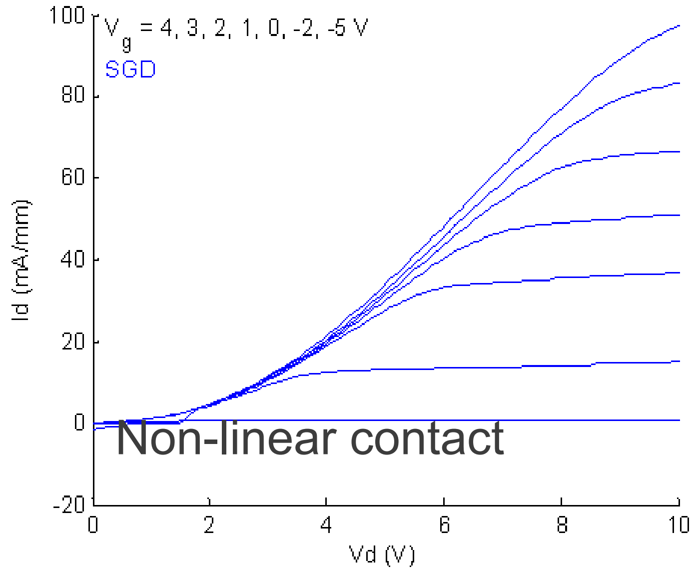
25/0 HEMT



45/30 HEMT



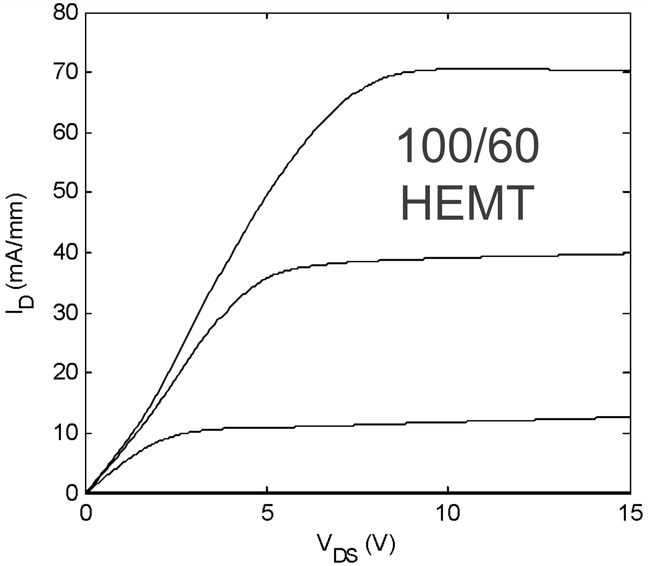
85/70 HEMT



Increasing Al Content

100/60 HEMT contacts working:

- High Al barrier content
- Reduced channel composition



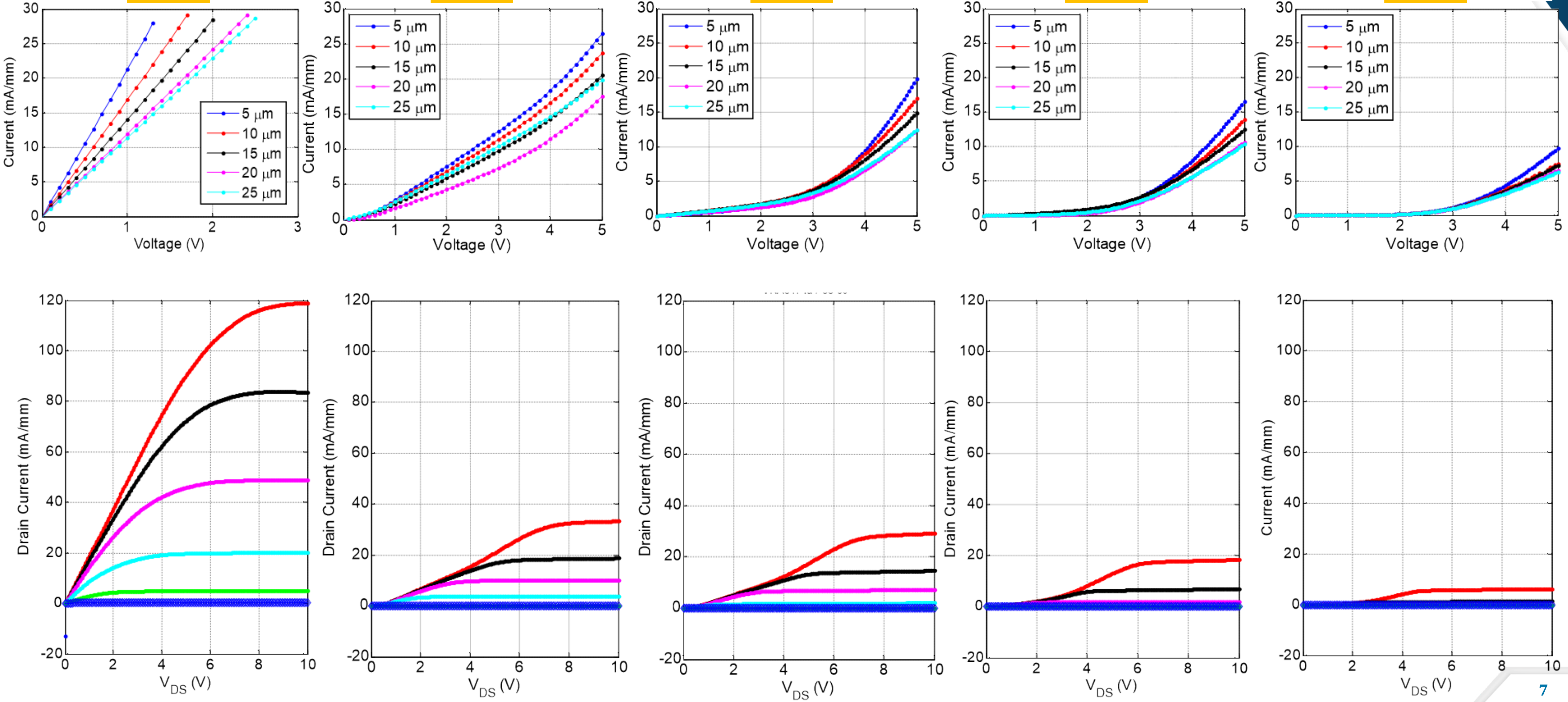
Why is this one working?

Example Experiment: Vary Channel Composition

Observed systematic decline in contacts with increasing channel composition

Barrier composition fixed at $Al_{0.85}Ga_{0.15}N$

50% | 55% | 60% | 65% | 70%

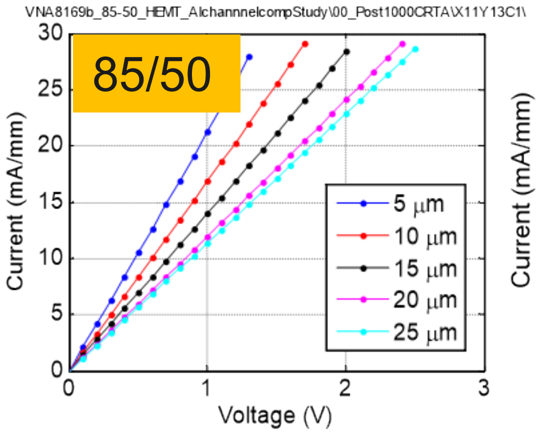


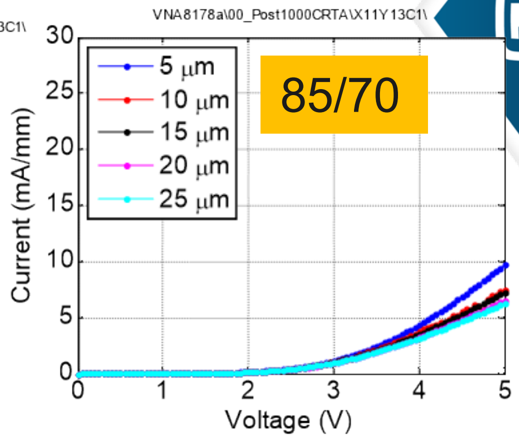
Barrier / Channel design impacts

Vary channel composition: 85/50,55,60,65,70

Observed systematic decline in contacts with increased channel composition

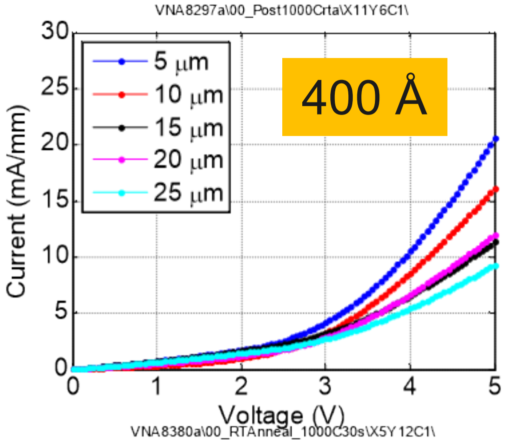
Channel charge concentration impact?

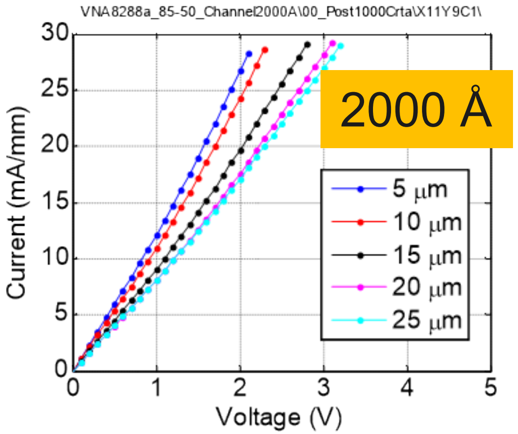




Vary channel thickness in 85/50.
Barrier thickness: 300 Å

Observed decline in contacts with thinner channels

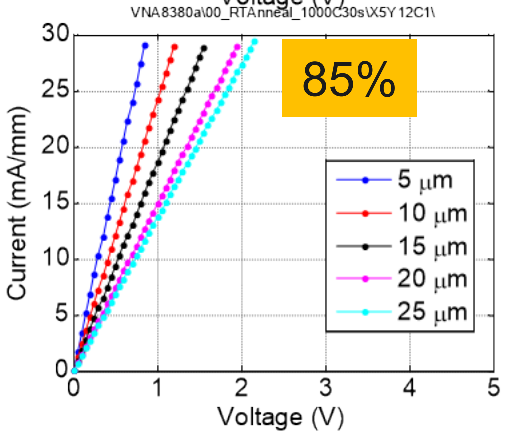


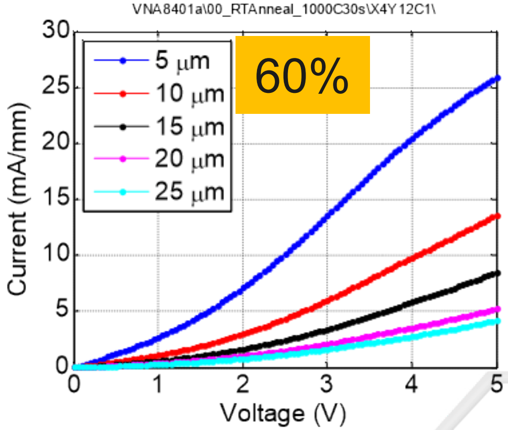


Vary barrier Al composition: 60, 65, 70, 75, 80, 85
Channel composition: 50

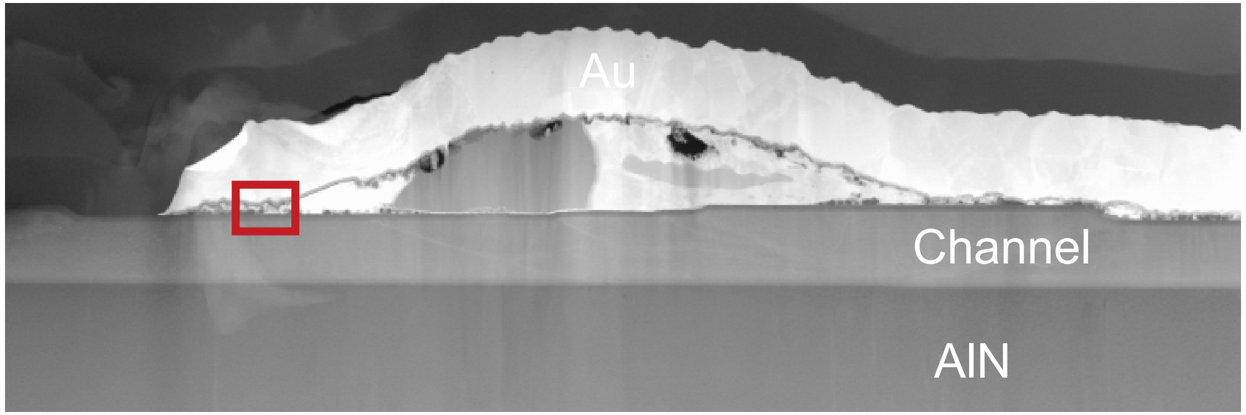
Observed degradation in sheet resistance with lower barrier composition

Channel charge concentration impact?

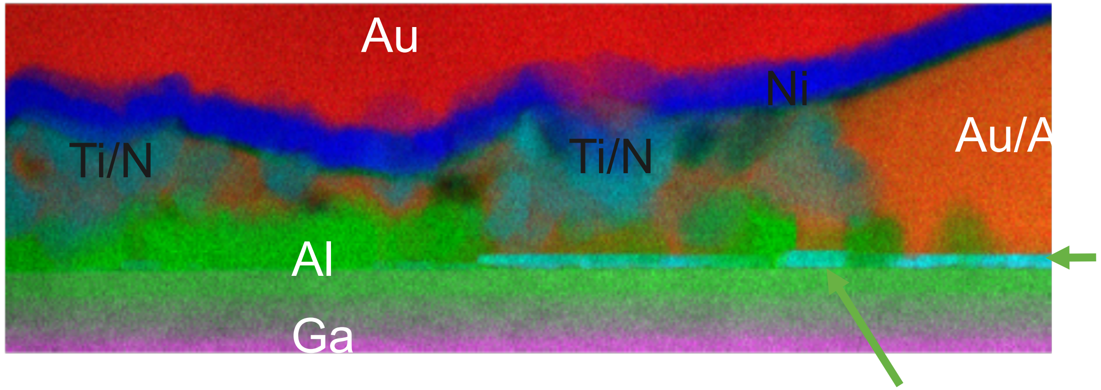


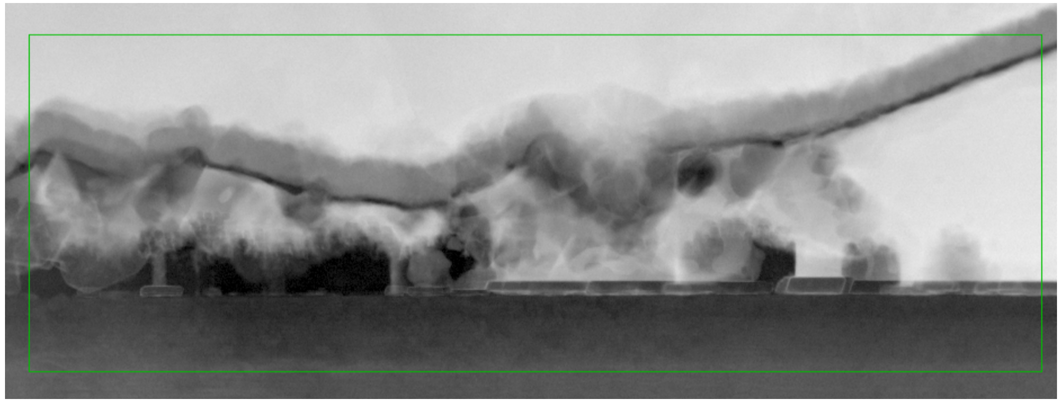


TEM: Ohmic contacts to 85/50 HEMTs



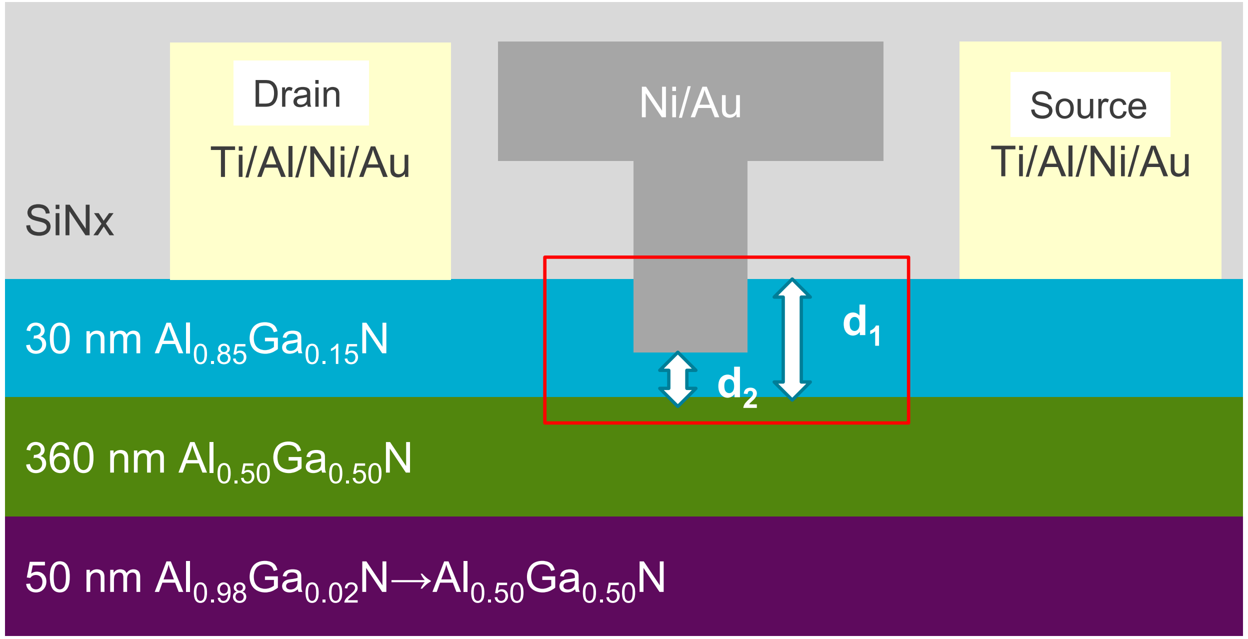
Observed interaction between the Ohmic metal and AlGaN barrier



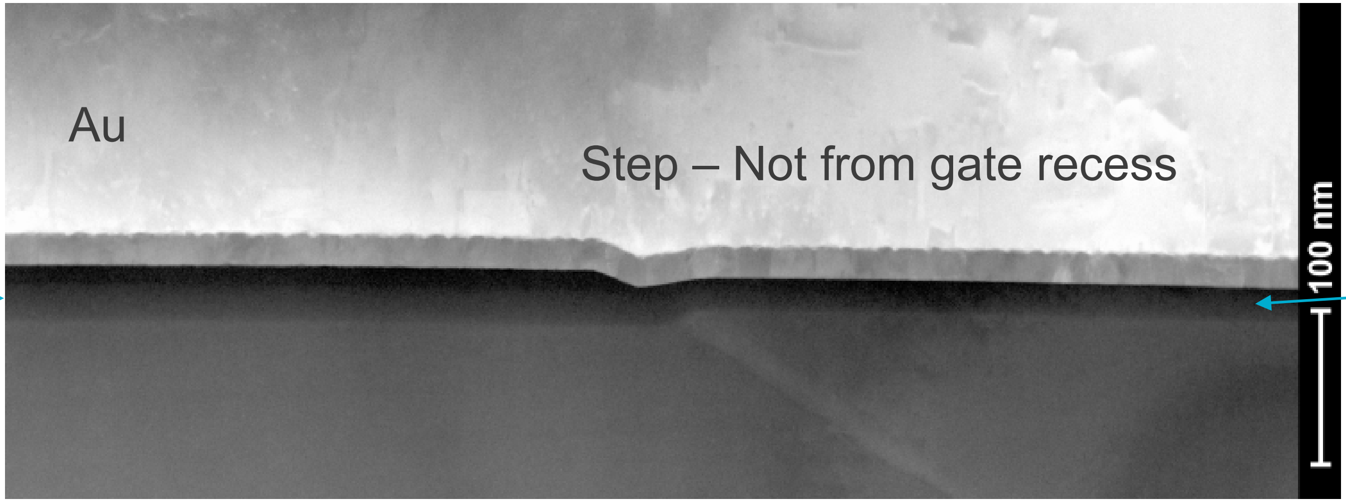


The Ohmic contact results are better, but what about the gates?

Gate



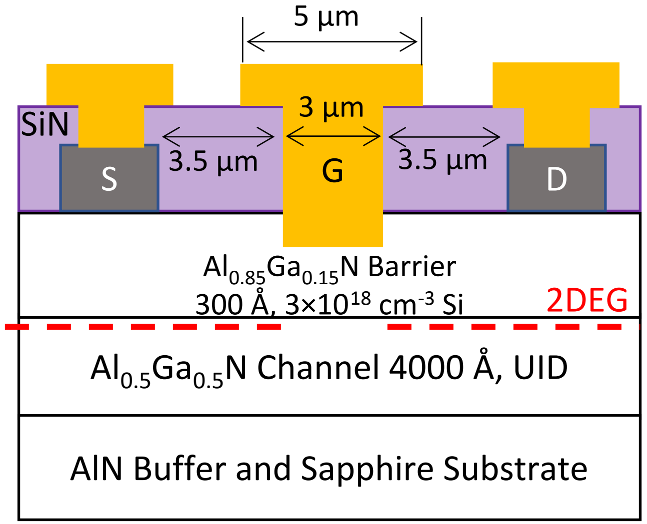
Barrier recess under gate for enhancement-mode devices



Note the low-Z nitride thickness change at the step

New problem: Gate leakage. Barrier thickness varies within gate area. E-mode barrier recess etch not effective.

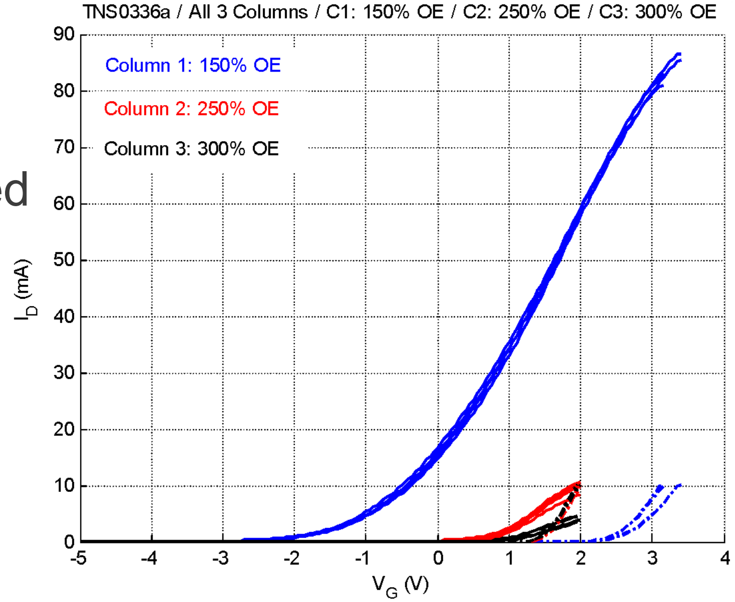
85/50 HEMT: Promising Ohmic Contacts, Gates Problematic

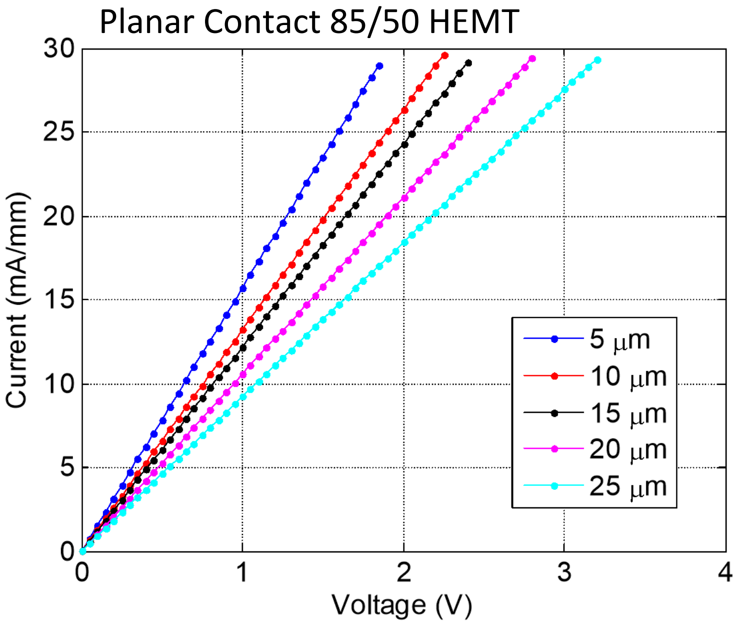


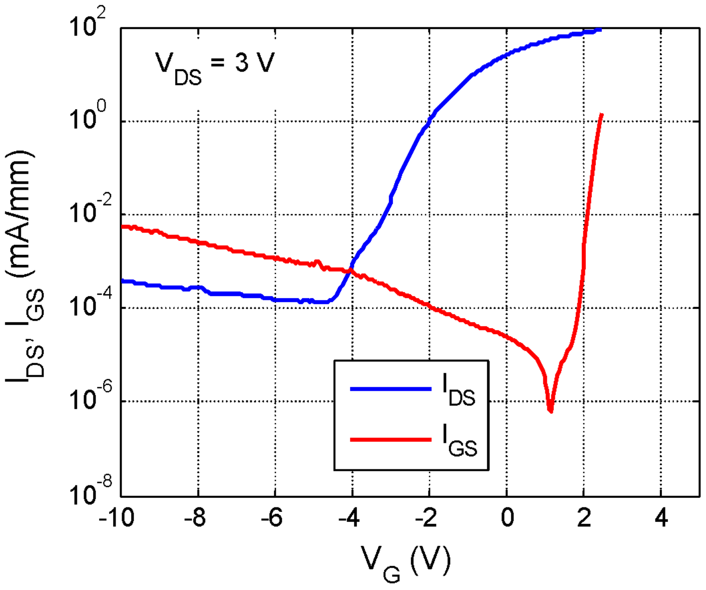
- 85/50 HEMT showed promising Ohmic contacts
- Specific contact resistance = 3x10^{-4} Ωcm²
- Gate Recess: Forward gate leakage limited voltage swing

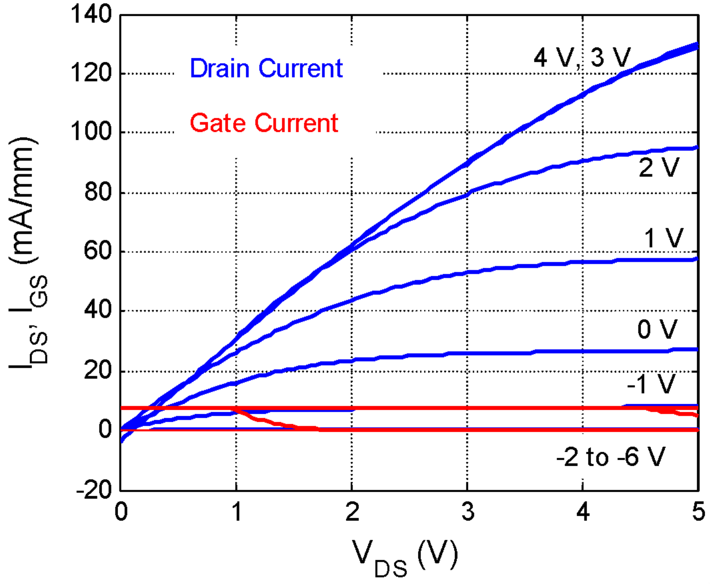
Next approaches:

1. Try a p-type gate
2. Try regrown source/drain contacts





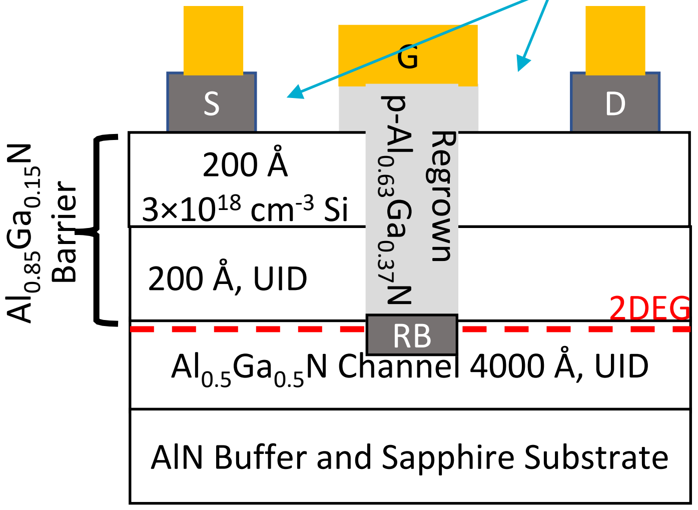




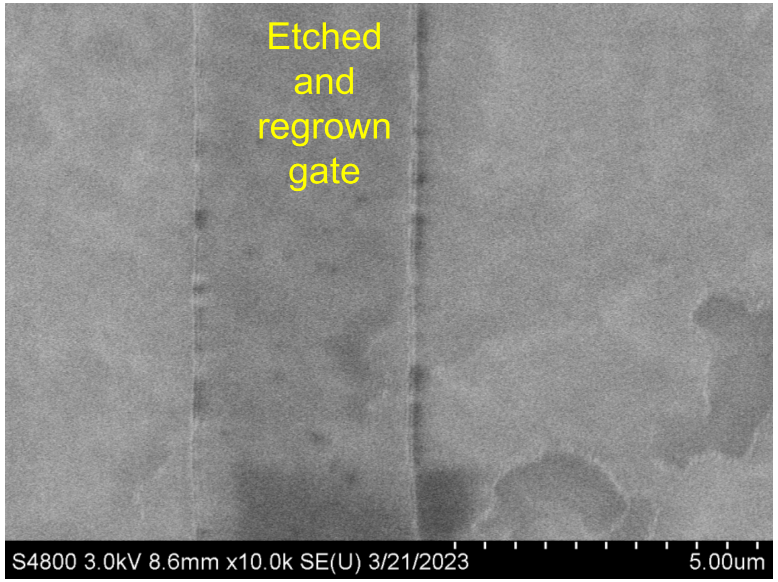
Klein et al., *Advanced Materials Interfaces*, p. 2301080.

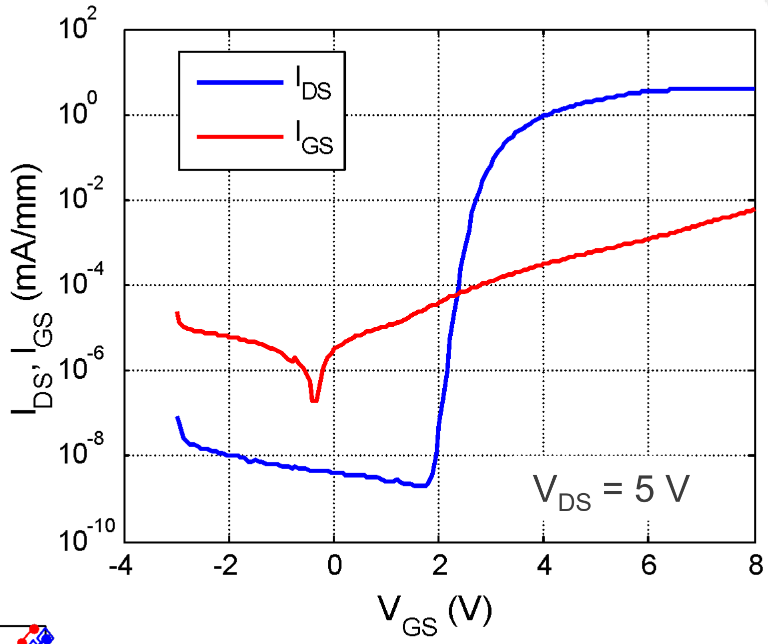
85/50 HEMT: Etched and Regrown p-AlGaN Gate

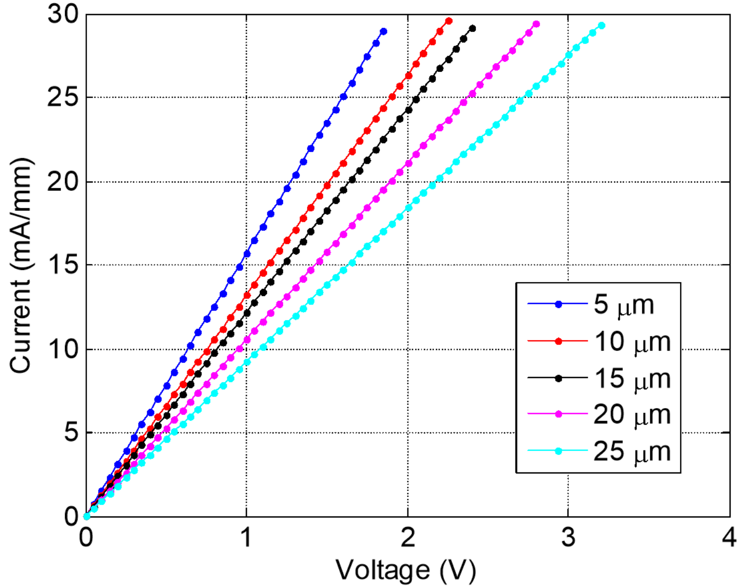
Etch p-AlGaN from access and Ohmic areas

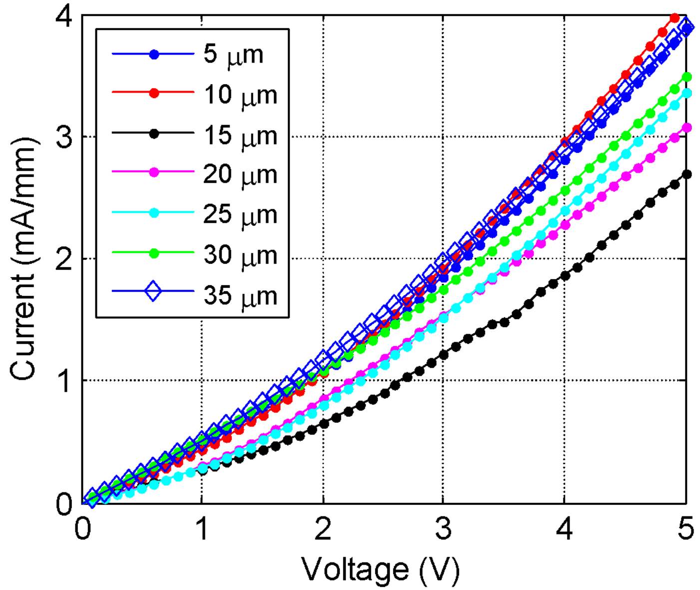


Regrown 85/50 HEMT









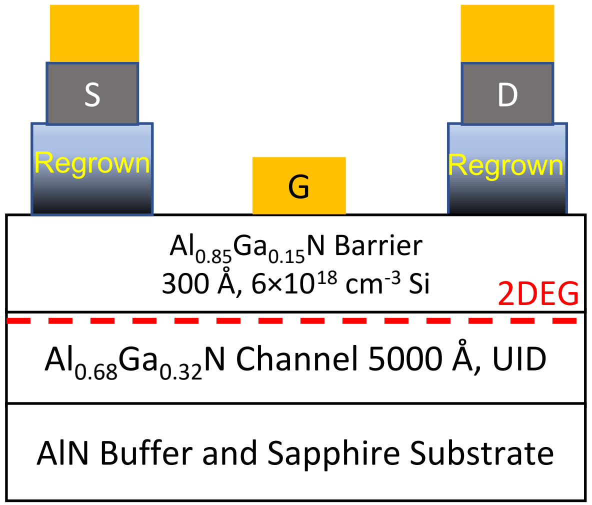
Improved Gate
- V_{TH} = 3.5 V
- Forward gate leakage reduced

→ Greater voltage swing

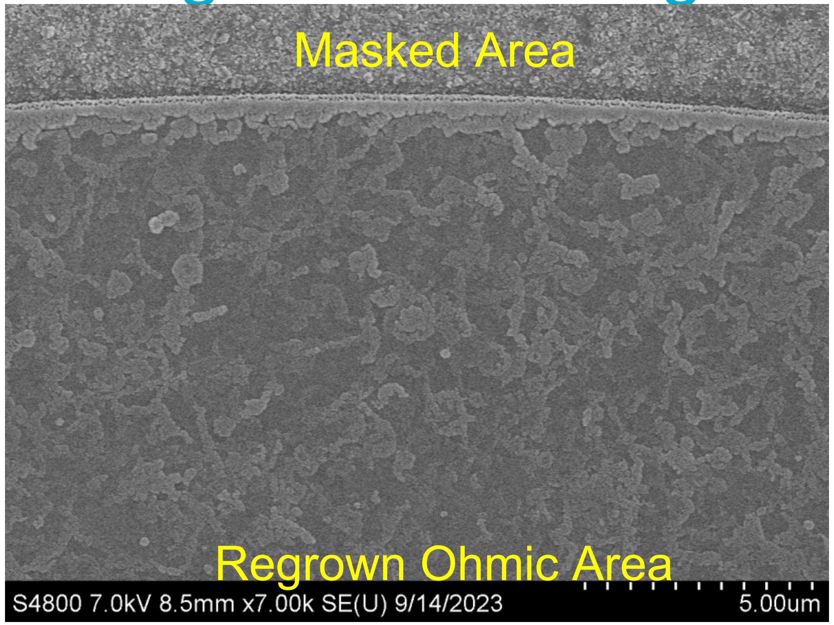
Ohmic Contacts Degraded
1. 200 Å UID barrier?
2. Access/Ohmic region etches?

Klein et al., *Advanced Materials Interfaces*, p. 2301080.

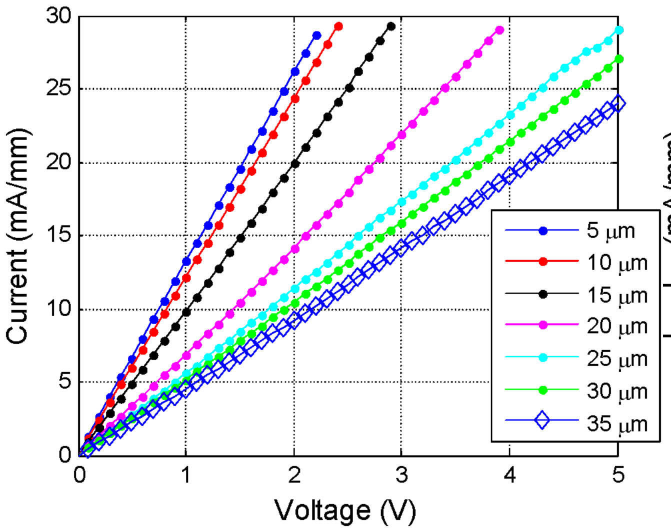
Compositionally reverse graded N++ regrown contacts

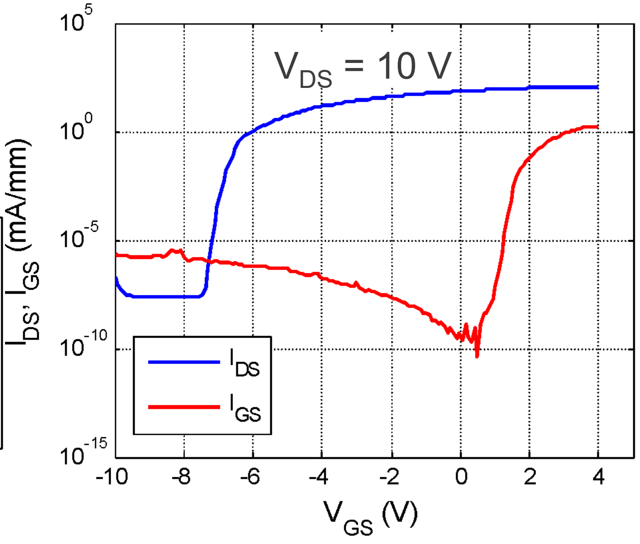


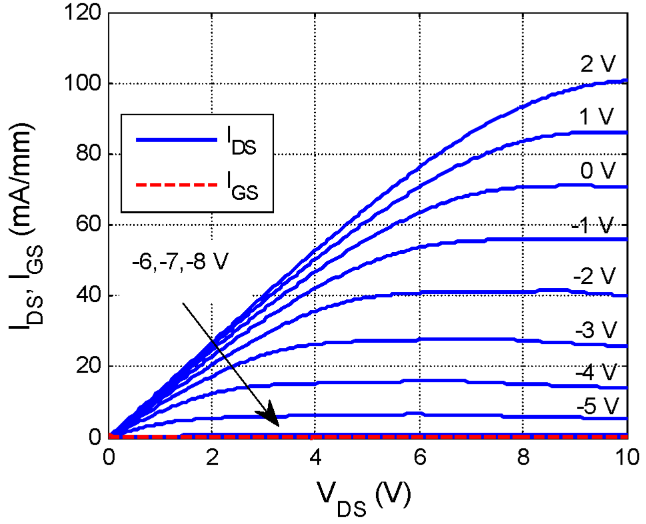
Regrown Contact 85/68 HEMT



- 85/68 HEMT
- Regrown, Compositionally Reverse Graded N++ Ohmic Contacts
- Minimum specific contact resistance = 4×10^{-6} Ωcm^2
- V_{TH} = -6.4 V
- High doping critical



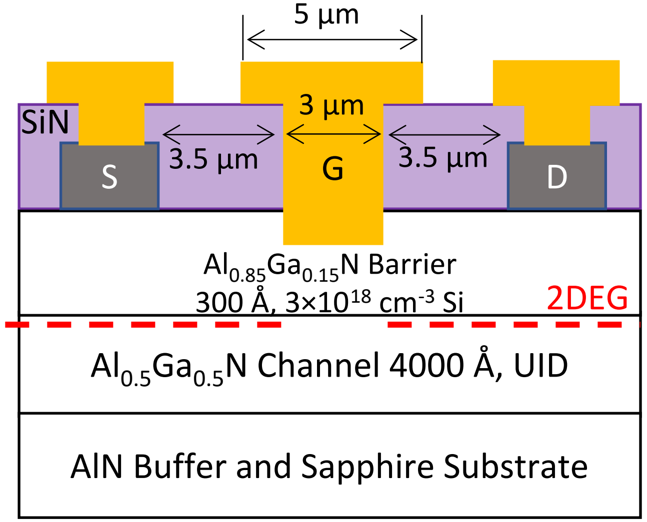




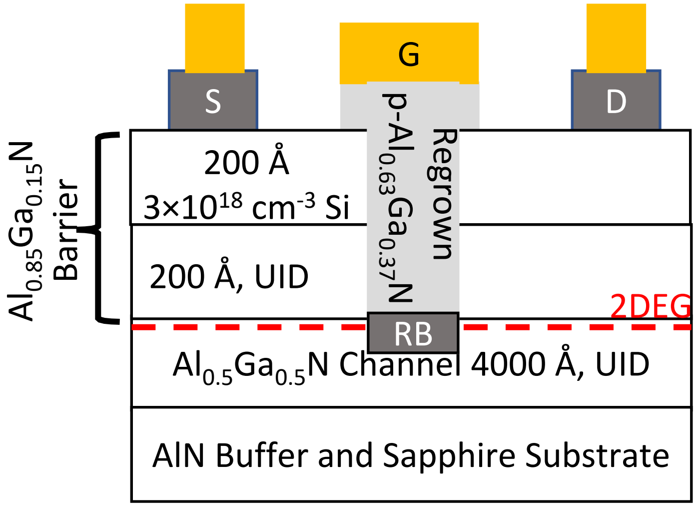
Klein et al., *Advanced Materials Interfaces*, p. 2301080.

Ohmic Contacts Summary

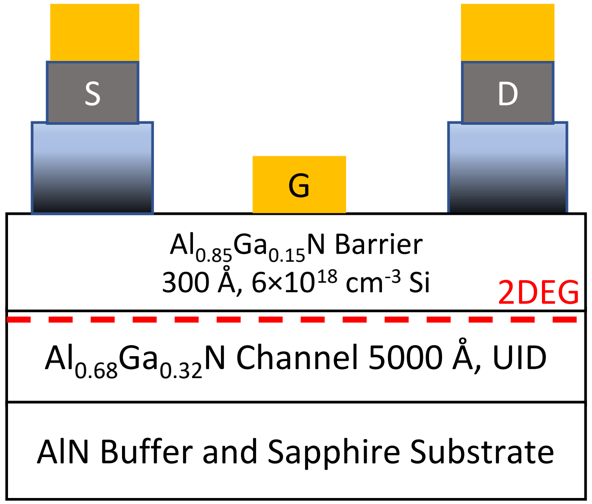
Approach	Average ρ_c [Ω cm²]	V_{TH} [V]	$J_{DS,}$max [mA mm^{-1}]	Ion-off
85/50: Planar Contacts	7.4×10^{-4}	-2.5	70.65	1.41×10^{5}
85/50: Etched + Regrown Gate	1.8	3.5	3.33	1.41×10^{8}
85/68: Regrown, compositionally reverse-graded N++	1.8×10^{-4}	-6.4	108.20	2.11×10^{9}



Planar Contact 85/50 HEMT



Regrown 85/50 HEMT



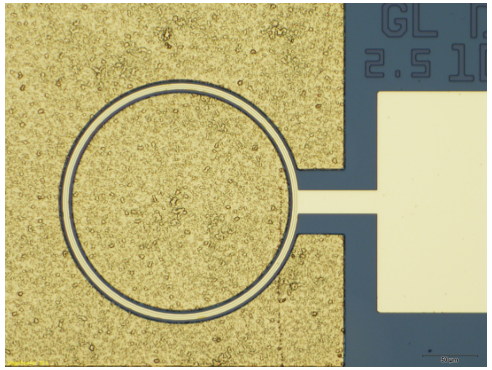
Regrown Contact 85/68 HEMT

- Need combination of low-resistance contacts with e-mode p-AlGaN gates
- Process integration challenging

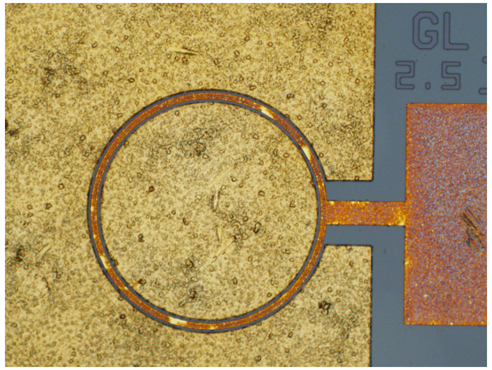
Klein et al., *Advanced Materials Interfaces*, p. 2301080.

High Operating Temperature AlGaN HEMTs

Motivation: High Operating Temperature Gate Metals in Air



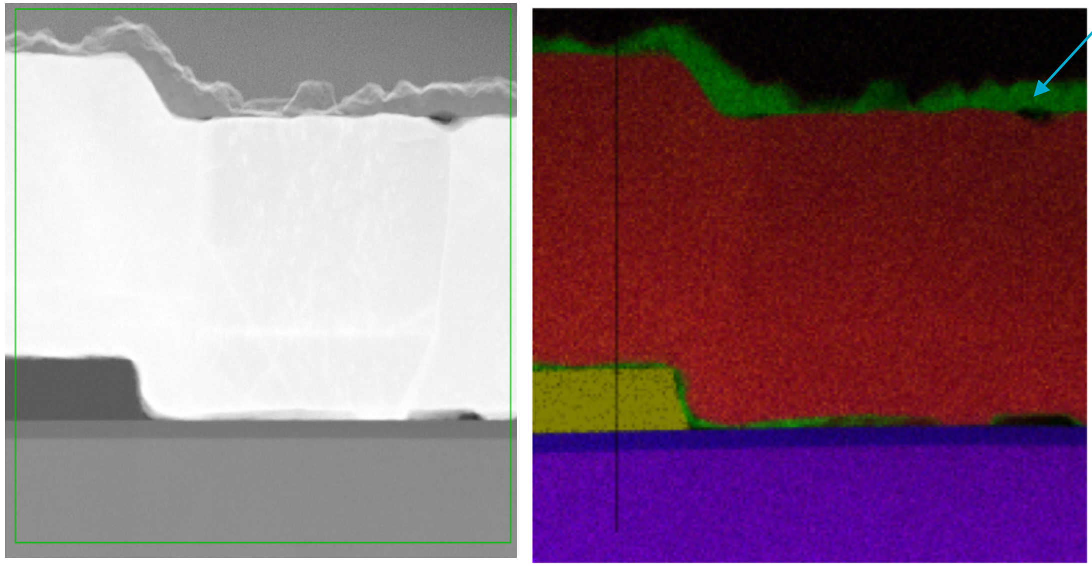
Before >300°C



After >300°C

- Ni oxidizes and migrates to the top
- Result: Brittle contacts

Need better gate metals



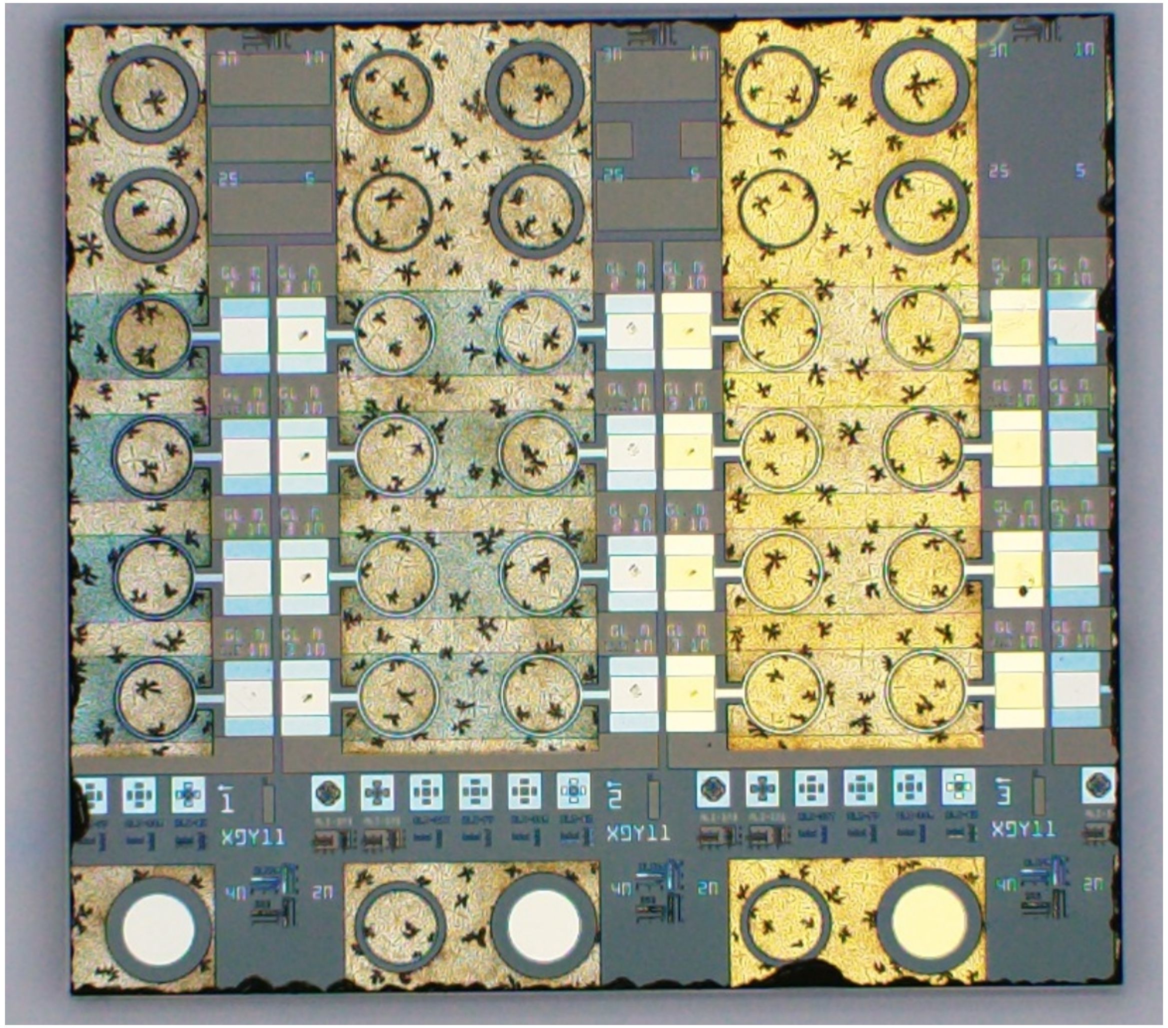
Red = Au
Green = Ni-Cu-O
Blue = Al-low Ga-N
Magenta = Al-high Ga-N
Yellow = Si-N

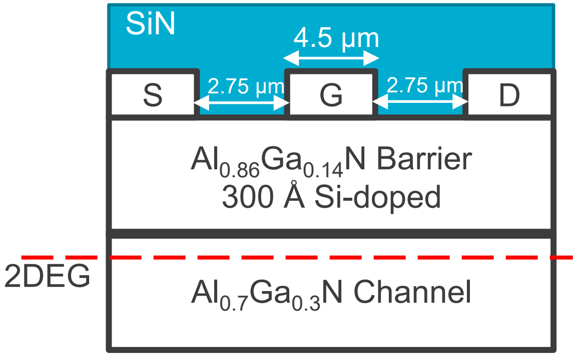
P. H. Carey, *Journal of the Electron Devices Society,* vol. 7, pp. 444-452, 2019.

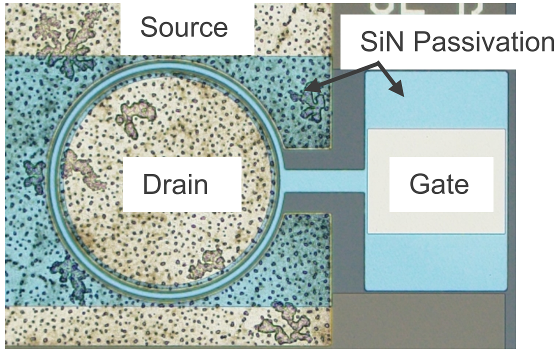
Experiment

Goal: Identify appropriate gate metal for AlGaN HEMTs operating in extreme temperatures and in air.

W Gate 2000 Å | Pd Gate 2000 Å | Pt/Au Gate 200 Å / 2000 Å







Pattern standard Ohmic contacts

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

Gate Metal

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

Characterize

DC Electrical Sweeps at chuck temperatures: 50, 100, 200, 300, 400, 500, 600°C

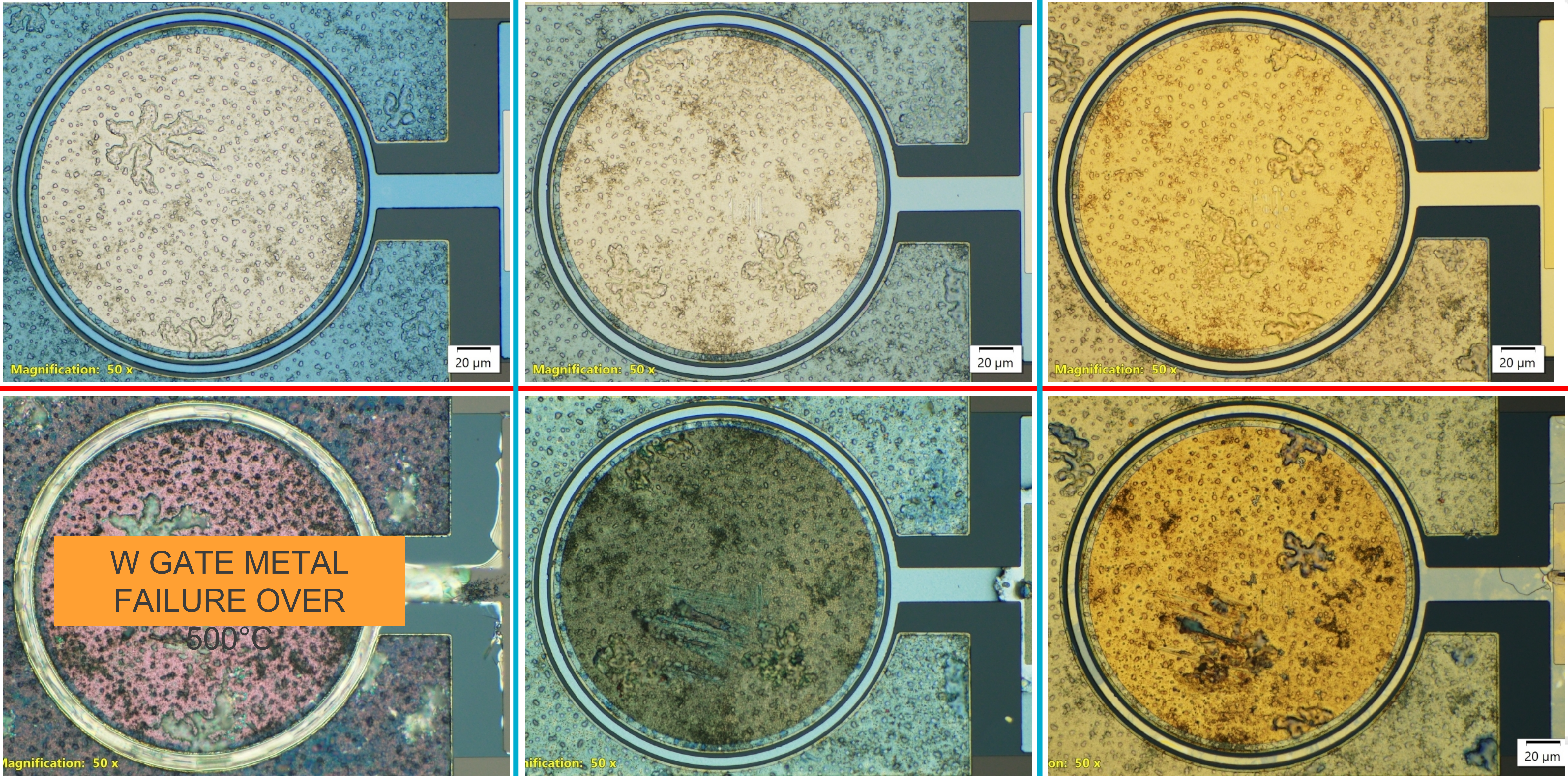
B. A. Klein, A. A. Allerman, and A. M. Armstrong, *Applied Physics Letters,* vol. 124, no. 10, 2024.

Visual Inspection

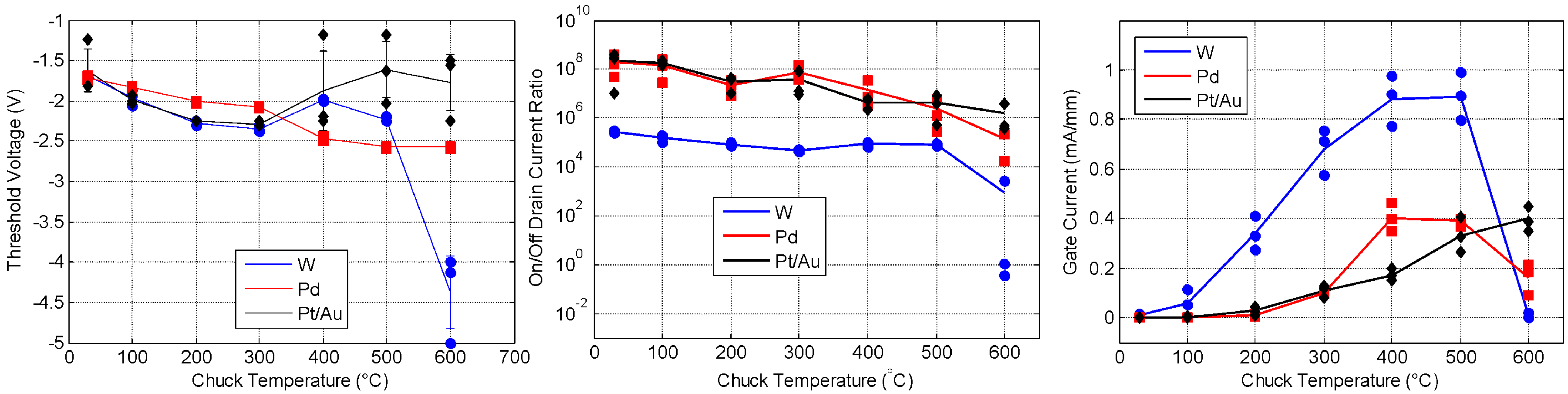
2000 Å W | 2000 Å Pd | 200 Å Pt / 2000 Å Au

FROM FAB

AFTER TESTING TO 600°C



Electrical Data Summary: Room Temp – 600°C



Gate Metal	Thickness (Å)	ΔV_{TH} (V) T_{Chuck} = 30 vs. 600°C	I_{ON}/I_{OFF} T_{Chuck} = 600°C	$I_{G,F}$ @ V_G=3 V (mA/mm) T_{Chuck} = 600°C
W	2000	-2.69 (Failure)	8.8×10^2 (Failure)	0 (Failure)
Pd	2000	-0.86	1.5×10^5	0.17
Pt/Au	200 / 2000	0.15	1.5×10^6	0.39

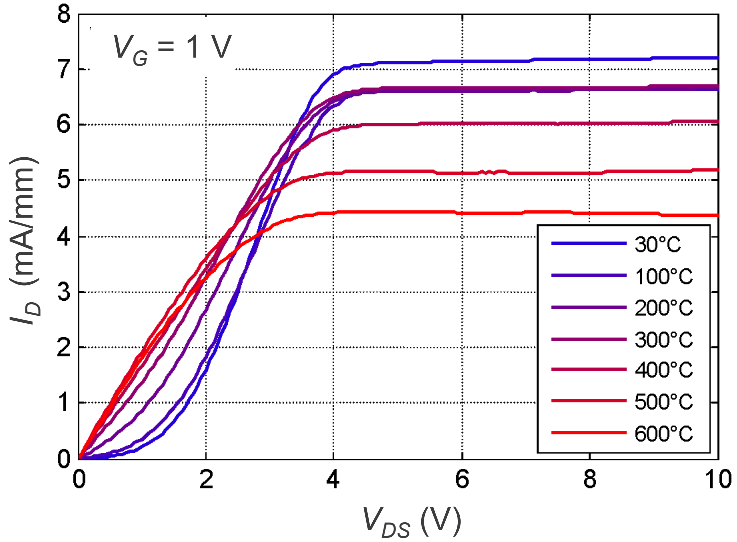
Was larger between 300°C and 600°C (42% largest change)

Change between 30°C and 600°C

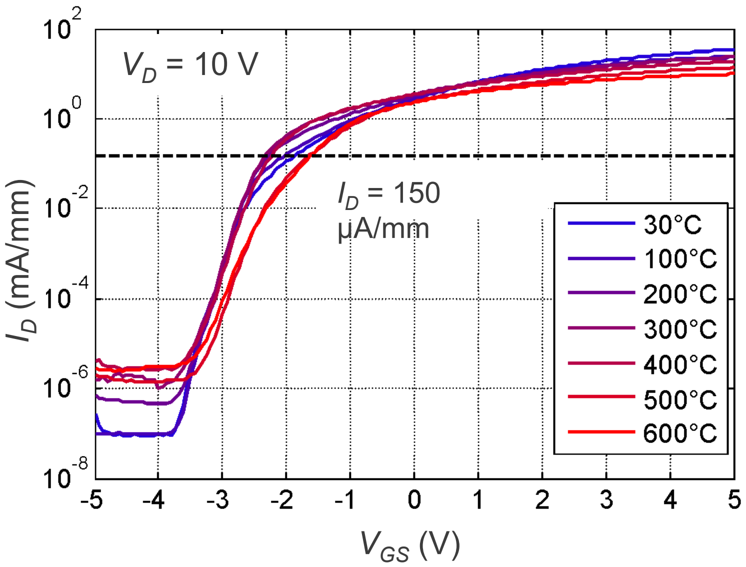
- Threshold voltage : Pt/Au (9%), Pd (50%), W (Broke)
- Ion/Ioff: $>1\text{x}10^5$ for Pt/Au and Pd
- Forward Gate Current: Pt/Au was most favorable

B. A. Klein, A. A. Allerman, and A. M. Armstrong, *Applied Physics Letters*, vol. 124, no. 10, 2024.

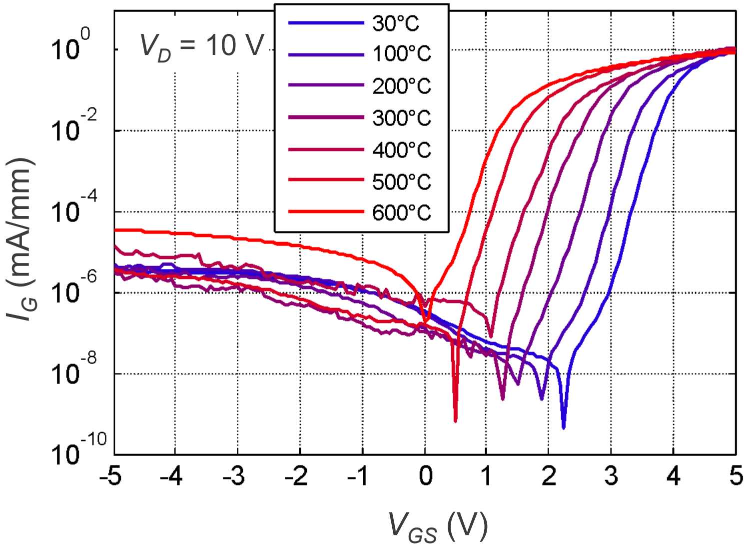
Pt/Au Gates: DC Electrical Sweeps



- 38% Decrease in I_{DS}
- Source/Drain contacts become Ohmic



- Off-state leakage stabilizes at 300°C



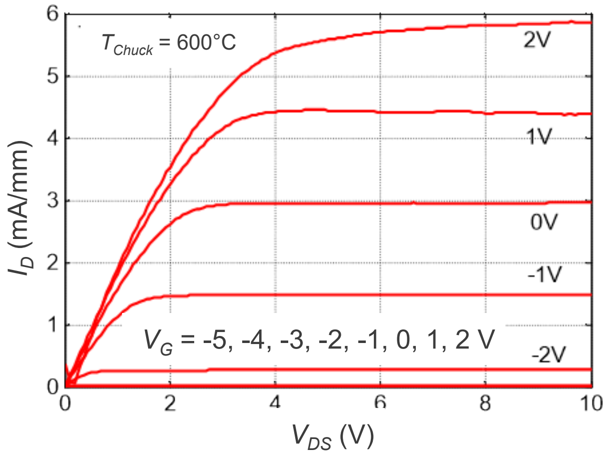
- Forward gate current turn-on shifts negative
- Limits voltage swing with increasing temperature
- Next experiments: P-AlGaN gates over T

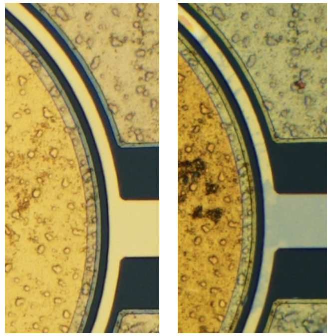
B. A. Klein, A. A. Allerman, and A. M. Armstrong, *Applied Physics Letters*, vol. 124, no. 10, 2024.

Conclusions

- Goal: Identify appropriate gate metal for AlGaN HEMTs operating in extreme temperatures and in air.
- Investigated: W, Pd, Pt/Au gates on $Al_{0.85}Ga_{0.15}N$ Barrier / $Al_{0.7}Ga_{0.3}N$ Channel transistors from 30°C to 600°C (chuck temperature).
- W gates failed over 500°C
- Pt/Au and Pd gates
  - Threshold voltage : Pt/Au (9%), Pd (50%)
  - Ion/Ioff: >1x10^5 for Pt/Au and Pd
  - Forward Gate Current: Pt/Au was most favorable

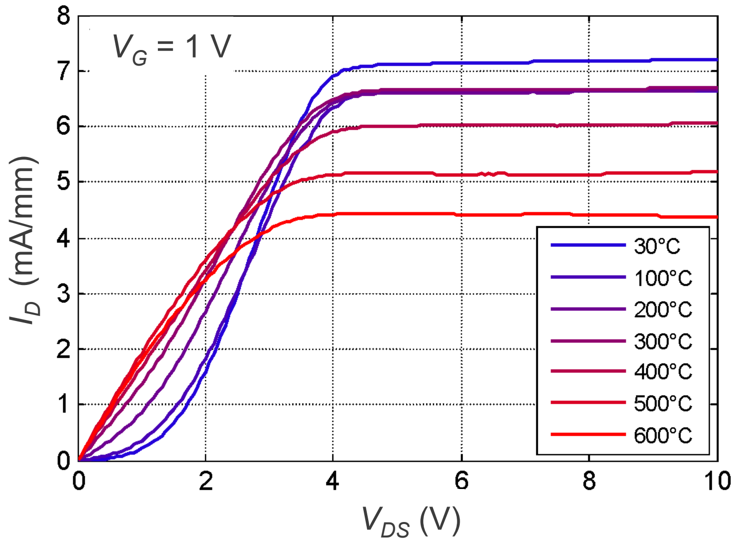
Pt/Au Gates

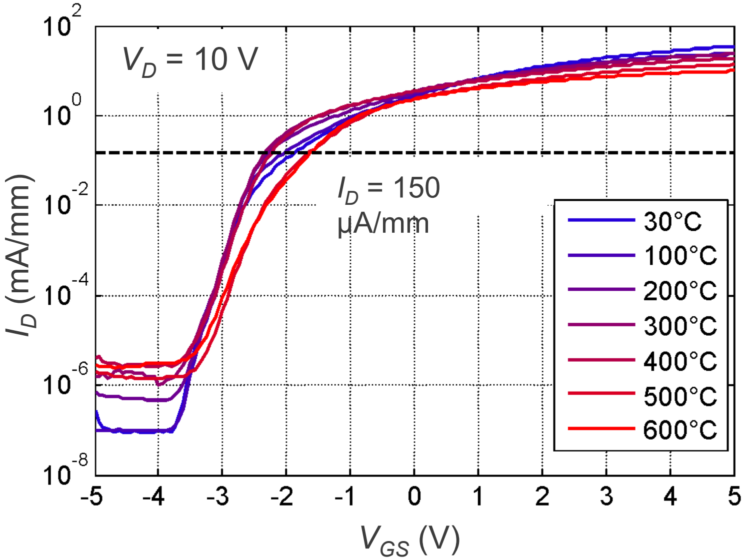


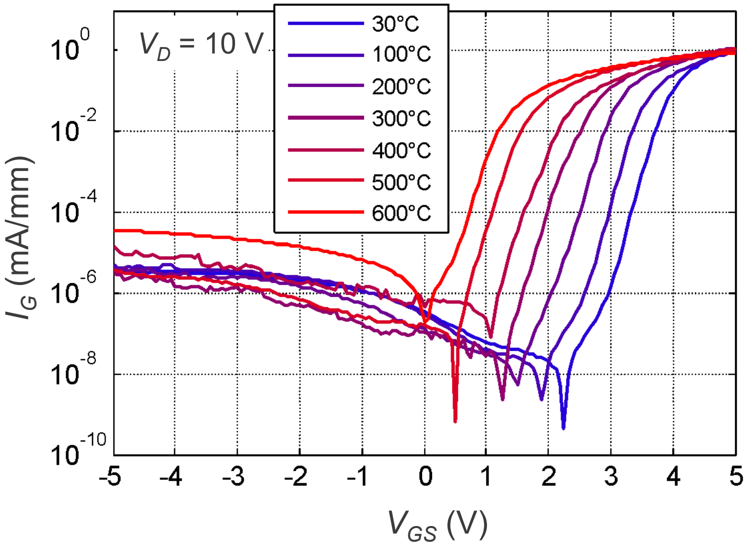


Before After

Testing at 600°C







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Addressing Challenges in AlGaN-Channel High Electron Mobility Transistors

Brianna Klein, Andrew Allerman, Andrew Armstrong, Mary Rosprim, Colin Tyznik, Jason Neely, Yinxuan Zhu, Chandan Joishi, Chris Chae, Jinwoo Hwang, Siddharth Rajan

2024 MRS Spring Meeting

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