Sandia National Laboratories

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RECENT ADVANCEMENTS IN (AL)GAN HIGH ELECTRON MOBILITY TRANSISTOR POWER ELECTRONICS AT SANDIA

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Power Electronics & Energy Conversion Workshop

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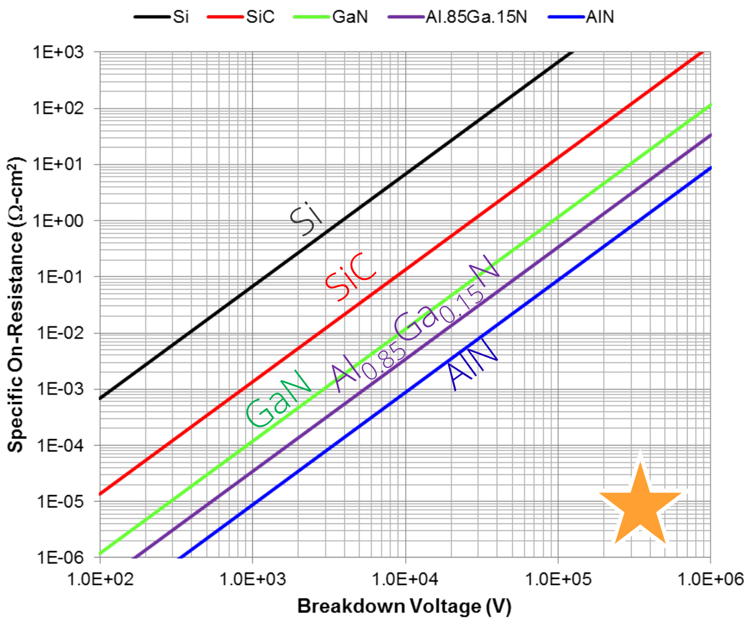
U.S. DEPARTMENT OF ENERGY

NNSA

MOTIVATION: ULTRA-WIDE BANDGAP TRANSISTORS

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
$Al_xGa_{1-x}N$	>3.4 - 6.0	4.9-15.4	~150-400	Interpolation	Interpolation
AlN	6.0	15.4	426	1.3	319
β-Ga_2O_3	4.9	10.3	180	1.1	11-27
Diamond	5.5	13.0	4500-7300	1.9-2.3	2290



Wide/Ultrawide Bandgap Advantages

- Large critical electric field: Large breakdown voltage / output power
- High operating temperature: Suppresses leakage and noise
- Radiation: Suppresses photocurrent and crystal damage

Challenges

- Electron mobility
- Threshold voltage control
- Ohmic contacts
- Packaging

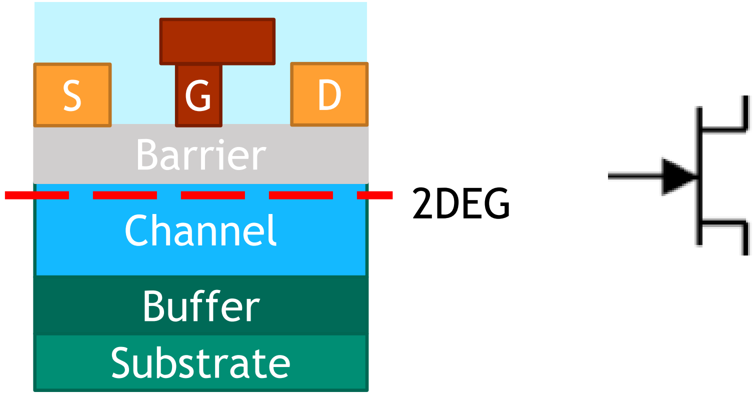
Goal: AlGaN-channel power transistor

OVERVIEW

Goal: AlGaN-channel power transistor

- Increase current
- Increase voltage
- Enhancement mode
- Packaging: Flip-chip bonding
- Monolithic integration: Small-scale integrated circuits

High Electron Mobility Transistor (HEMT)



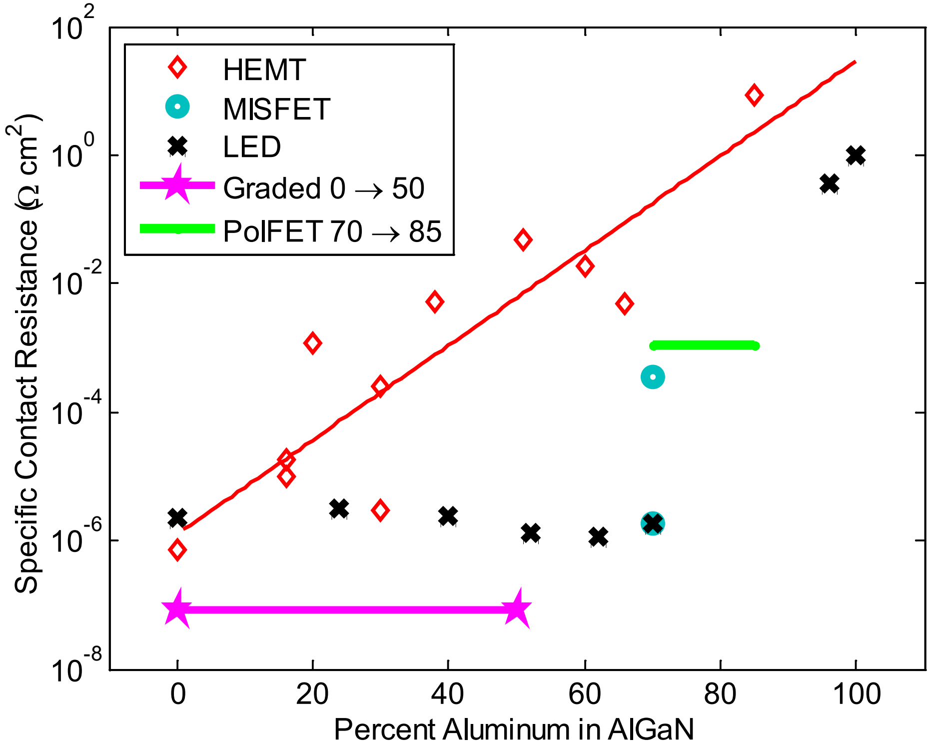
HEMT Cross-Section

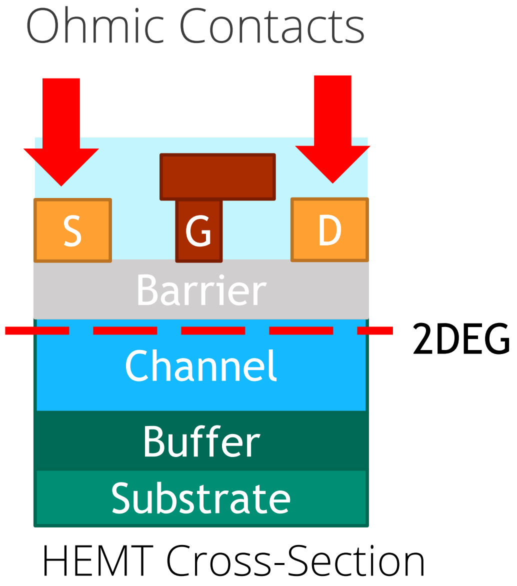
OVERVIEW

Goal: AlGaN-channel power transistor

- **Increase current**
- Increase voltage
- Enhancement mode
- Packaging: Flip-chip bonding
- Monolithic integration: Small-scale integrated circuits

OHMIC CONTACTS





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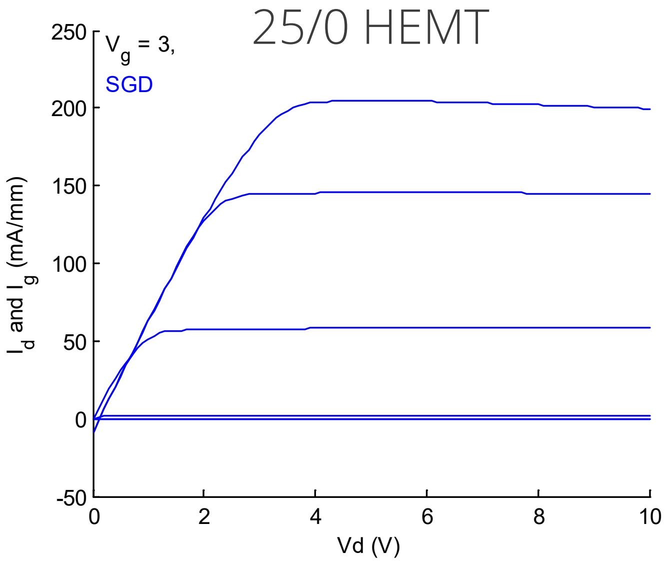
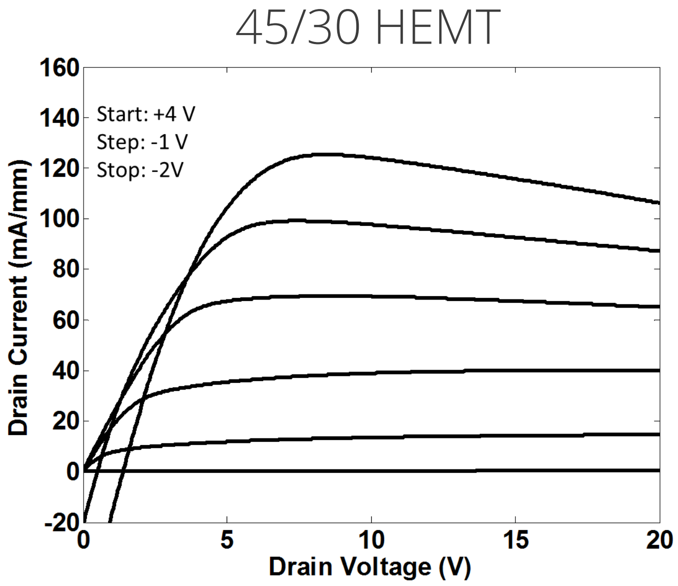
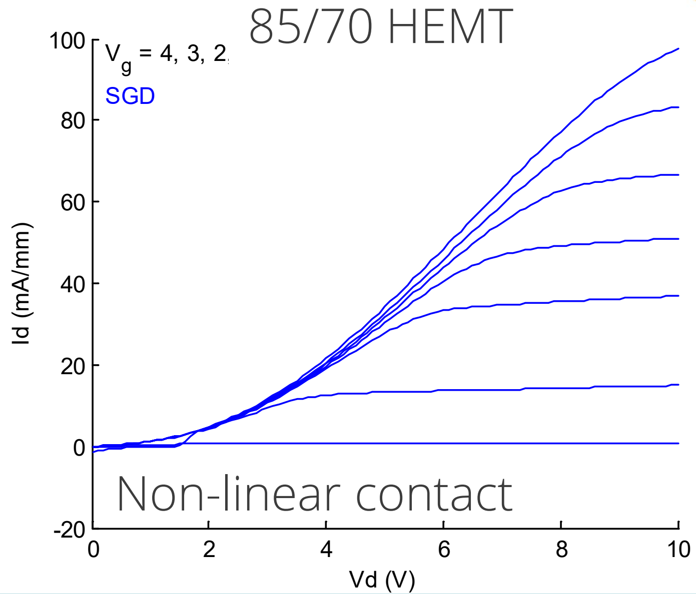
Which matters: Barrier composition or channel composition?
Increasing Al composition increases specific contact resistance

OHMIC CONTACTS: CHALLENGE OF INCREASING AL CONTENT


25/0 HEMT


45/30 HEMT

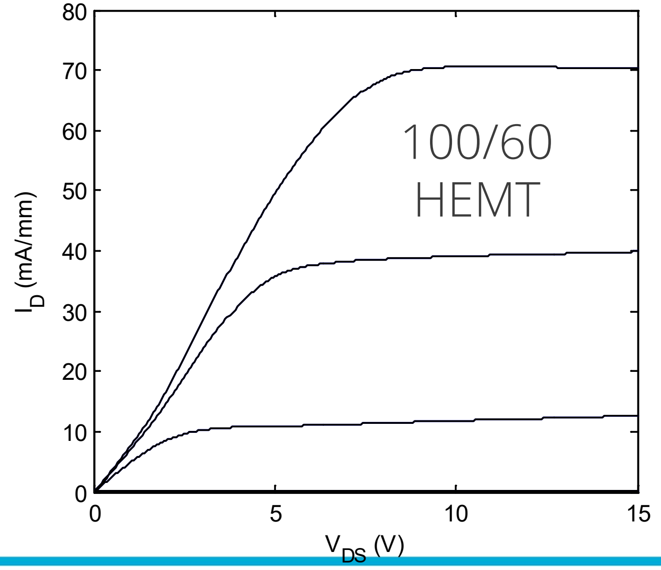

85/70 HEMT

Non-linear contact

Increasing Al Content

100/60 HEMT contacts working:

- High Al barrier content
- Reduced channel composition


100/60 HEMT

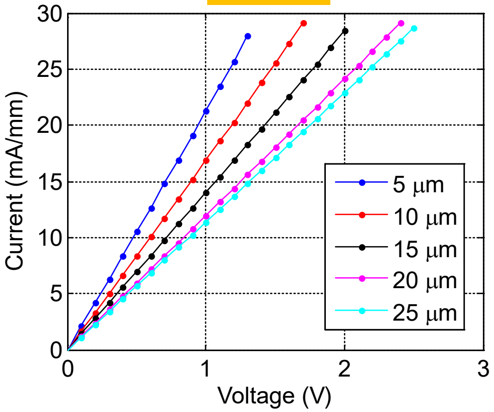
Why is this one working?

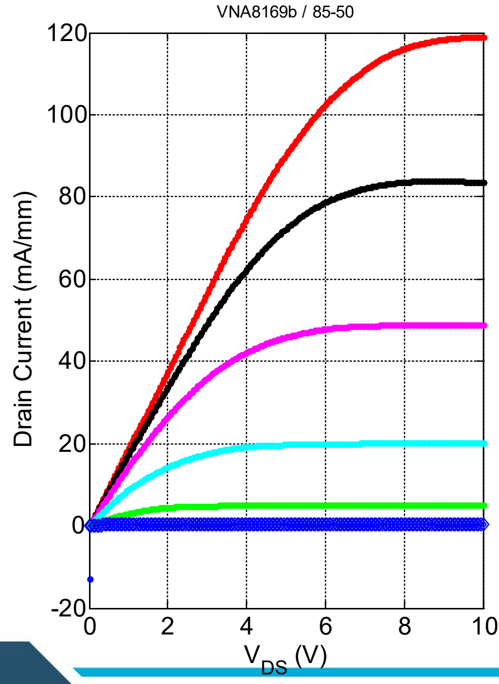
OHMIC CONTACTS

Example Experiment: Vary Channel Composition

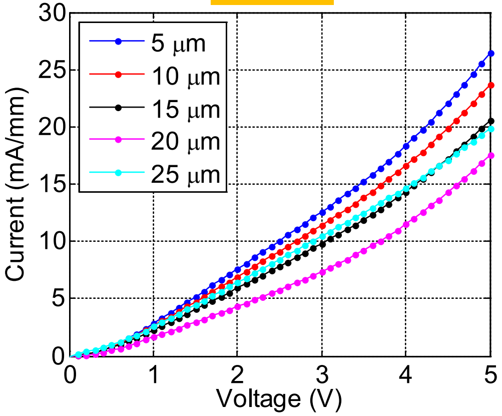
Observed systematic decline in contacts with increasing channel composition

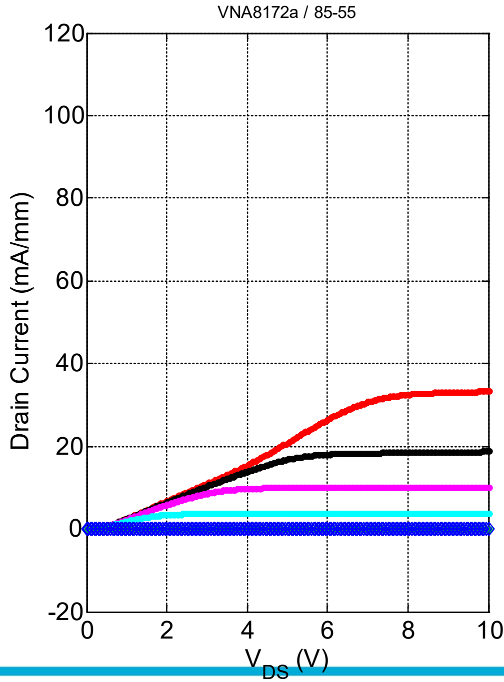
50%



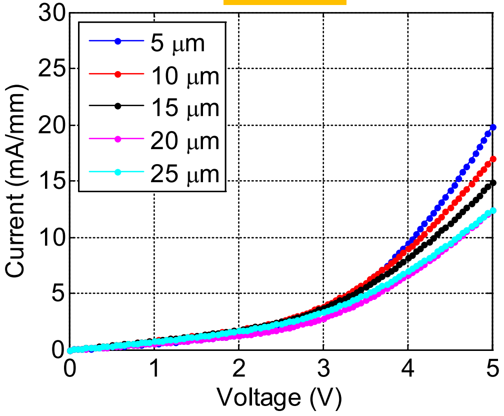


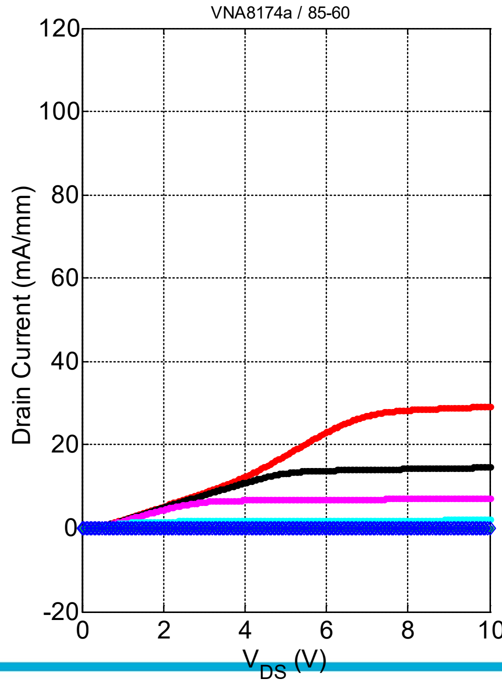
55%



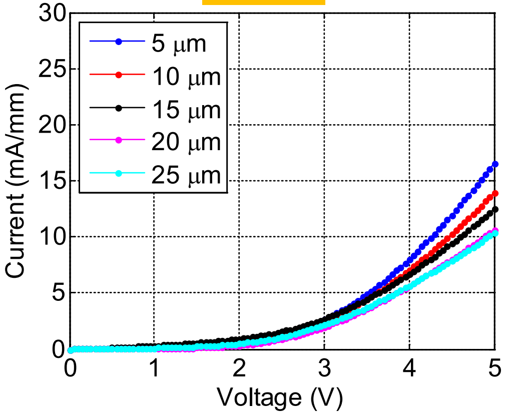


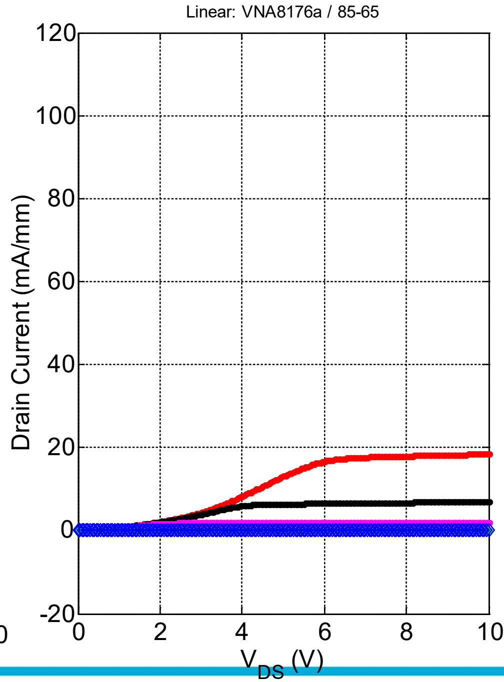
60%



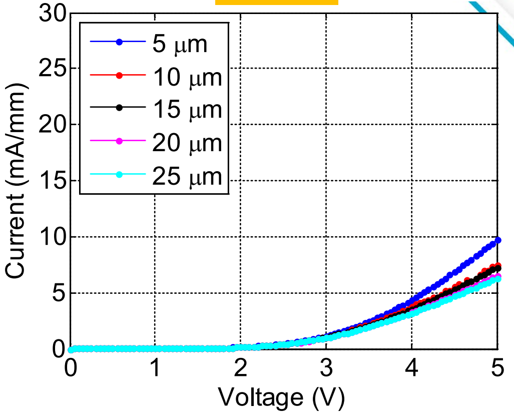


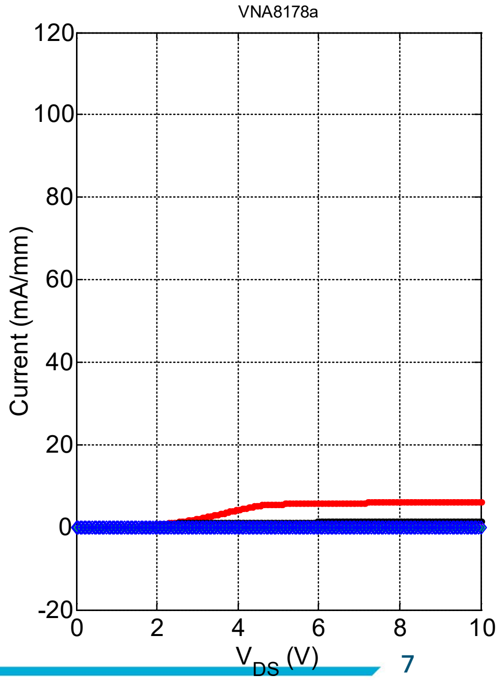
65%





70%

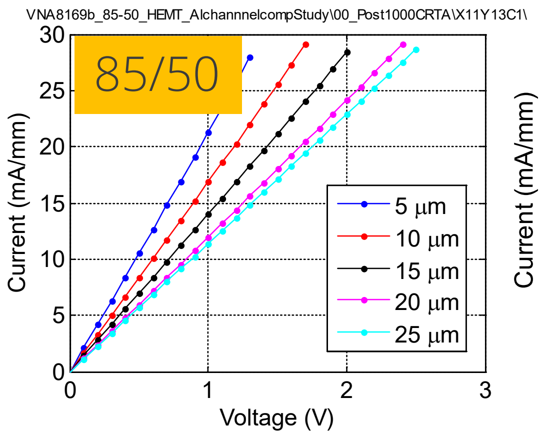


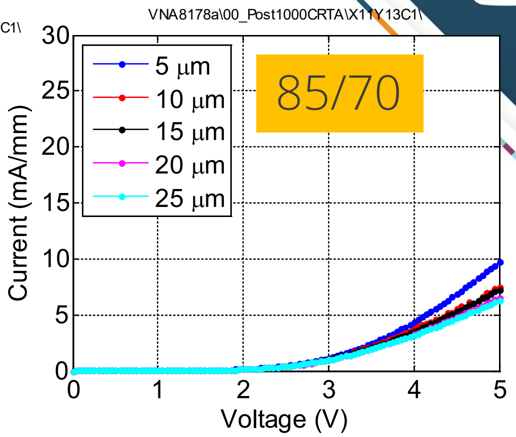


OHMIC CONTACTS

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

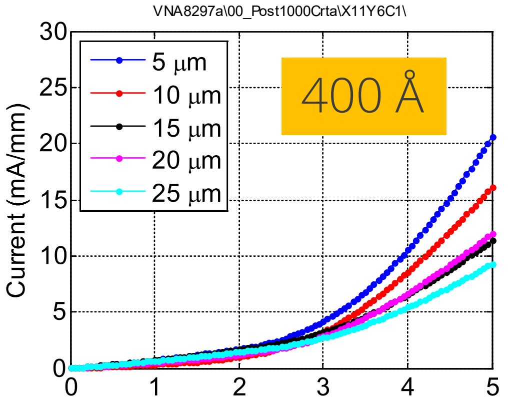
Observed systematic decline in contacts with increased channel composition

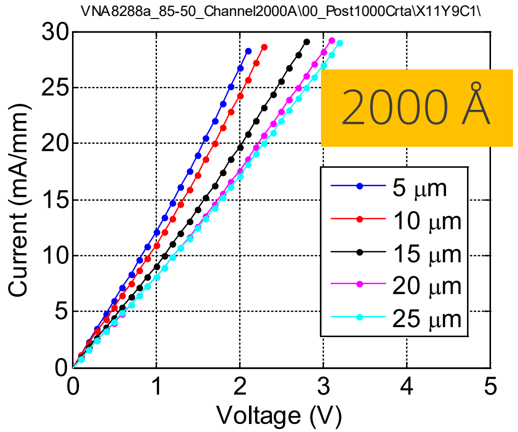




Vary channel thickness in 85/50.
Barrier thickness: 300 Å

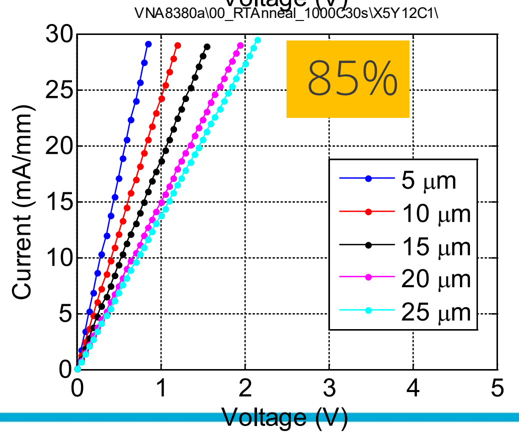
Observed decline in contacts with thinner channels

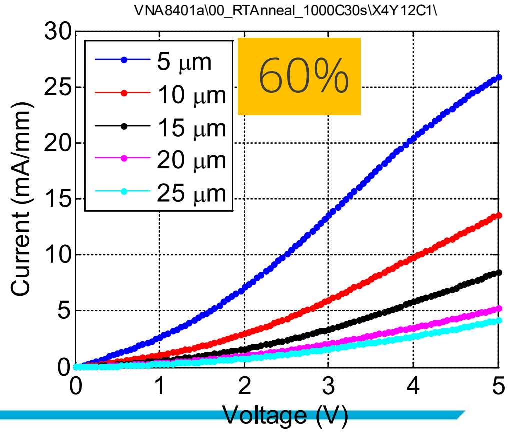




Vary barrier Al composition: 60, 65, 70, 75, 80, 85
Channel composition: 50

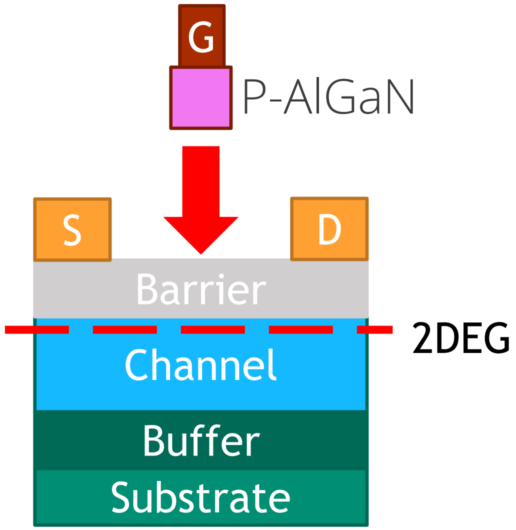
Observed degradation in sheet resistance with lower barrier composition



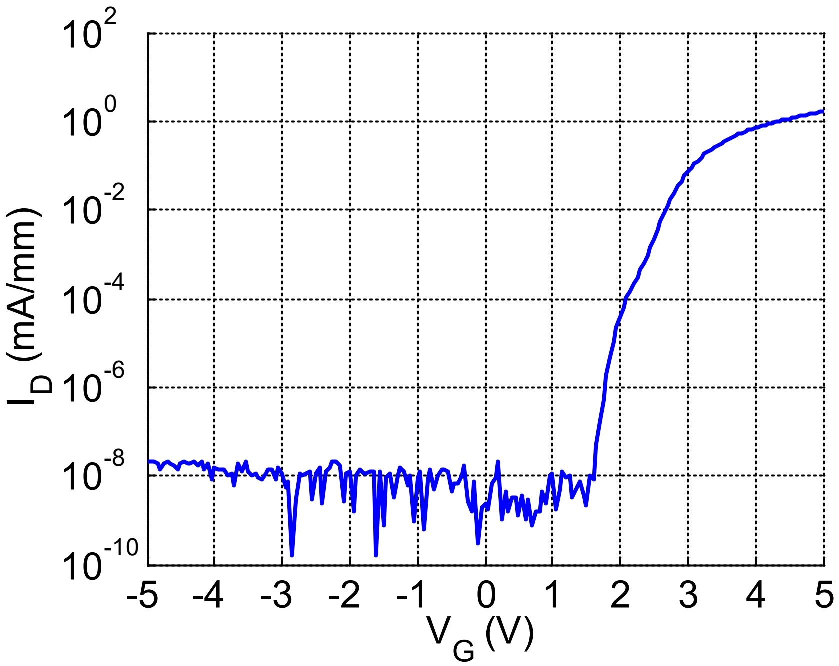


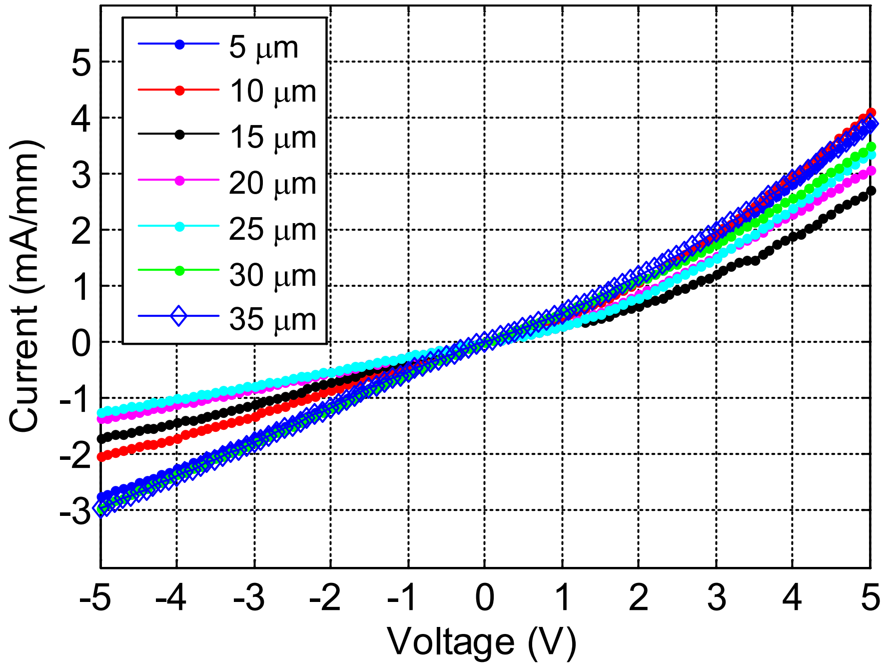
New problem: Gate leakage.

OHMIC CONTACTS: 85/50 HEMT WITH P-ALGAN → Reduce leakage



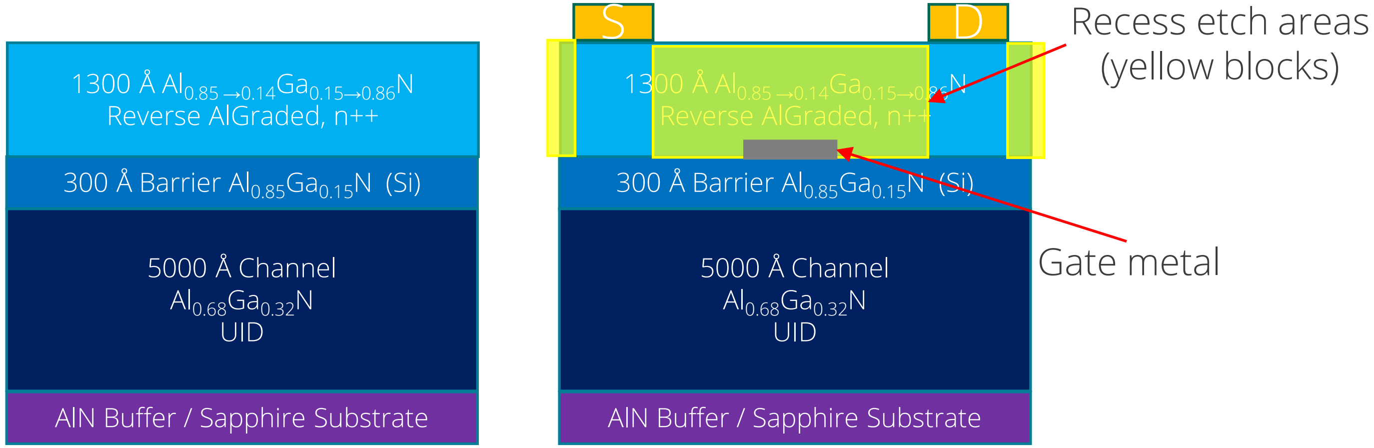
85/50 HEMT
+
P-AlGaN Gate





- Adding a p-AlGaN gate degraded the Ohmic contacts
- Specific contact resistance = 7×10^{-2} Ω•cm²
- Off-state gate leakage reduced

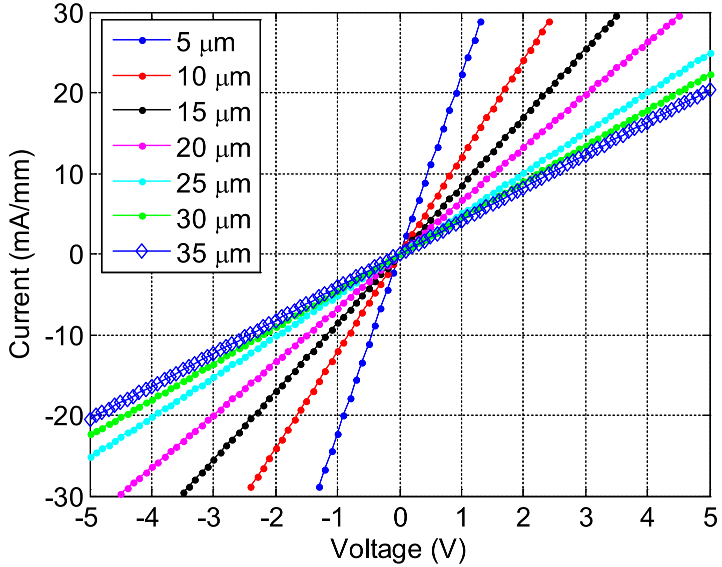
OHMIC CONTACTS: REVERSE-GRADED N++

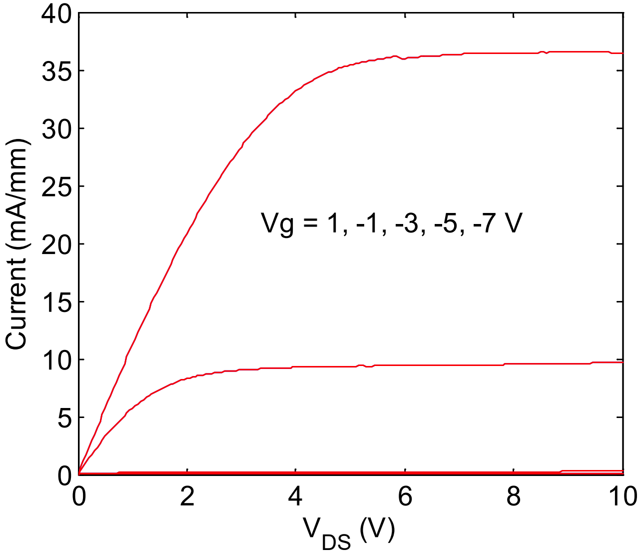


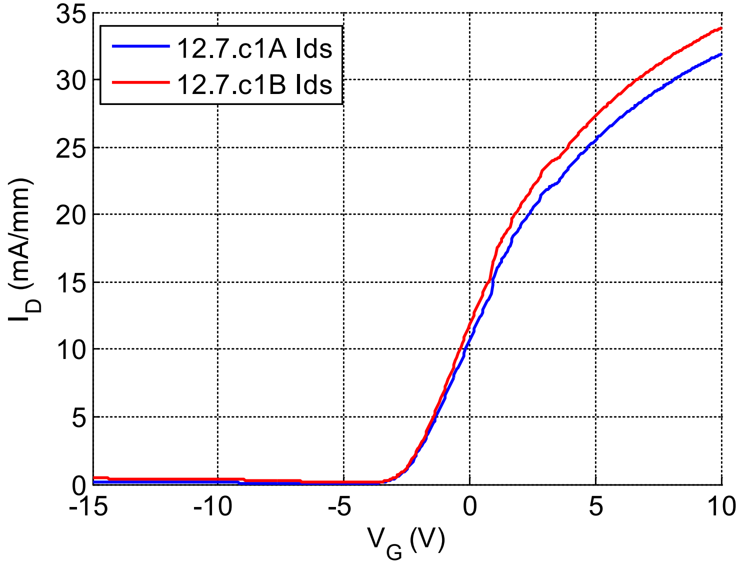
- Etch depth within 2% of target; 32 Å average over-etch
- Demonstrated specific contact resistances in the low 10^{-5} Ω•cm²
- Demonstrated gate modulation
- Problem: Gate leakage

Etch target = 1300 Å

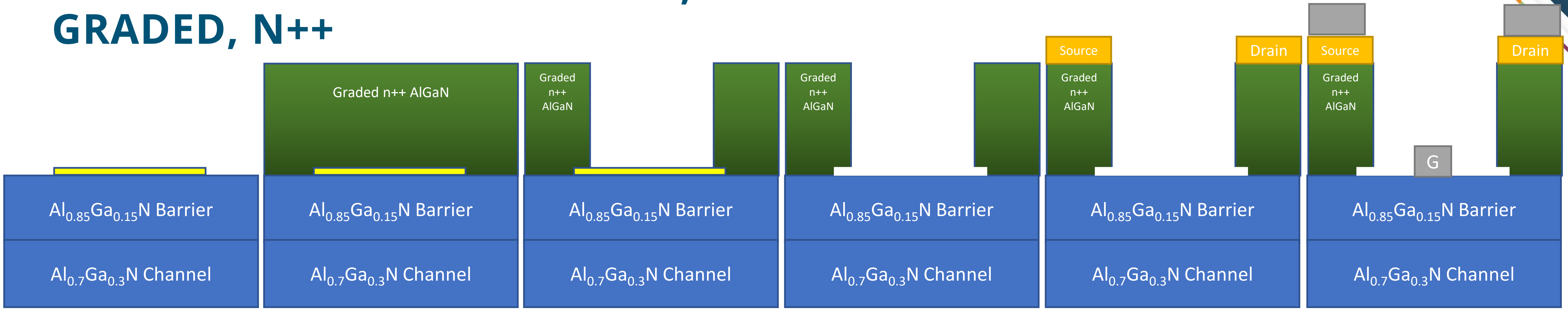
Measured average etch depth = 1332 Å



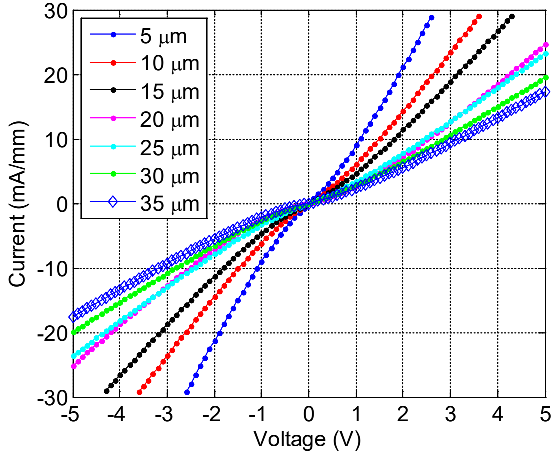


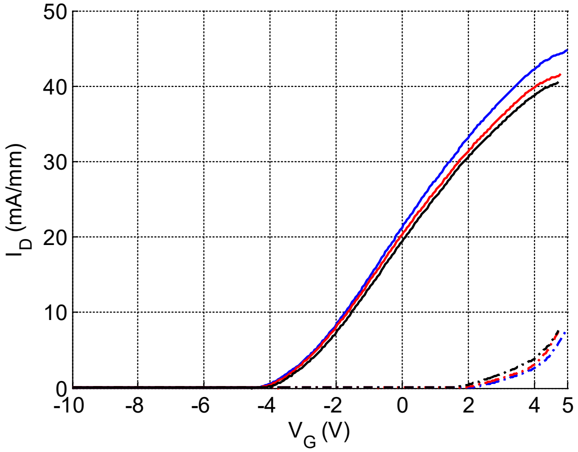


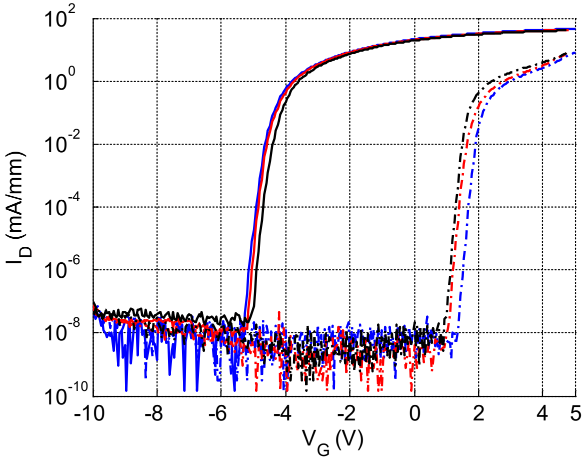
OHMIC CONTACTS: REGROWN, AL COMPOSITIONALLY REVERSE-GRADED, N++

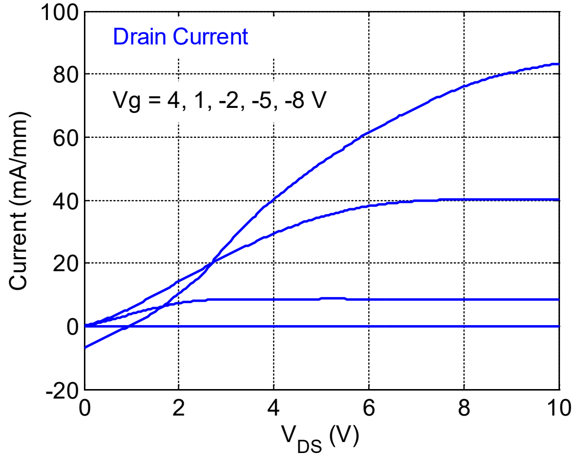


1. Deposit regrowth mask over access + gate
2. Graded regrowth
3. Etch regrowth over access + gate
4. Remove mask
5. Ohmic metal + optional RTA
6. Gate metal dep.



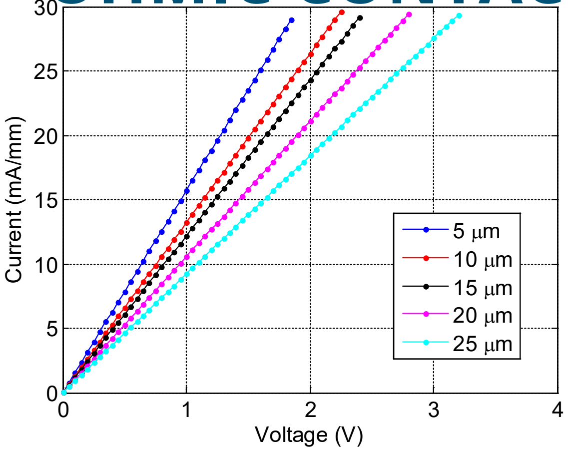


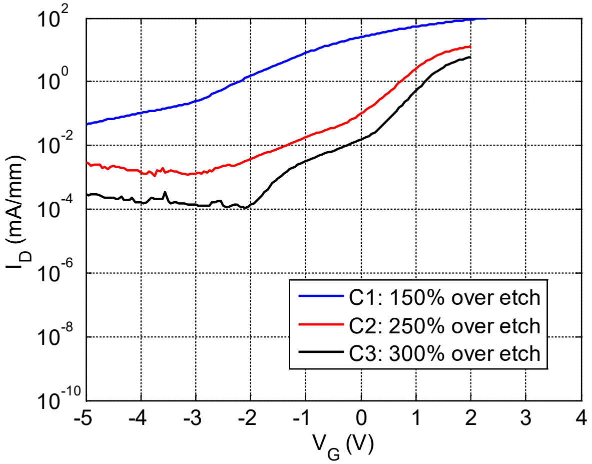




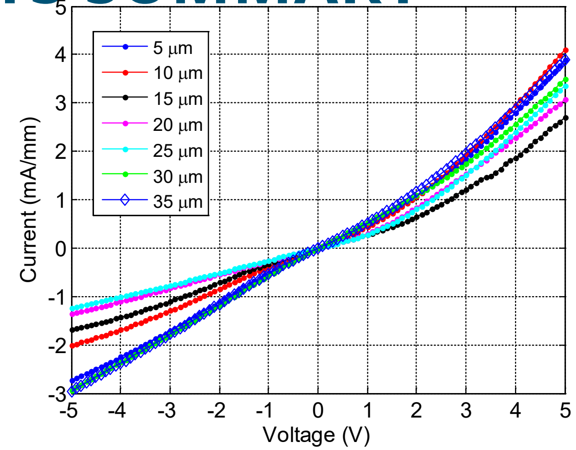
- Regrowth mask
- Regrown reverse-grade Ohmic contacts
- Specific contact resistance of 5×10^{-4} Ω·cm² → Can't replicate low contact resistance of as-grown structure
- Low off-state gate leakage

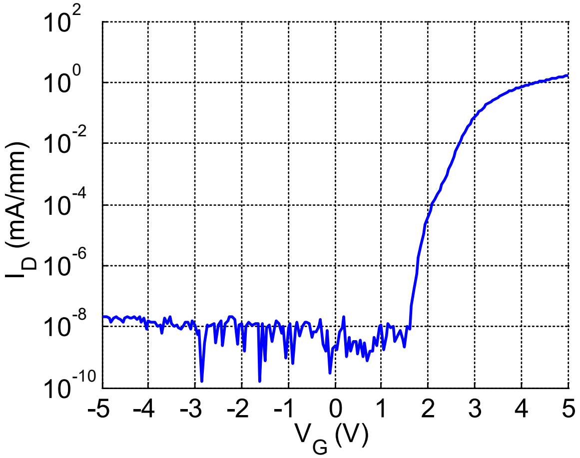
OHMIC CONTACTS SUMMARY



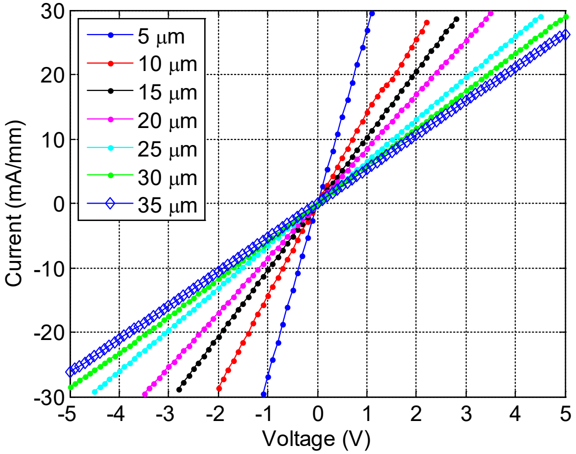


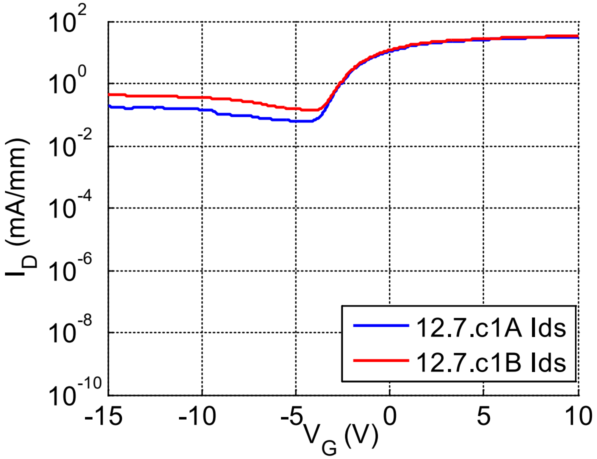
- 85/50 HEMT
- Planar Ohmic contacts
- Low contact resistance
  - $3\times10^{-4}\ \Omega\cdot cm^2$
- High gate leakage



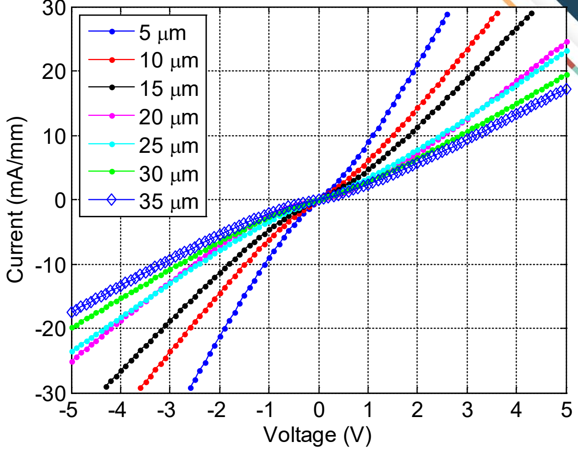


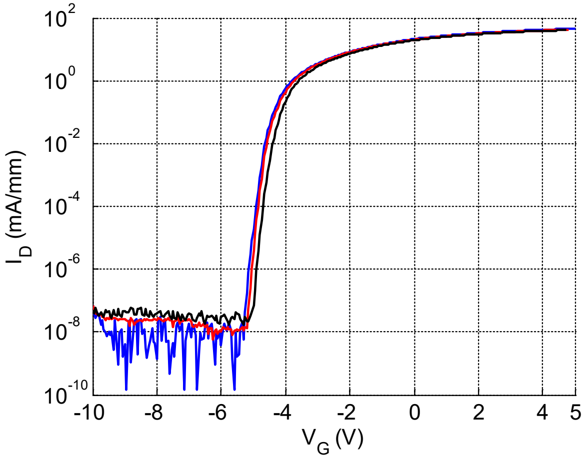
- 85/50 HEMT + p-AlGaN Gate
- Planar Ohmic contacts
- High contact resistance
  - $7\times10^{-2}\ \Omega\cdot cm^2$
- Low gate leakage





- 85/70 HEMT
- Continuously grown reverse-graded n++ contacts
- Low contact resistance
  - 1 to 3 x $10^{-5}\ \Omega\cdot cm^2$
- High gate leakage

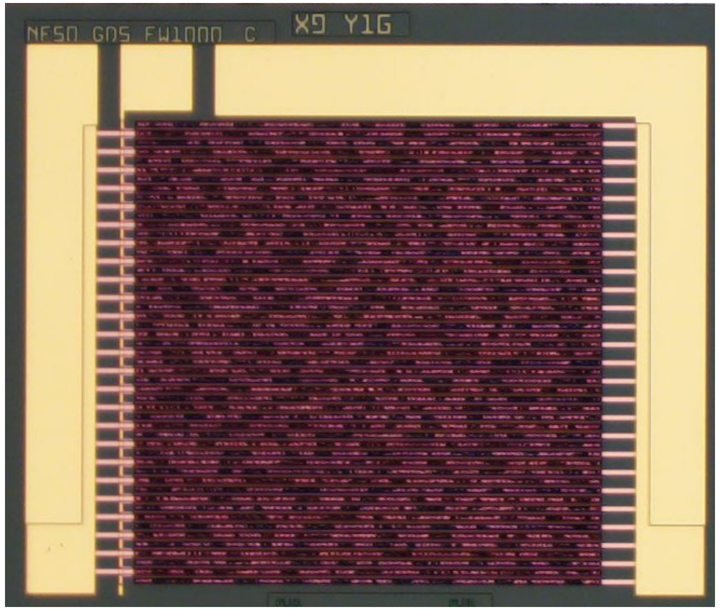


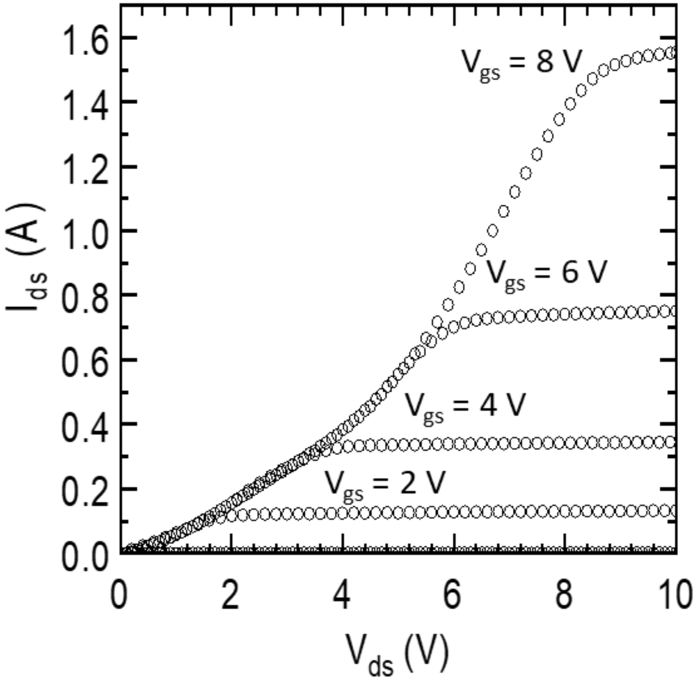


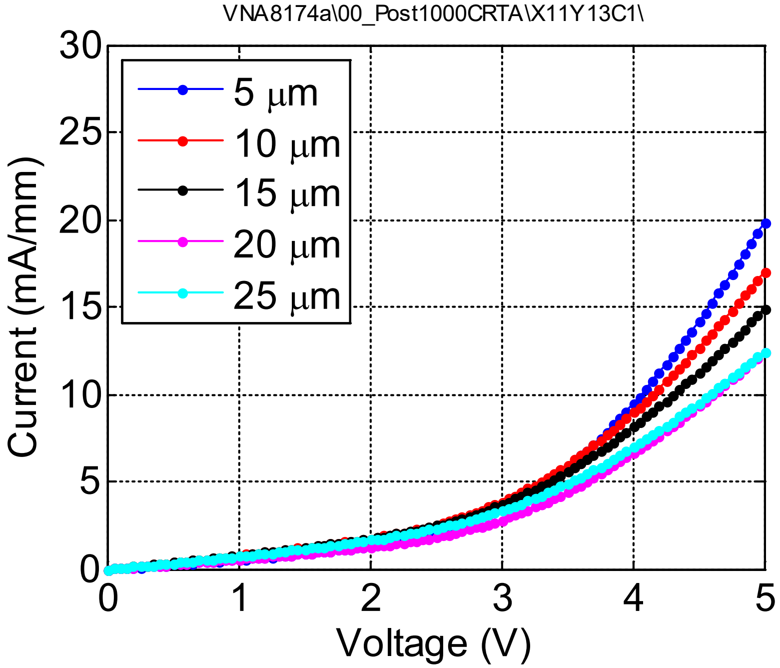
- 85/70 HEMT
- Regrown graded contacts
- Increased contact resistance
  - $5\times10^{-4}\ \Omega\cdot cm^2$
- Low gate leakage

Haven't been able to get low-resistance contacts and low-leakage gates simultaneously

ALGAN HEMT DRAIN CURRENT TODAY

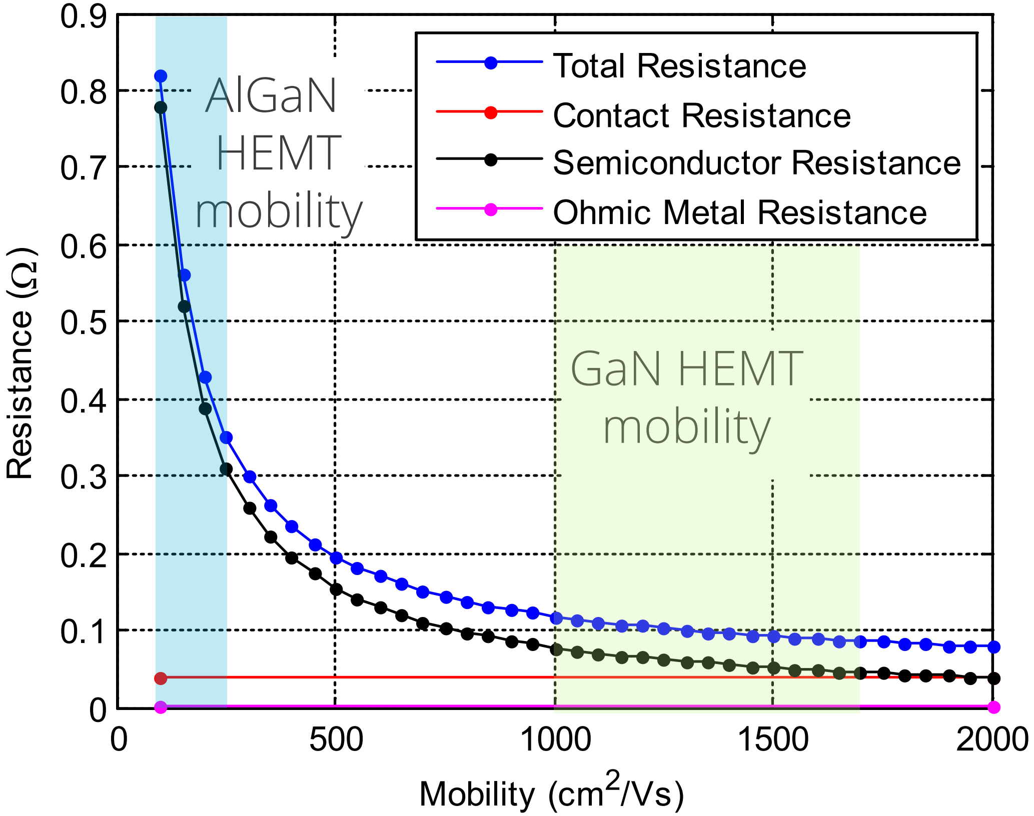


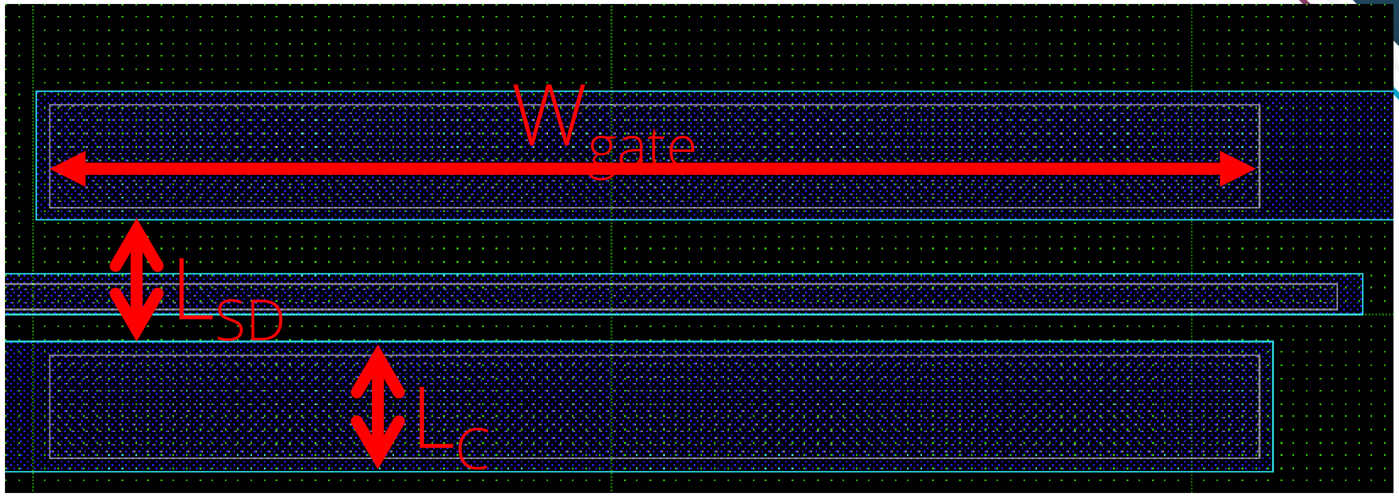




- 85/60 HEMT → Compromise between contact resistance and gate leakage
- Pulsed testing: Normally-off flip-chip device capable of > 1 A I_{ds}
- *What improvements do we need to focus on?*

RESISTANCE CONTRIBUTION ANALYSIS





Source-Drain Spacing	L_{SD}	5 μm
Ohmic Contact Length	L_C	10 μm
Gate Width	W_{gate}	50 mm
Specific contact resistance	p_c	1×10^{-4} Ω•cm²
2DEG Sheet Charge Density	n_s	8×10^{12} cm^{-2}
2DEG Mobility	μ	100 to 2000 cm²/V•s
Sheet Resistance (Ohmic metal)	$R_{sheet\ (metal)}$	1.7 Ω/sq

- Compare resistance from 2DEG, Semi-to-Metal Contacts, and Electrodes
- Predicts that AlGaN HEMTs are limited by the 2DEG channel resistance
- Need to minimize channel resistance

$$R_{OhmCont} = \frac{\rho_c}{W_{Gate} L_C}$$

$$R_{SD,2DEG} = \frac{L_{SD}}{W_{Gate}} \frac{1}{q n_s \mu}$$

$$R_{OhmMet} = R_{Sheet} \frac{L}{W}$$

OVERVIEW

Goal: AlGaN-channel power transistor

- **Increase current: 1 A today. Tackle channel resistance.**
- Increase voltage
- Enhancement mode
- Packaging: Flip-chip bonding
- Monolithic integration: Small-scale integrated circuits

OVERVIEW

Goal: AlGaN-channel power transistor

- Increase current: 1 A today. Tackle channel resistance.
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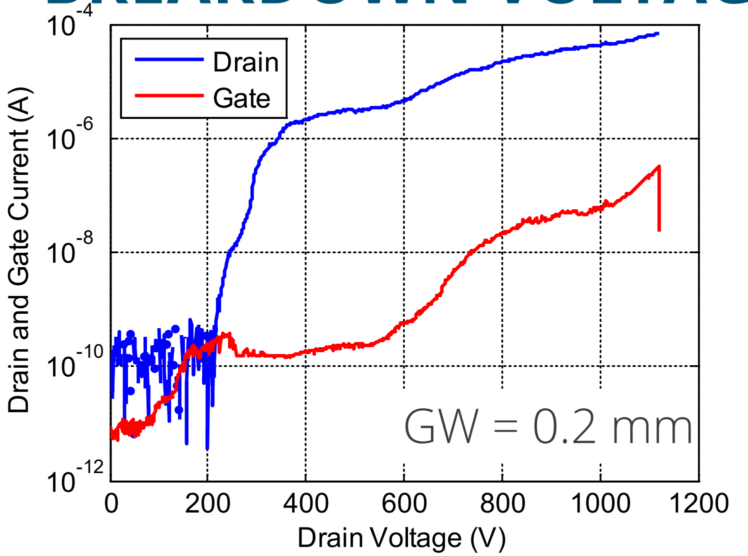
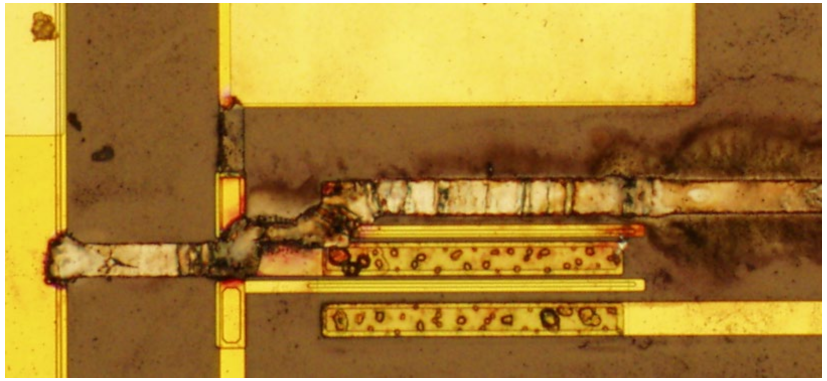
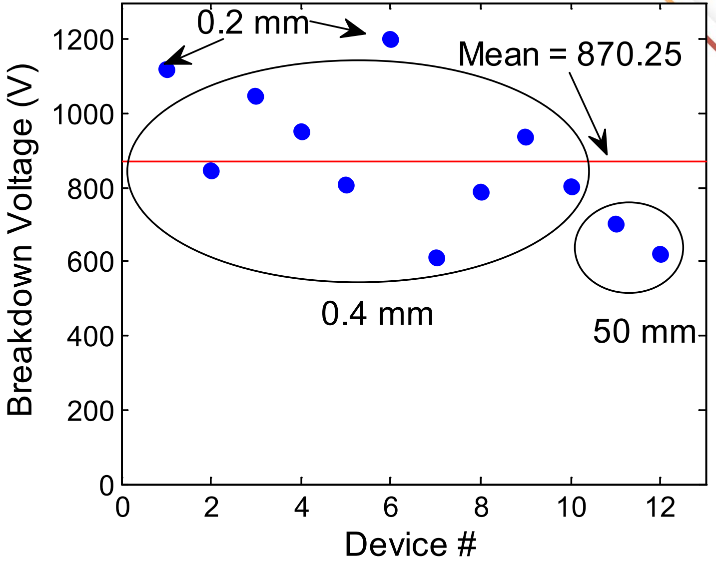
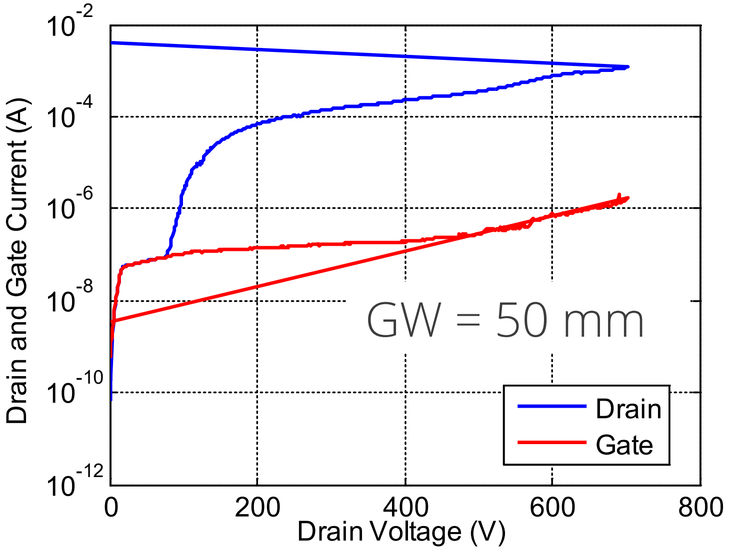
BREAKDOWN VOLTAGE: 85/70 ALGAN HEMT

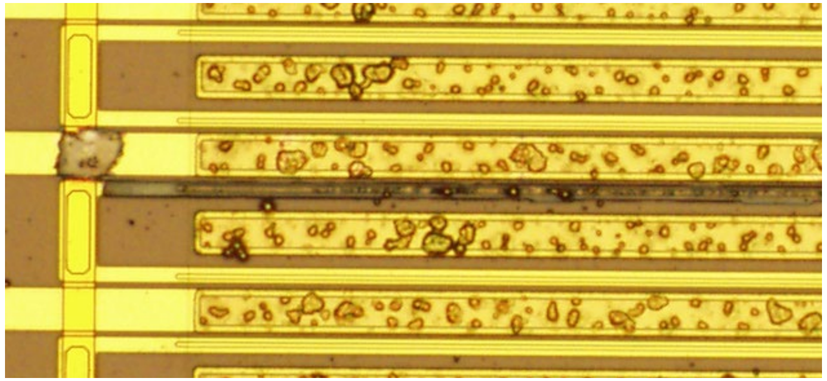




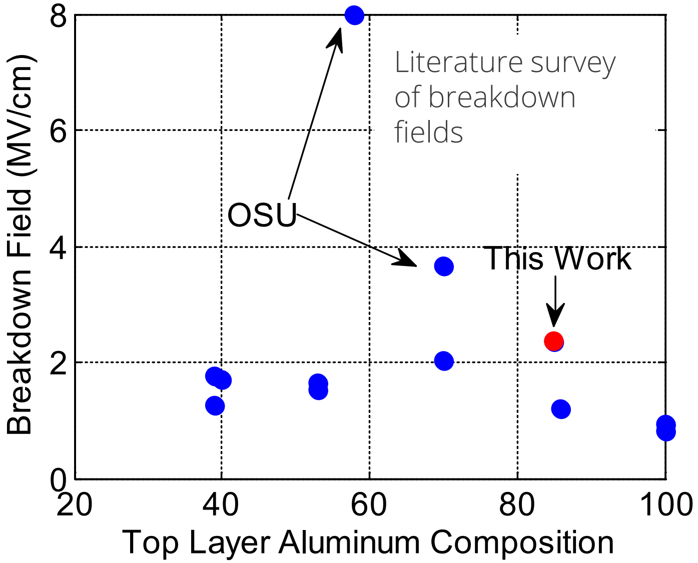
GD = 5.1µm
VBR = 1204 V
Breakdown Field = 2.35 MV/cm







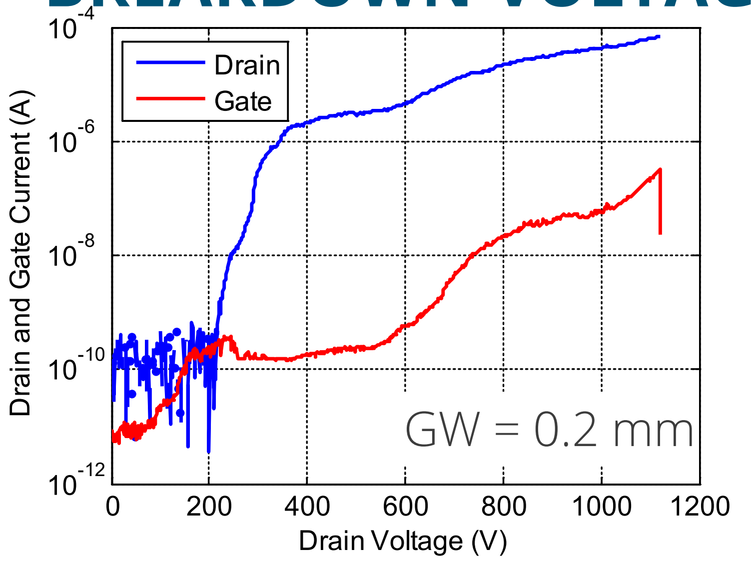
GD = 5.1µm
VBR = 702 V
Breakdown Field = 1.38 MV/cm

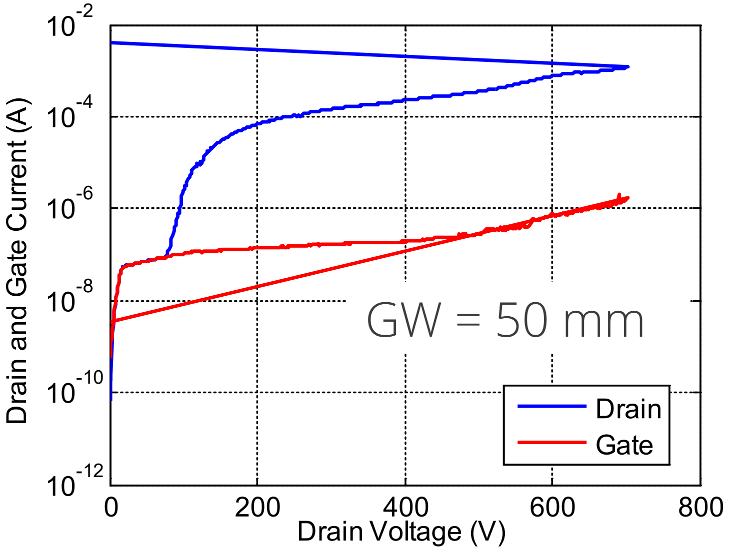


Reference list in extra slides

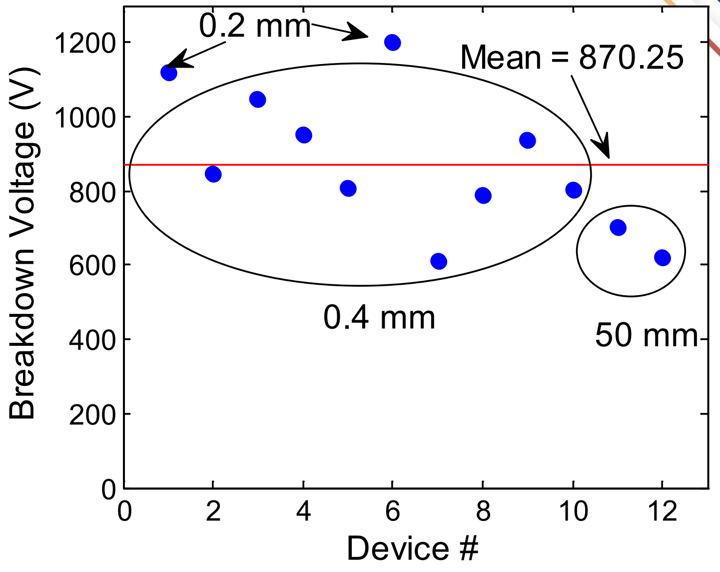
B. A. Klein *Journal of Radiation Effects Research and Engineering*, vol. 39, no. 1, pp. 149-155, 2021.

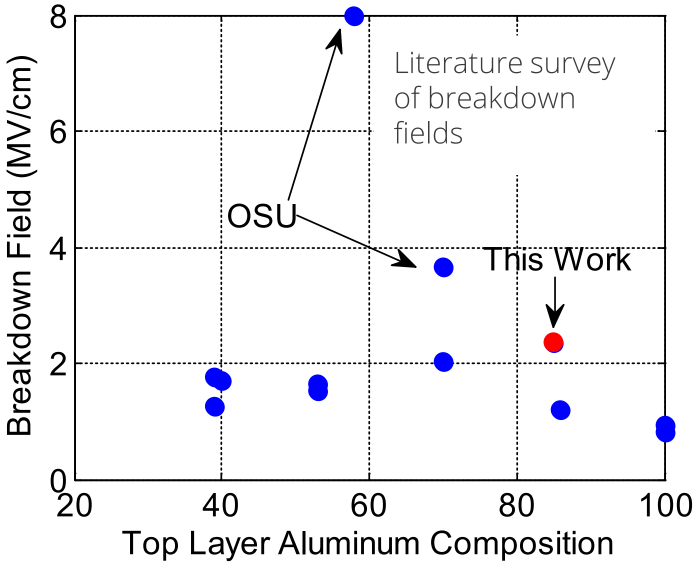
BREAKDOWN VOLTAGE: 85/70 ALGAN HEMT





- Achieved reasonable breakdown voltage / breakdown field
- Further improvements would enable reduced gate-to-drain spacing
- Next challenge: electric field management through high-k passivation





Reference list in extra slides

B. A. Klein *Journal of Radiation Effects Research and Engineering*, vol. 39, no. 1, pp. 149-155, 2021.

OVERVIEW

Goal: AlGaN-channel power transistor

- Increase current: 1 A today. Tackle channel resistance.
- **Increase voltage: 650 – 1200 V, 2.3 MV/cm field. E-field management**
- Enhancement mode
- Packaging: Flip-chip bonding
- Monolithic integration: Small-scale integrated circuits

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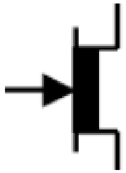
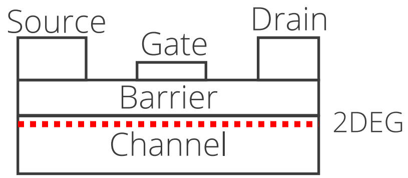
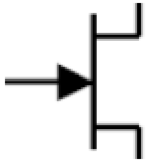
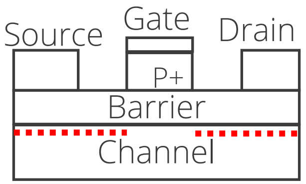
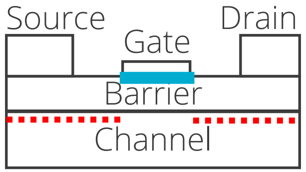
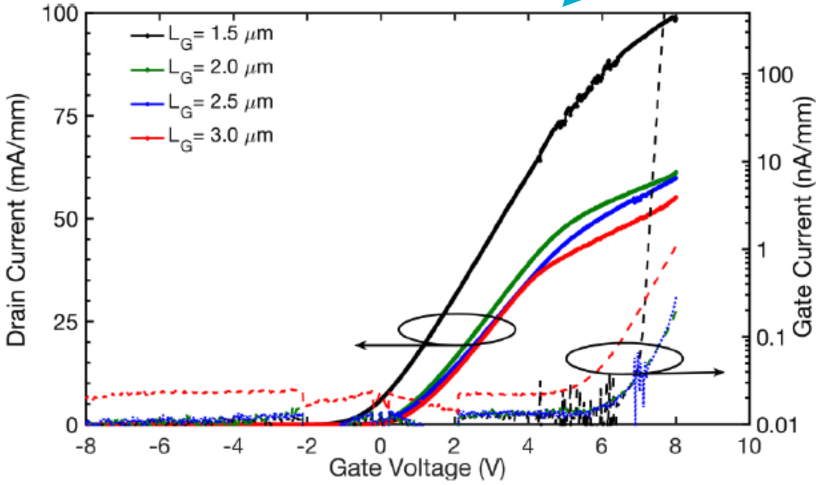
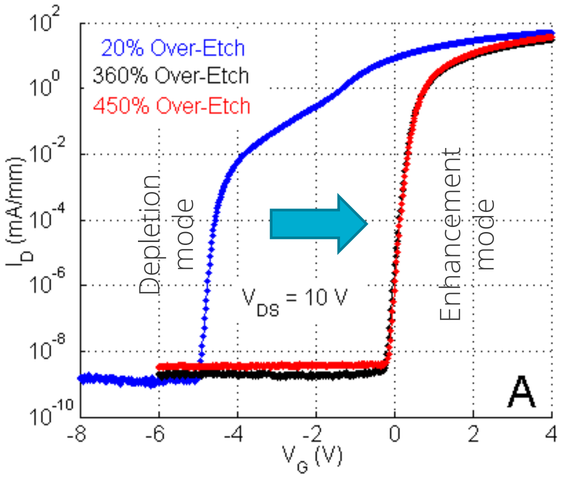
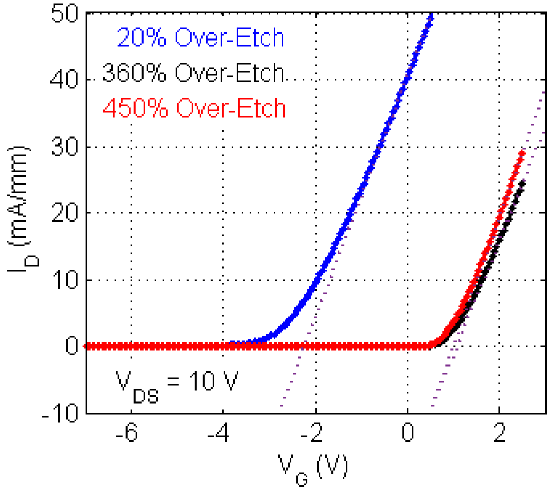
ENHANCEMENT MODE

Depletion-Mode (normally on)			AlGaN HEMTs are innately D-mode
Enhancement-Mode (normally off)		 P-Gate  Fluorine Treatment	Two approaches for E-mode already successfully implemented at Sandia

- Two approaches
- Gate threshold was shifted to positive values
- D-mode devices were integrated on the same chip



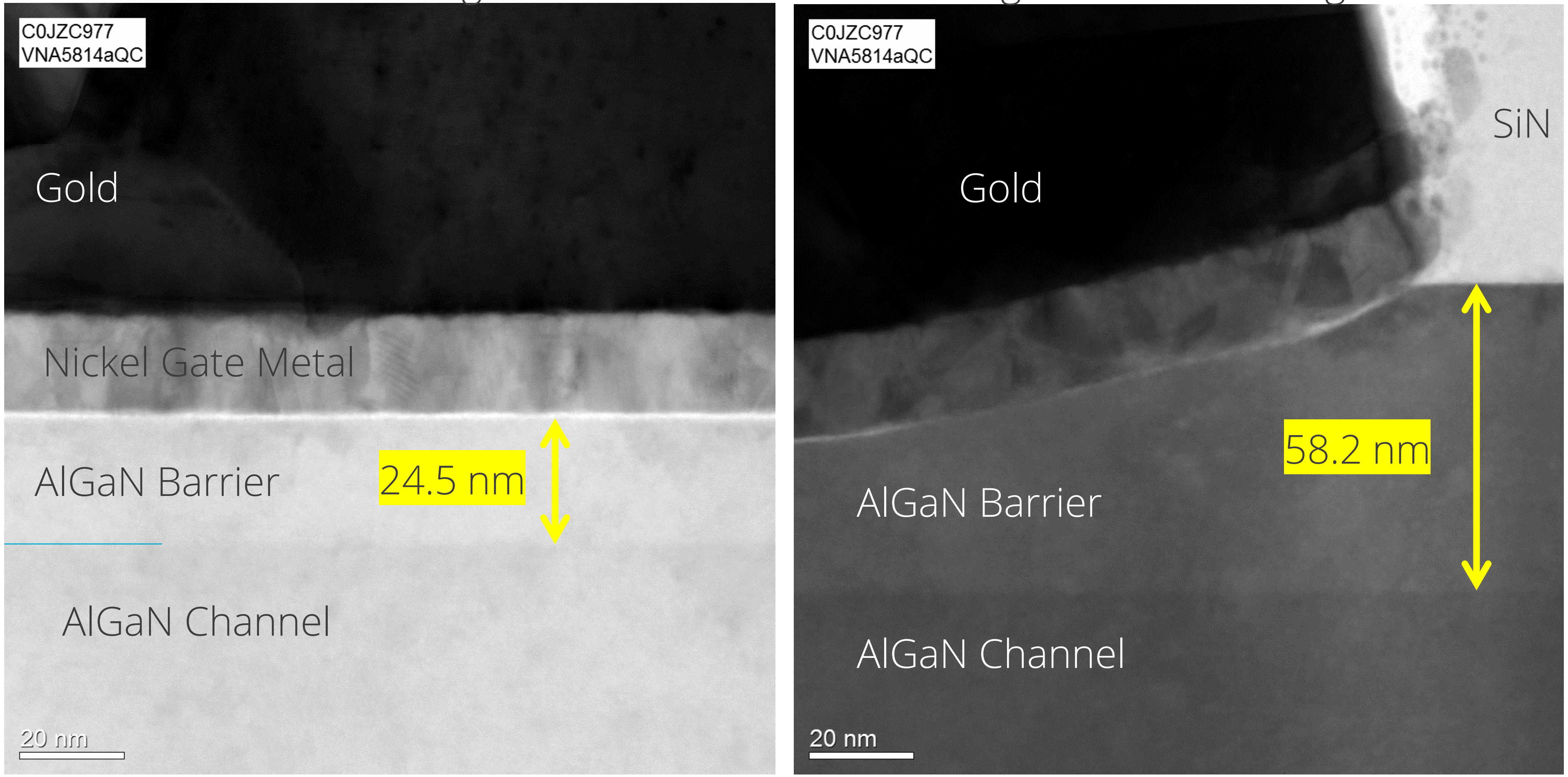




E. A. Douglas, *Journal of Vacuum Science & Technology B*, vol. 37, no. 021208, 2019.
B. A. Klein *Applied Physics Letters*, vol. 114, no. 112104, pp. 112104-1,5, 2019.

ENHANCEMENT MODE: BARRIER RECESS + FLUORINE IONS

Barrier was recessed over half of total thickness



Threshold voltage shift is from both fluorine ion implantation and barrier recess etching

ENHANCEMENT MODE: BARRIER RECESS + FLUORINE IONS

Step-stress tests confirmed stability of the enhancement-mode threshold voltage

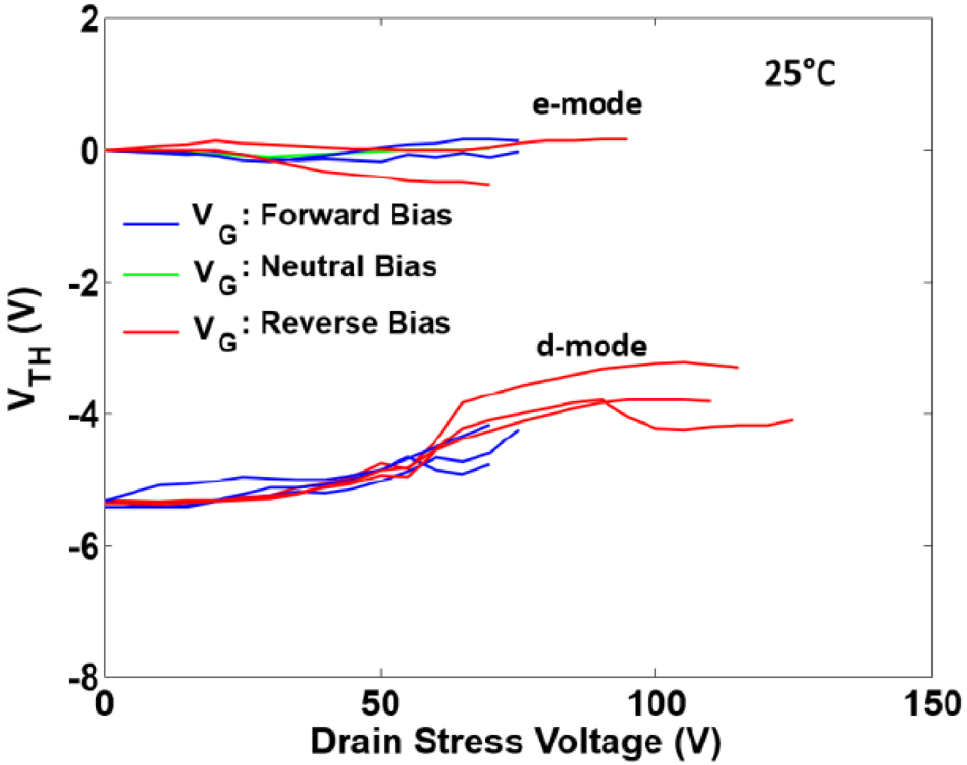


Figure 7. *V_{TH} shift vs. V_{DS} stress for d- and e-mode HEMTs stressed at 25°C and V_{GS} = +3 V (forward bias), +0.5 V or -2 V (e- and d-mode neutral bias), -2 V (reverse bias, e-mode), or -10 V (reverse biase, d-mode).*

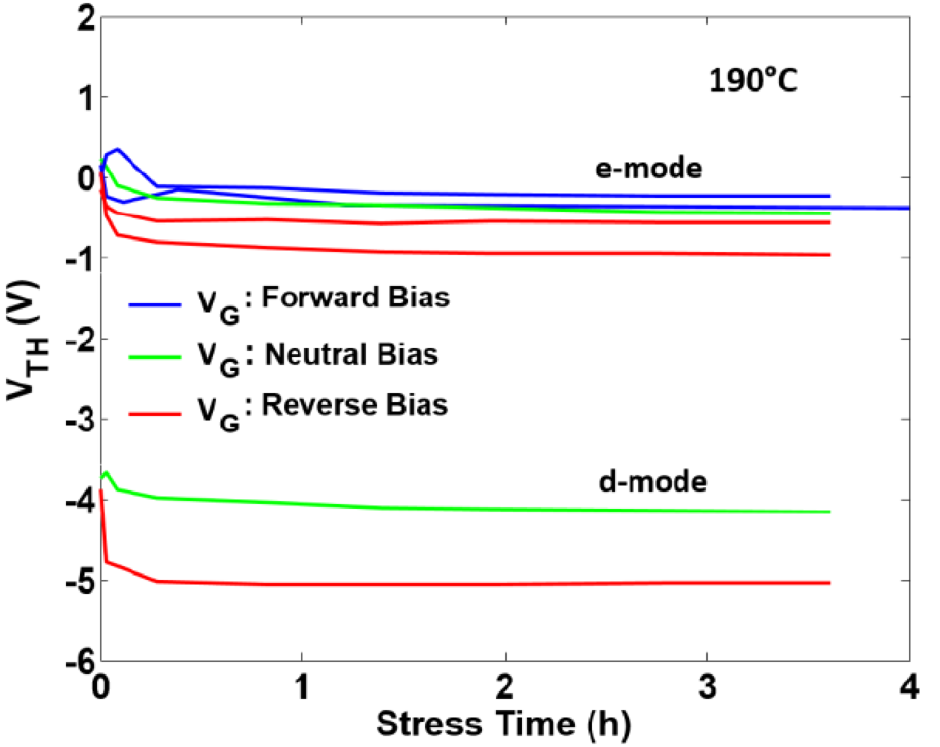


Figure 8. *V_{TH} stability measured during stress interruptions for e-mode and d-mode HEMTs stressed at 190°C under forward (V_{GS} = +3 V), neutral (V_{GS} = +0.5 V for e-mode and V_{GS} = -2 V for d-mode) and reverse (V_{GS} = -2 V for e-mode and V_{GS} = -10 V for d-mode) bias all with V_{DS} = 50 V.*

A. G. Baca *et al.*, "Stability in Fluorine-Treated Al-Rich High Electron Mobility Transistors with 85% Al-Barrier Composition," presented at the 2019 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, USA, 2019.

OVERVIEW

Goal: AlGaN-channel power transistor

- Increase current: 1 A today. Tackle channel resistance.
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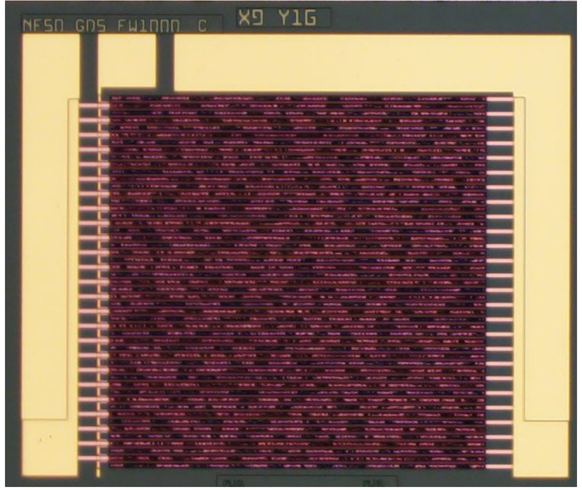
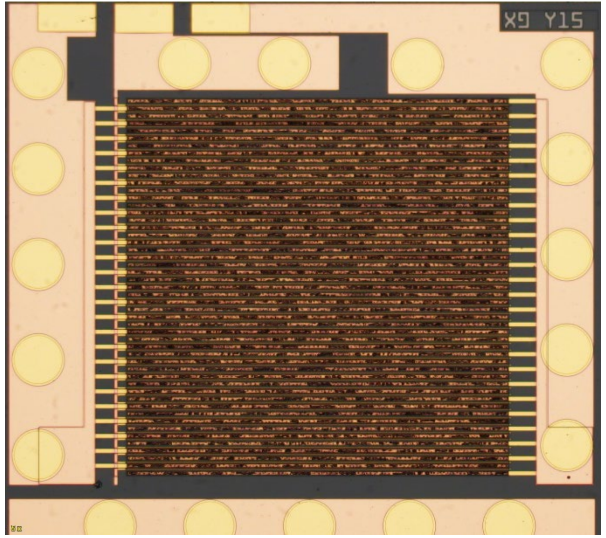
FLIP CHIP

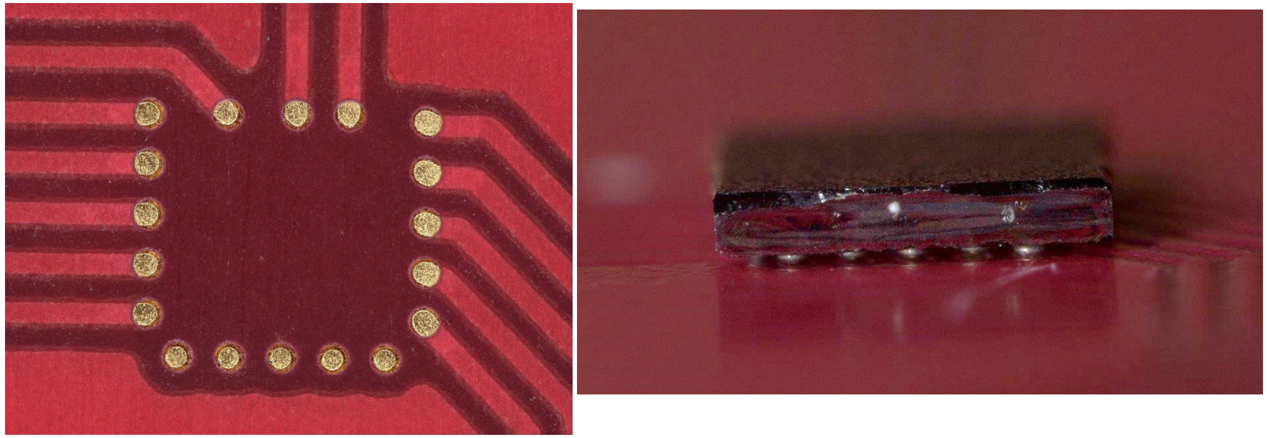
Standard Layout

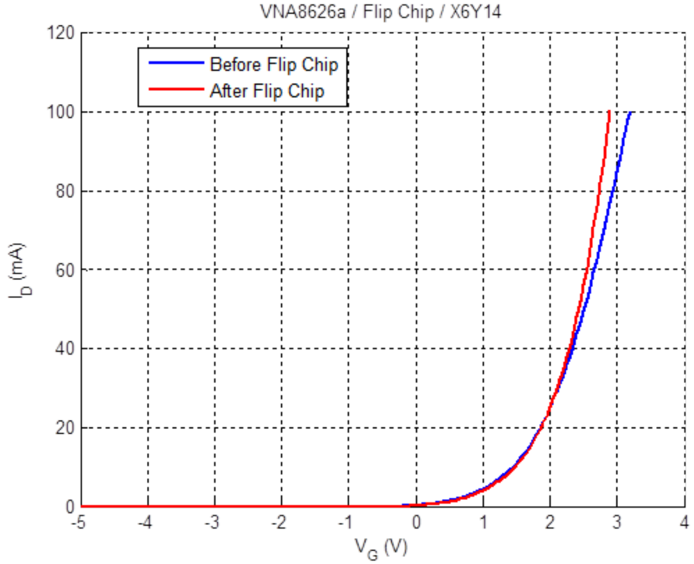


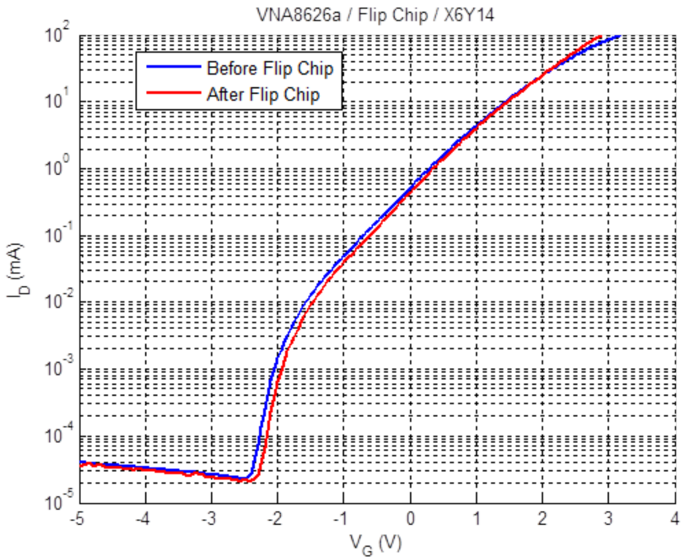
Flip Chip Layout



Flip Chip Test Board

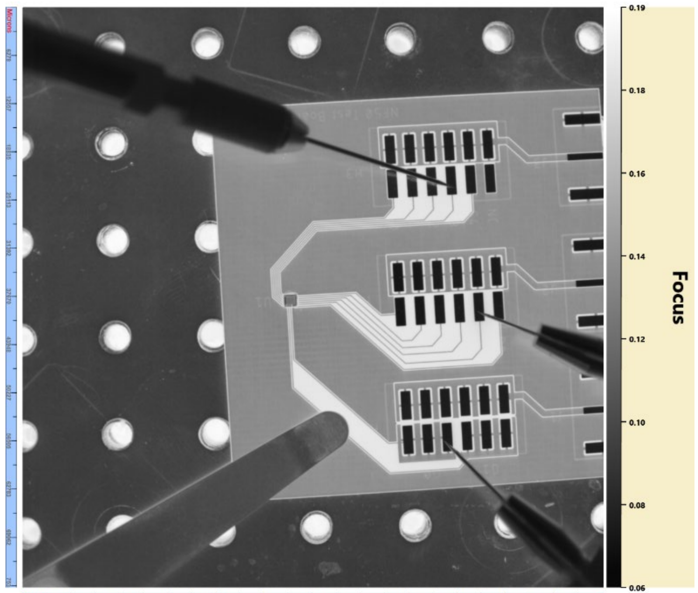


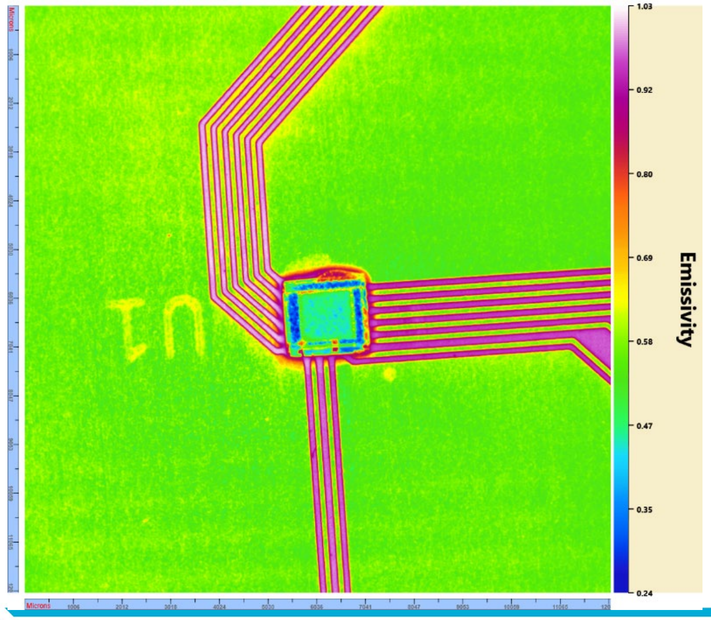


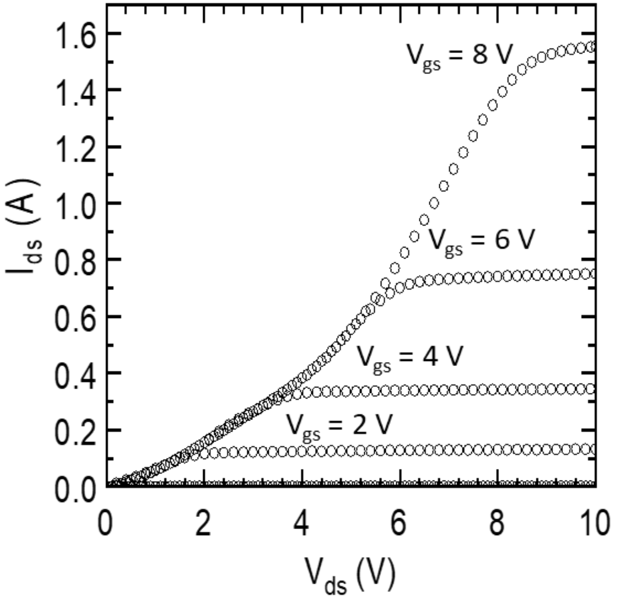


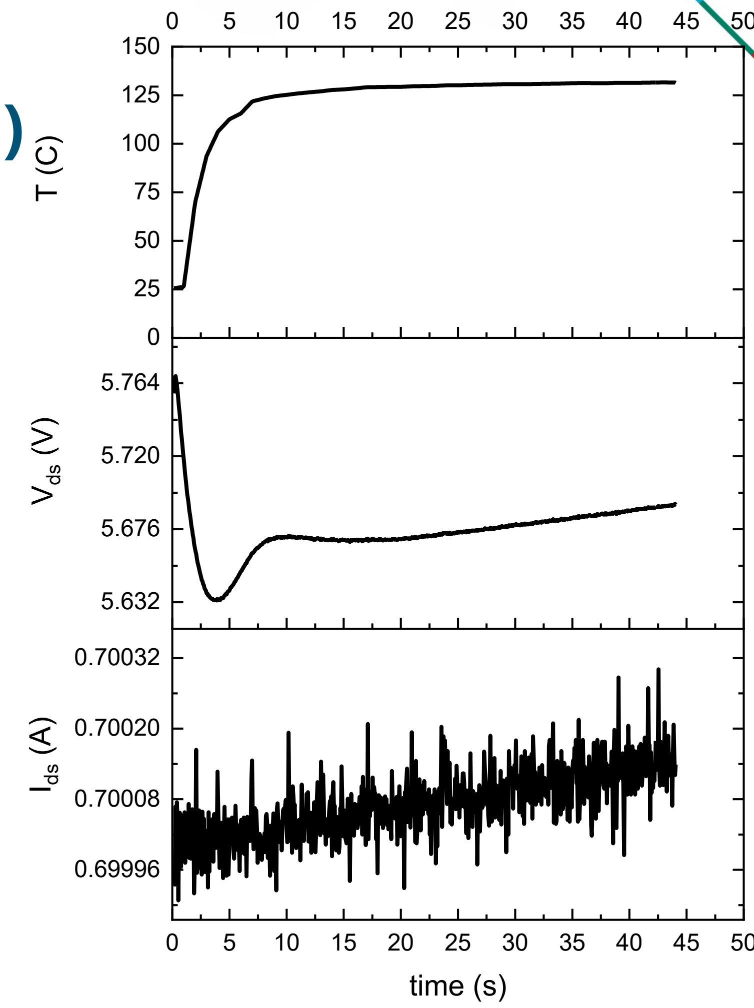
- Observed increased drain current after flip-chip
- Possibly due to increased number of contact points to chip
- Reduced parasitic resistance

FLIP CHIP: ELECTRICAL RESULTS (85/60 HEMT)









RMS Testing
Period = 5 ms
t_{on} = 3 ms
I_{on} = 0.7 A
Duty cycle (D) = 60%
$I_{RMS} = I_{on}\mathrm{sqrt}(D)$ = 0.54 A

Pulsed testing: > 1 A I_{ds}
RMS testing: >0.54 A; stable
Thermal management needed in next design iteration

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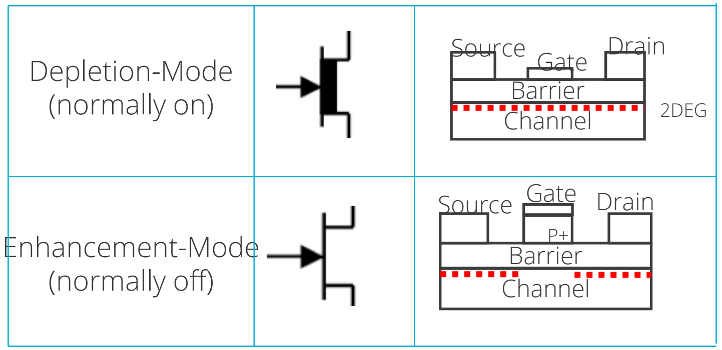
INCREASING COMPLEXITY: SMALL-SCALE INTEGRATED CIRCUITS

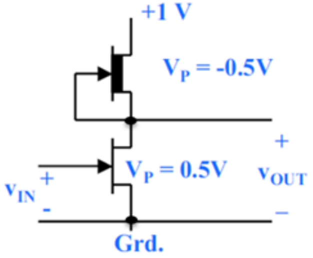
Logic

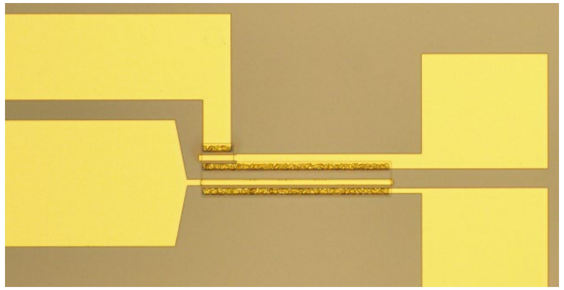

Depletion-Mode (normally on)

Enhancement-Mode (normally off)

Combine

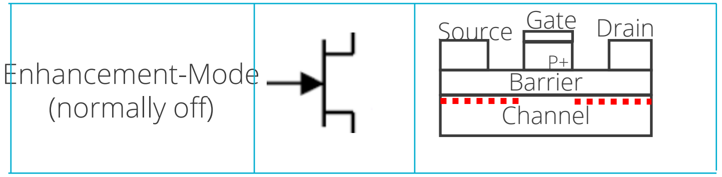
Depletion-load logic



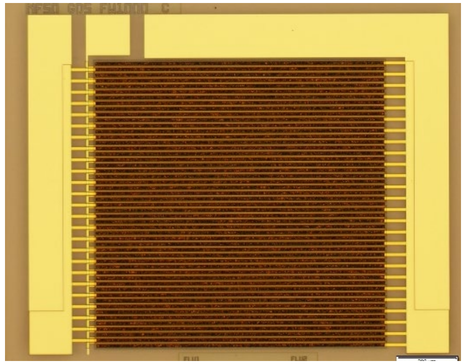


Inverter

High-Current E-mode Switch

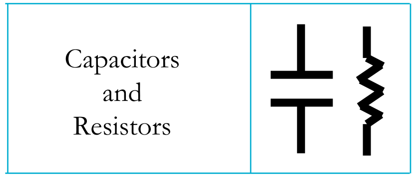

Enhancement-Mode (normally off)

Increase gate periphery

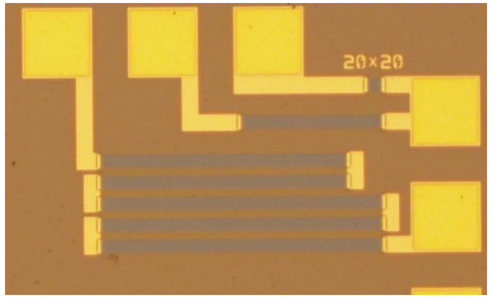


High-Current Switch

Passives


Capacitors and Resistors

Start with existing designs



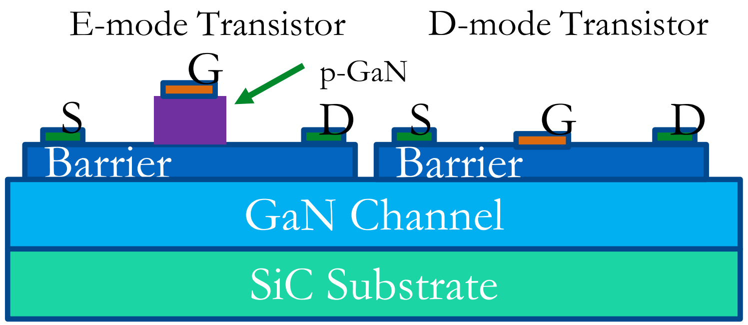
Resistors

These are being developed on GaN HEMTs

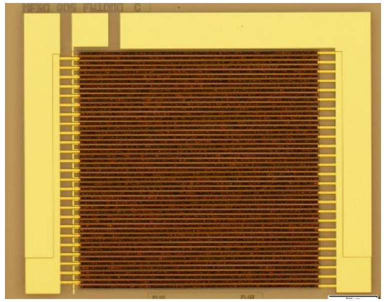
SMALL-SCALE INTEGRATED CIRCUITS

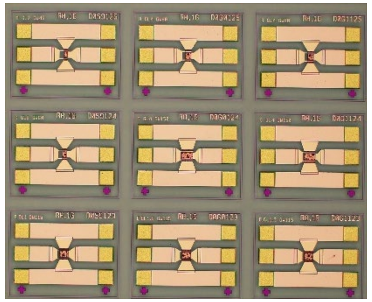
GaN: Wide bandgap semiconductor

- High breakdown strength: Fabricate power transistors
- Etch depth controlled threshold voltage: adjacent e- and d-mode devices → fabricate logic control circuitry

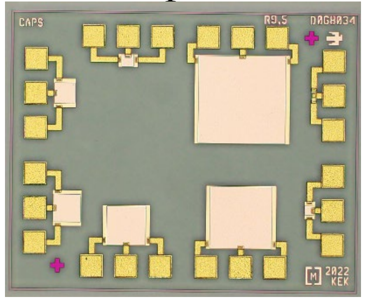


Discrete Transistors

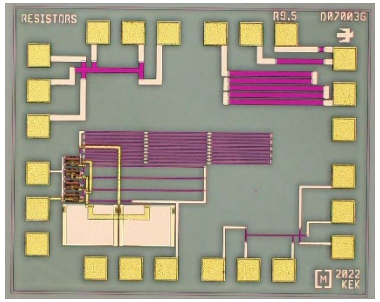

50 mm GaN HEMT


Discrete test HEMTs

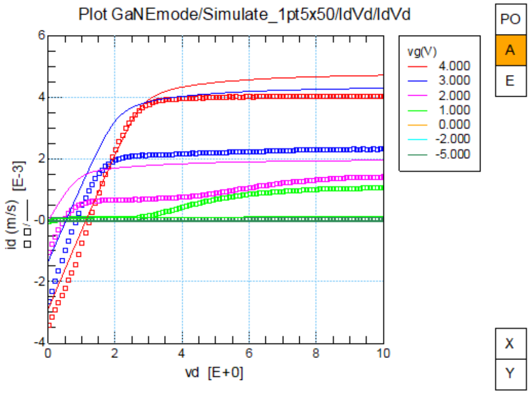
Passive components: Resistors and Capacitors

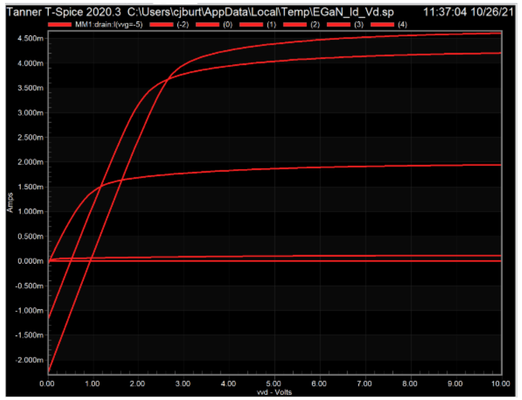


Capacitors on GaN



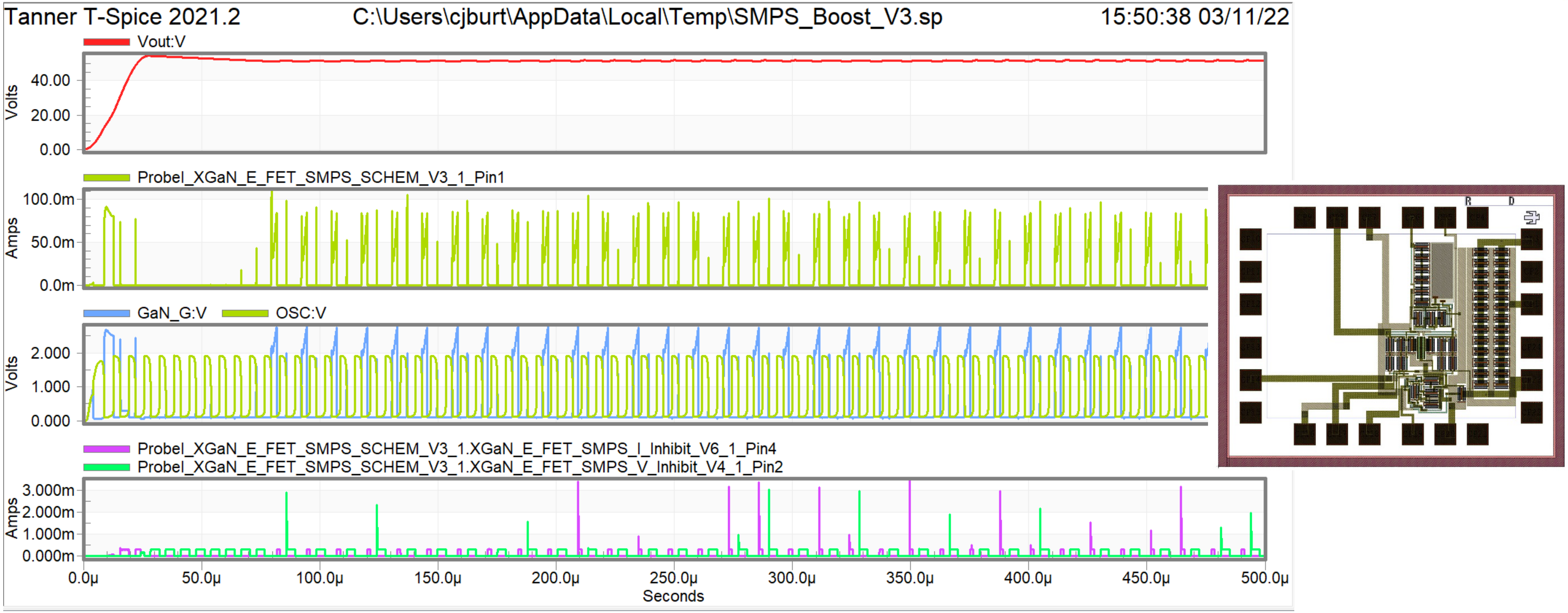
TaN Resistors on GaN




Tanner T-Spice 2020.3 C:\Users\cjburt\AppData\Local\Temp\EGaN_Id_Vd.sp 11:37:04 10/26/21

Built models from electrical test data to design integrated circuits

INCREASING COMPLEXITY: SMALL-SCALE INTEGRATED CIRCUITS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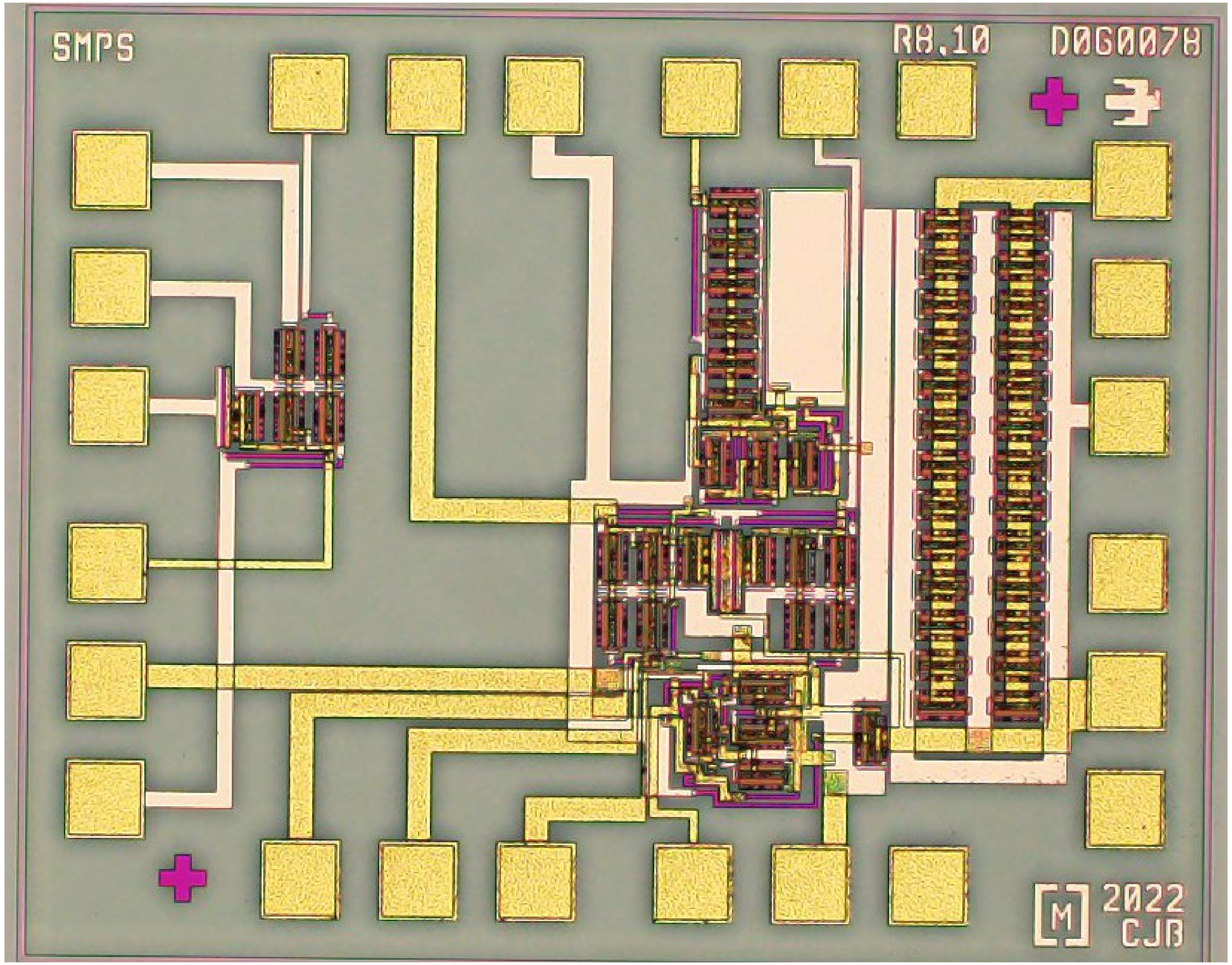
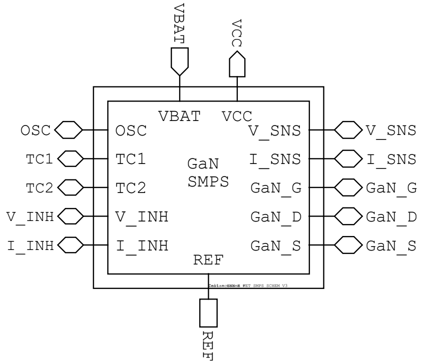
INCREASING COMPLEXITY: SMALL-SCALE INTEGRATED CIRCUITS

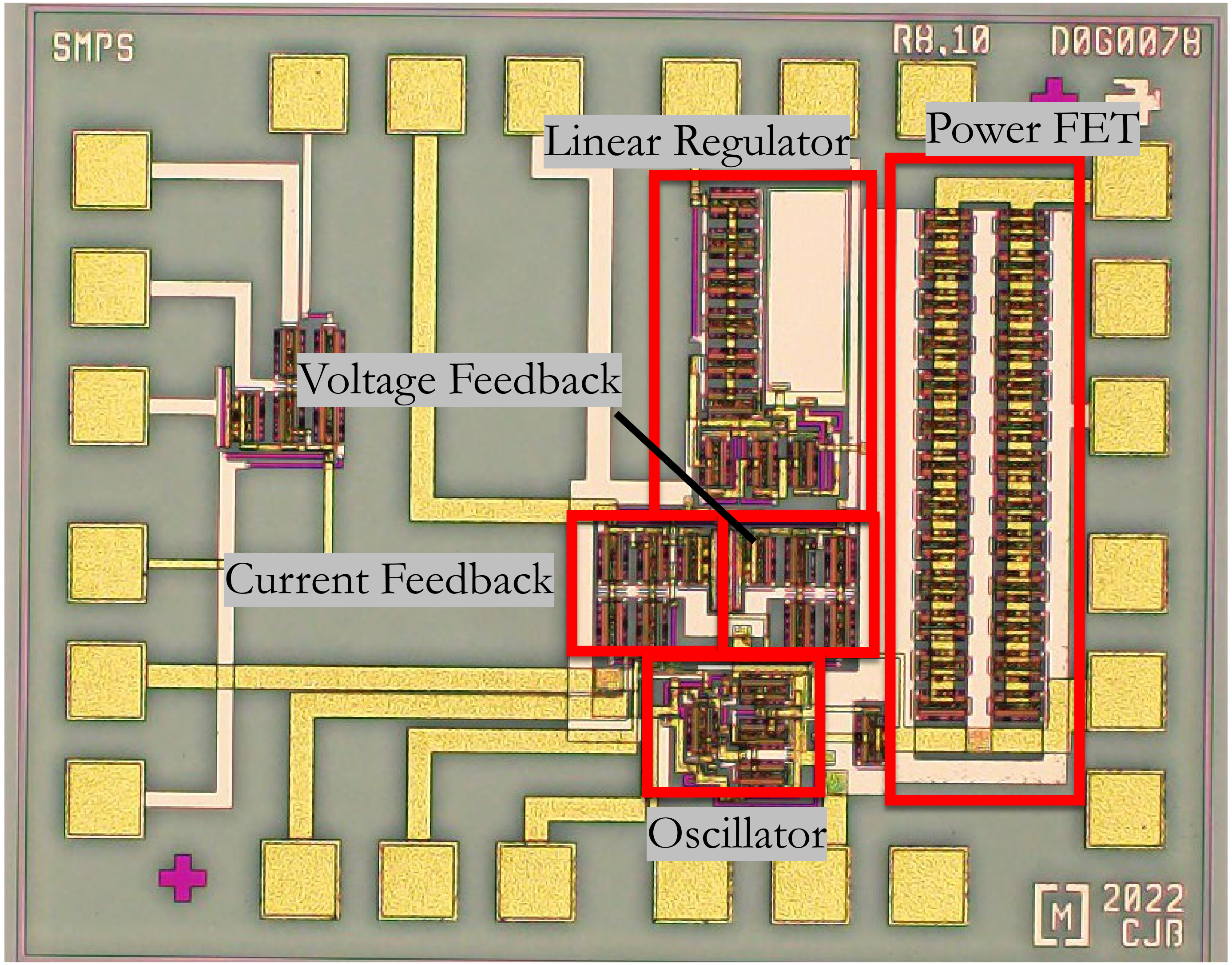


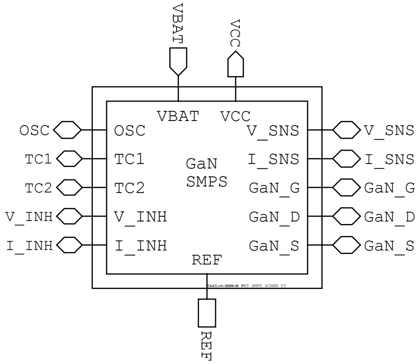


Chip Features:

- Voltage Regulator
- Programmable Oscillator
- Voltage Feedback
- Current Feedback
- D, G, S connections for power FET

INCREASING COMPLEXITY: SMALL-SCALE INTEGRATED CIRCUITS





Chip Features:

- Voltage Regulator
- Programmable Oscillator
- Voltage Feedback
- Current Feedback
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Circuits are in development

- We don't have working devices yet
- On-wafer-test data → Improve fabrication

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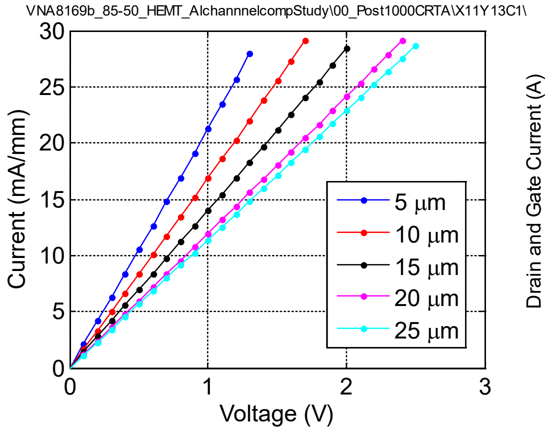
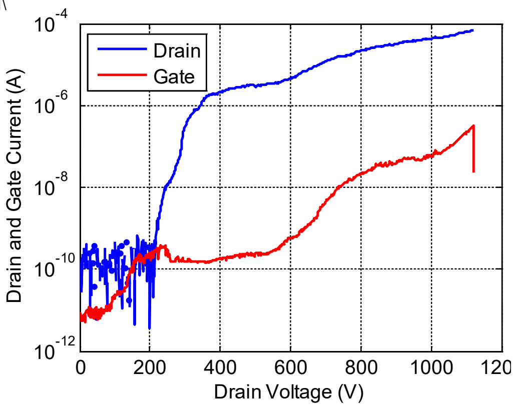
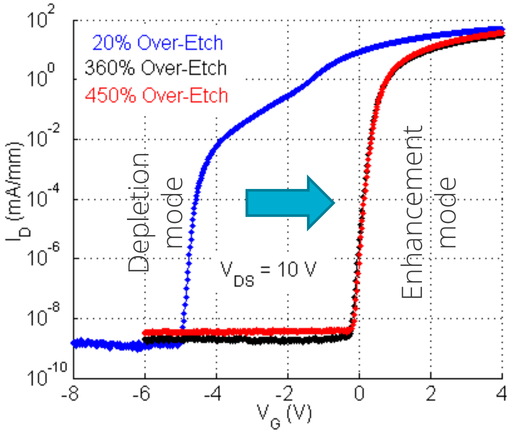
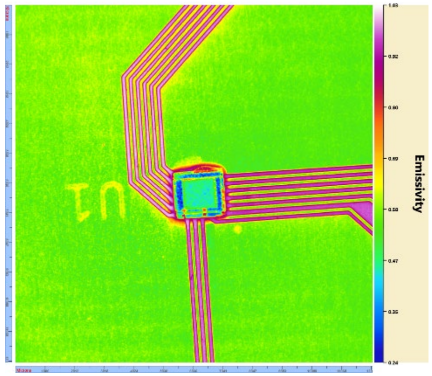
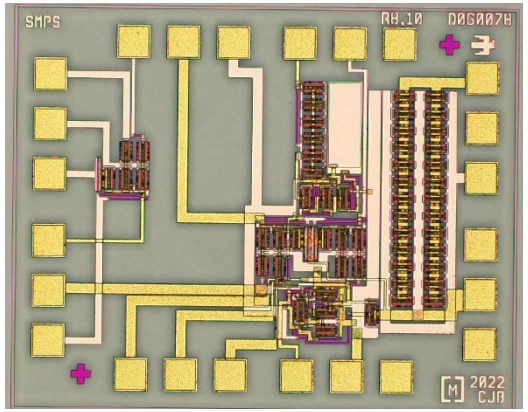










Sandia National Laboratories

Exceptional service in the national interest

RECENT ADVANCEMENTS IN (AL)GAN HIGH ELECTRON MOBILITY TRANSISTOR POWER ELECTRONICS AT SANDIA

Brianna Klein, Andy Allerman, Andy Armstrong, Mary Rosprim, Collin Burt, Jason Neely, Matt McDonough, Helen Chung, Luke Yates, Kimberly Kropka, Albert Colon, Rafmag Cabrera, Tony Rice, Colin Tyznik, Ben Matins, Erica Douglas, Bob Kaplar

Power Electronics & Energy Conversion Workshop

August 2nd – 3rd, 2023

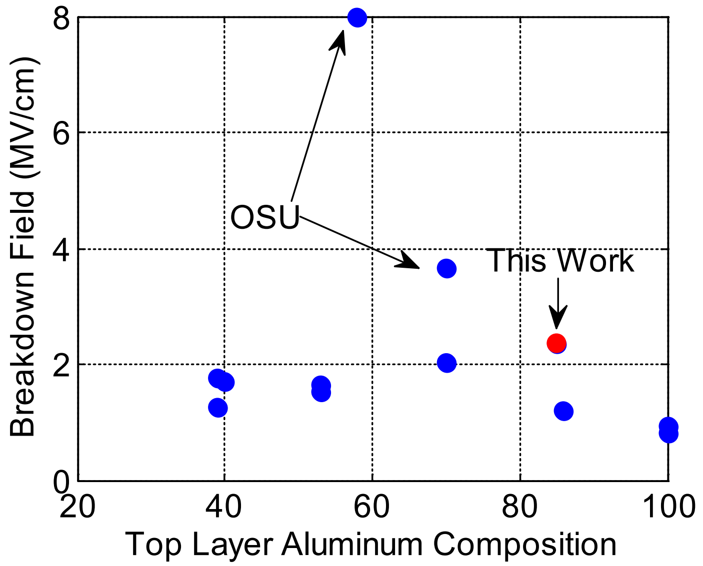
U.S. DEPARTMENT OF ENERGY

NNSA

EXTRA SLIDES

BREAKDOWN VOLTAGE REFERENCES

Reference	Barrier / Channel (Al%)	Breakdown voltage (V)	G-D spacing	Breakdown field (MV/cm)
Nanjo 2008 [1]	40/20	Not reported	----	----
Nanjo 2008 [2]	53/38	1650	10 µm	1.65
Nanjo 2008 [2]	53/38	463	3 µm	1.54
Nanjo 2008 [2]	39/16	381	3 µm	1.27
Nanjo 2009 [3]	39/16	>350	2 µm	1.75
Tokuda 2010 [4]	86/51	1800	15 µm	1.2
Nanjo 2013 [5]	40/15	1700	10 µm	1.7
Baca 2016	100/85	810	10 µm	0.81
Okumura 2018	100 (MESFET)	2370	25 µm	0.948
Bajaj 2018 [6]	70 (MOSFET)	620 (>3.6 MV/cm)	1.7 µm	3.65
Bajaj 2016 [7]	70 (MISFET)	224	1.1 µ	2.04
Razzak 2020 [8]	58 (Diode)	155	0.18 µm	8.5
THIS WORK	85/70	1204	5.1 µm	2.35



[1] T. Nanjo *et al.*, "First Operation of AlGaN Channel High Electron Mobility Transistors," *Applied Physics Express* vol. 1, no. 011101, 2008.

[2] T. Nanjo *et al.*, "Remarkable breakdown voltage enhancement in AlGaN channel high electron mobility transistors," *Applied Physics Letters,* vol. 92, no. 263502, 2008.

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