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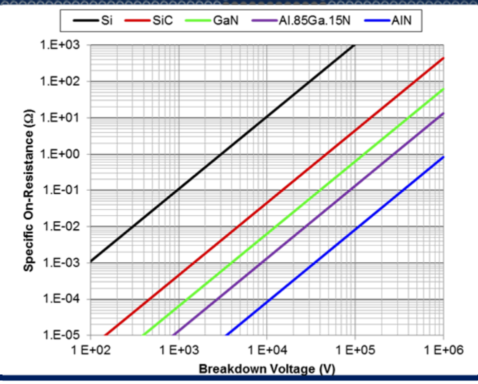
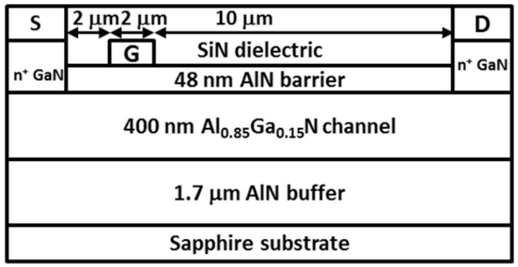
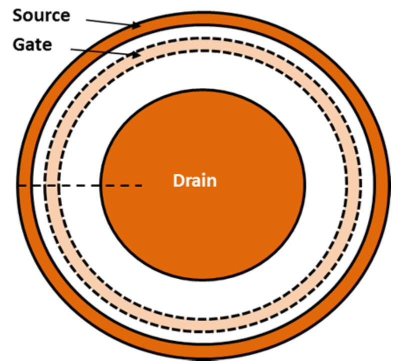
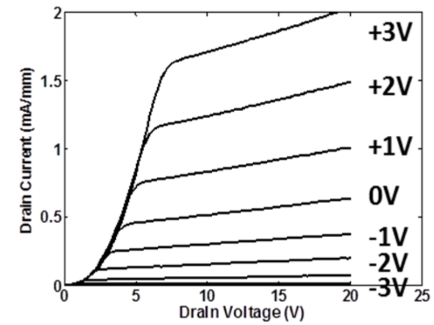








ULTRAWIDE BANDGAP POWER ELECTRONICS

An AlN/$Al_{0.85}Ga_{0.15}$N High Electron Mobility Transistor with A Regrown Ohmic Contact

Albert G. Baca, Andrew M. Armstrong, Andrew A. Allerman, Erica A. Douglas, Carlos A. Sanchez, Michael P. King, Michael E. Coltrin, Christopher D. Nordquist, Torben R. Fortune, and Robert J. Kaplar

Device Research Conference

June 20, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Outline

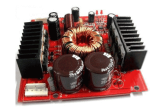
- Motivation
- Extending the Lateral Figure-of-Merit with Ultra-Wide Bandgap Semiconductors (UWBG)
- Prior AlGaN-channel HEMT Results
- HEMT Structure and Characterization
- HEMT Fabrication
- HEMT Electrical Characteristics and Analysis
- HEMT Breakdown Voltage and Current Conduction Analysis
- Summary

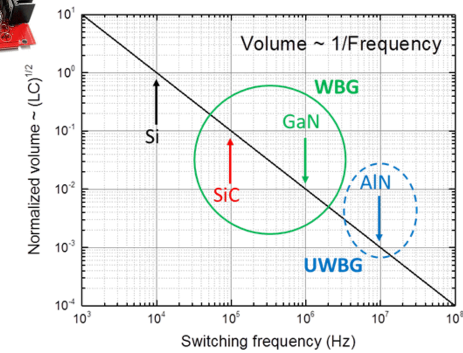
Motivation: Power switching, rf Power Amplifiers and rf Switches

Power Conversion Applications

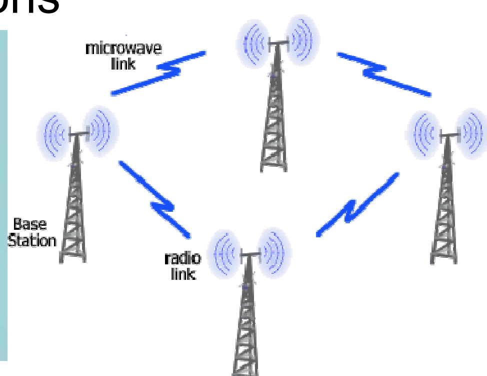
UWBG materials and devices may enable *another order-of-magnitude reduction* in power converter size and weight!

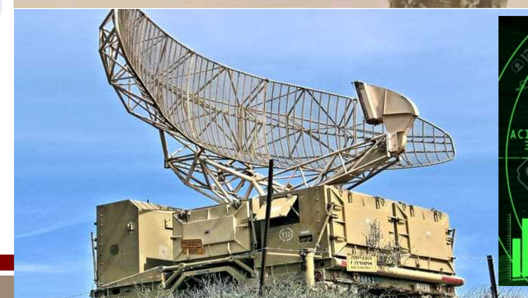
UWBG





rf Power Applications





UWBG may enable *improved power and efficiency*

Comparison of Materials Using Lateral Figure of Merit (based on conduction loss)

$Al_{0.85}Ga_{0.15}N$
Unexplored space
Heterostructures are available

$Al_{0.85}Ga_{0.15}N$ predicted to have meaningfully better *LFOM* than GaN at elevated temperatures

AlN - Unexplored space;
Not for HEMTs; how to dope?

Lateral Devices (e.g. conventional MOSFET, HEMT)

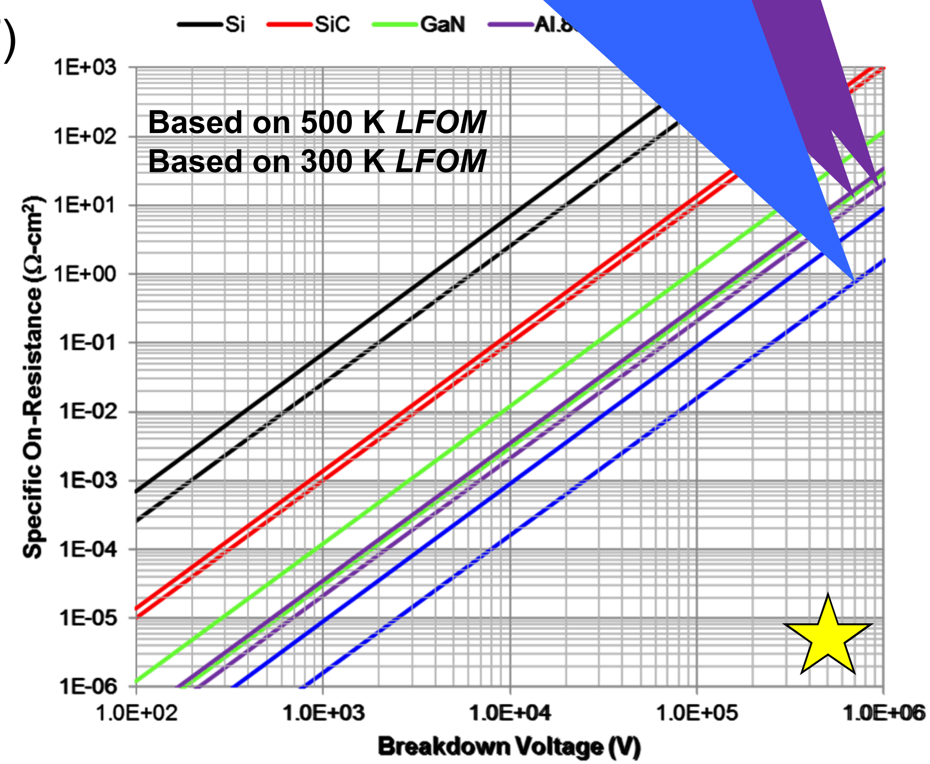
$$LFOM = \frac{V_{br}{}^2}{R_{on,sp}} = q\mu n_s E_C{}^2 \quad E_C = AE_g{}^{2.5}$$

Vertical Devices (e.g. pin diode, Insulated Gate Bipolar Transistor, Vertical MOSFET)

$$UFOM = \frac{V_{br}{}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_C{}^3$$

Material Parameters

	Mobility μ ($cm^2V^{-1}s^{-1}$)	Permitivitty ε (F/cm)	Bandgap E_g	Sheet Charge n_s (cm^{-2})	Critical Electric Field, E_C (V/cm)
Si	1300	11.4	1.1	2.0×10^{12}	3.0×10^{5}
SiC	260	9.7	2.9	2.0×10^{12}	3.4×10^{6}
GaN	1500	9.5	3.4	1.0×10^{13}	3.7×10^{6}
$Al_{0.85}Ga_{0.15}N$	150	8.35	5.78	1.0×10^{13}	1.4×10^{7}
AlN	1400	8.5	6.2	1.0×10^{13}	1.7×10^{7}



Model the Mobility across the AlGaN Composition Range

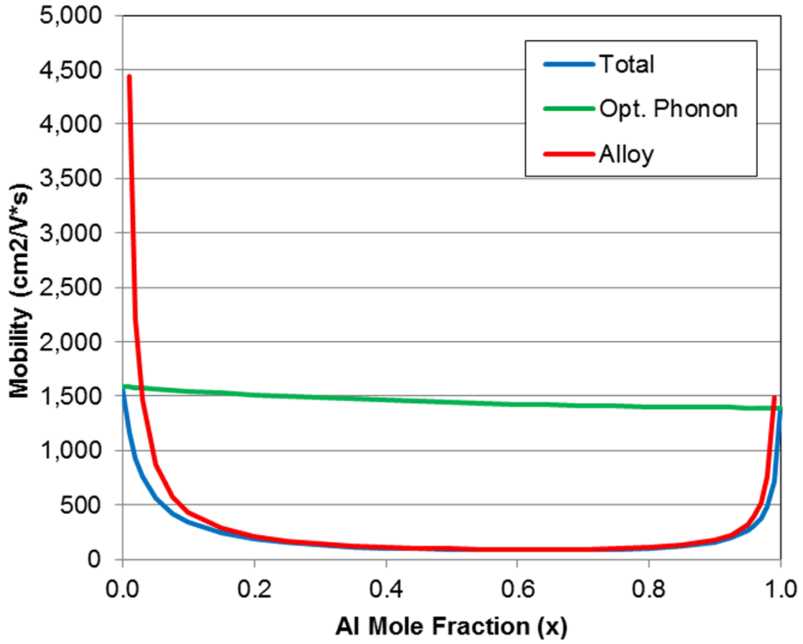
Mobility is related to the average carrier-relaxation time $\langle\tau\rangle$, $\mu = \frac{q\langle\tau\rangle}{m^*}$

When more than one carrier relaxation mechanism is important, their contributions are usually combined via "Matthiessen's Rule"

$$\frac{1}{\mu_{tot}} = \frac{1}{\mu_A} + \frac{1}{\mu_{PO}} + \frac{1}{\mu_{II}} + \cdots$$

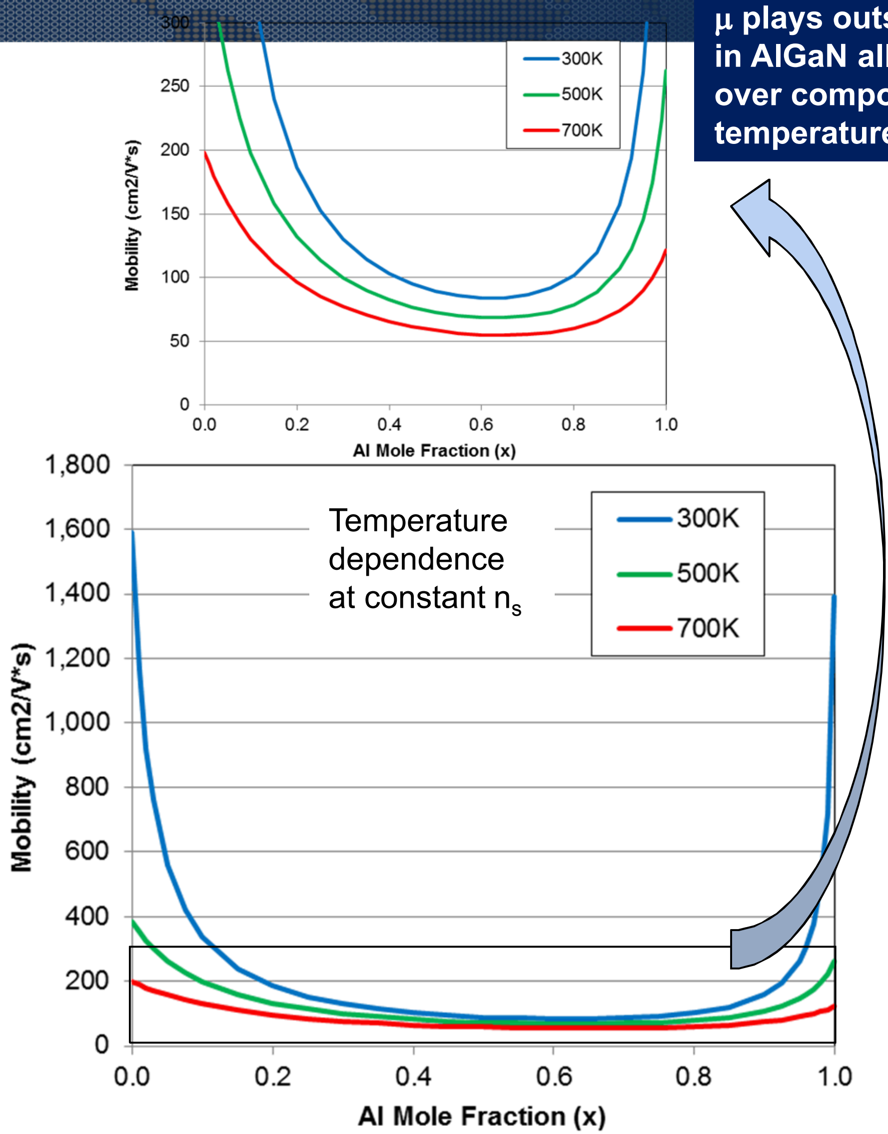
Alloy scattering: $\mu_A = \frac{q\hbar^3}{m_{eff}^2 (\Delta V_o)^2 \Omega_o x(1-x)} \cdot \frac{16}{3b}$

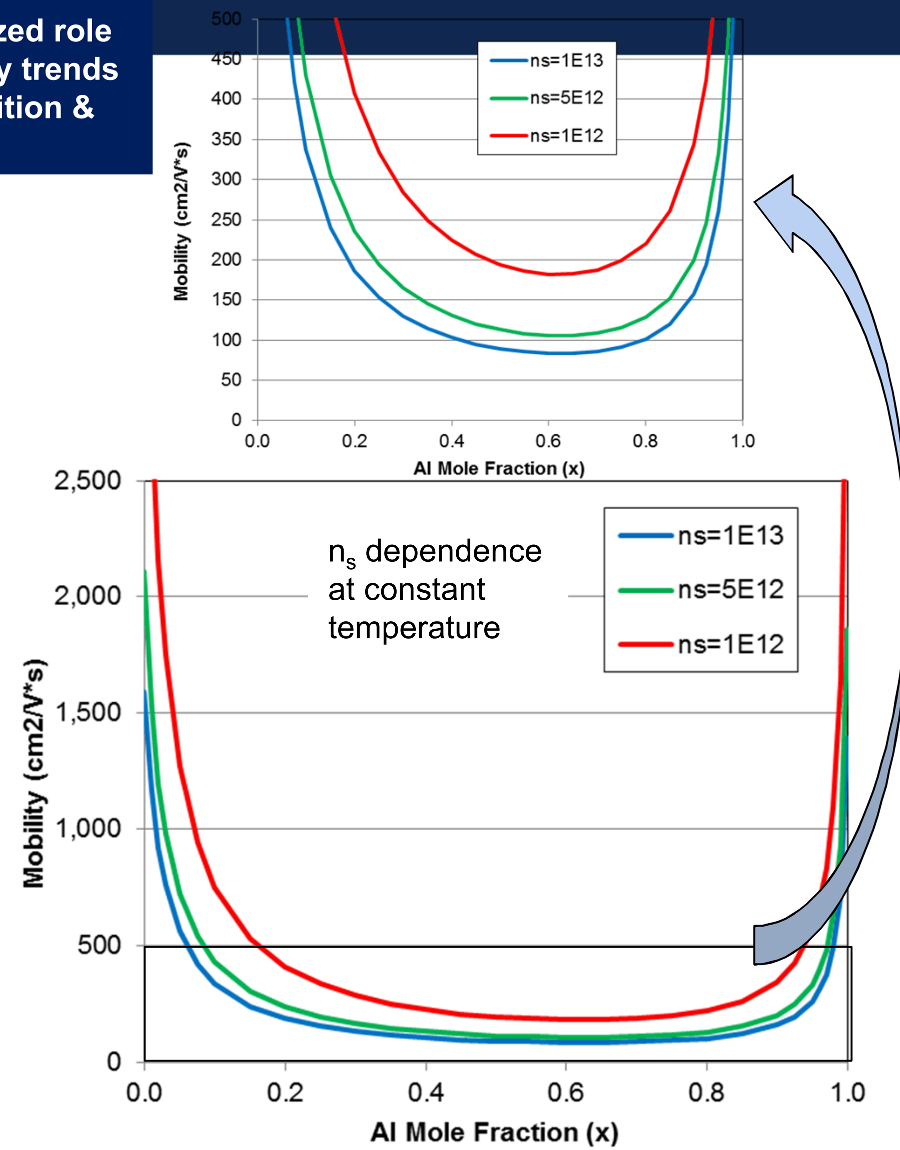
Polar optical phonon scattering: $\mu_{PO} = \frac{2k_o \hbar^2 F \epsilon_o \epsilon_p}{q m_{eff}^2 \omega_o N_B(T) G(k_o)}$



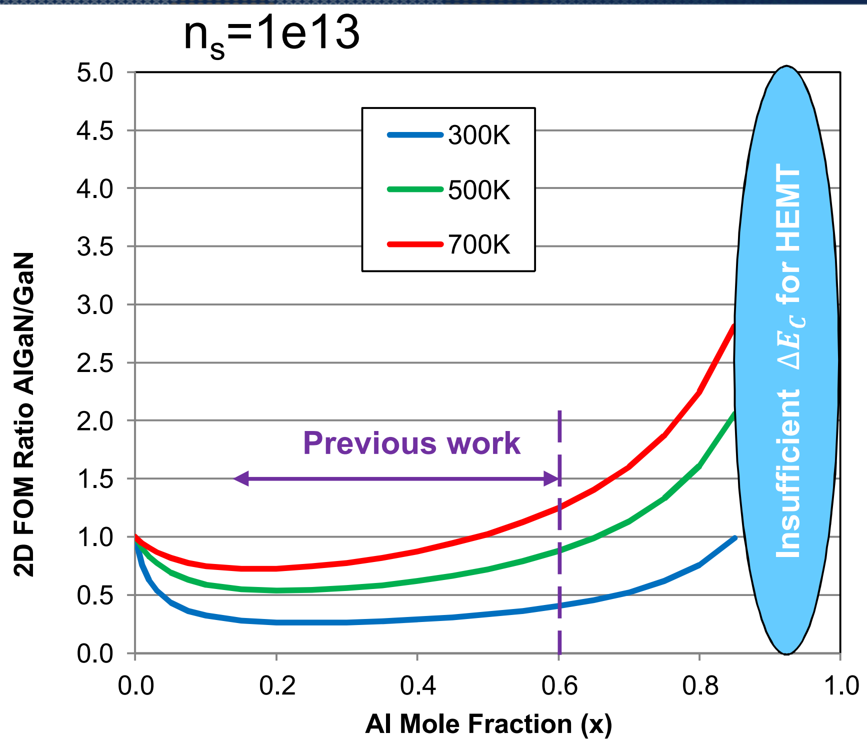
Mobility for AlGaN Alloys

μ plays outsized role in AlGaN alloy trends over composition & temperature

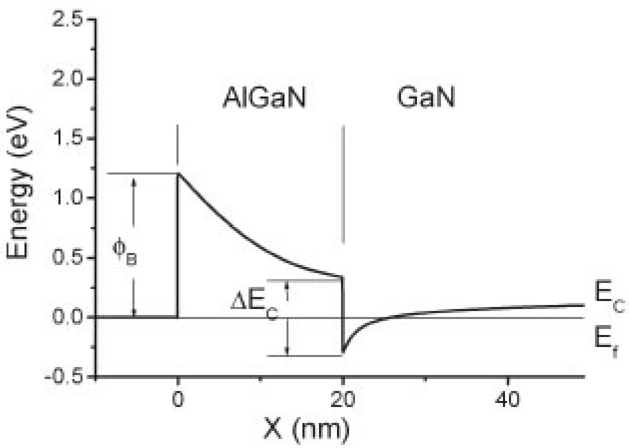




Normalized Lateral Figure of Merit for AlGaN Alloys



Constant n_s=1e13 requires a substantial ΔE_C



- AlGaN-channel HEMTs offer meaningful LFOM advantage over wide bandgap semiconductors at *elevated temperatures*, but not at room temperature

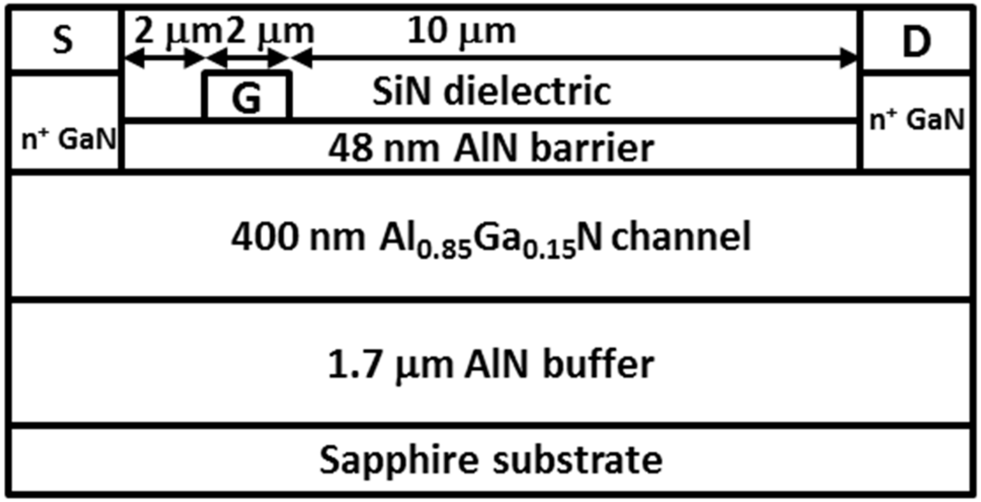
History of Prior $Al_yGa_{1-y}N$/ $Al_xGa_{1-x}N$ HEMT Research

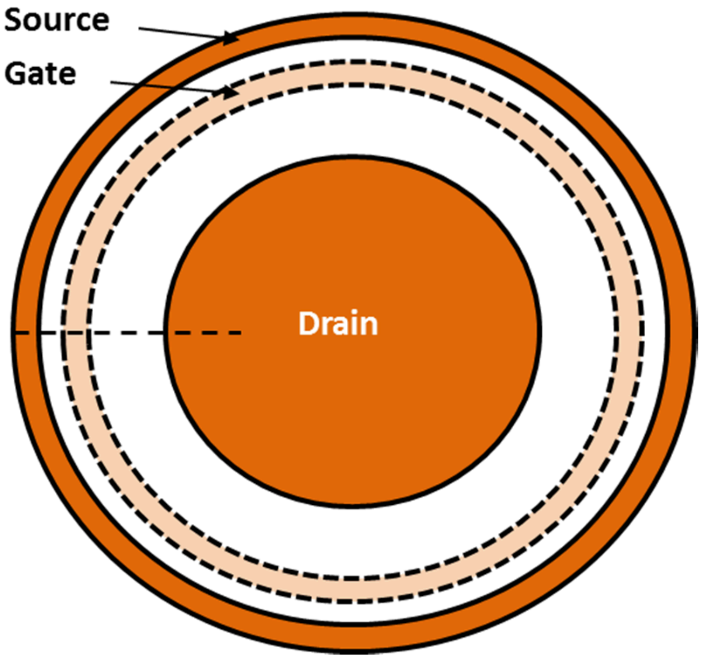
Year	x =	y =	citation
2008	.16 .38	.39 .53	T. Nanjo, M. Takeuchi, M. Suita, T. Oishi, Y. Abe, Y. Tokuda and Y. Aoyagi, Appl. Phys. Lett. **92**, 263502 (2008).
2010	.51	.86	H. Tokuda, M. Hatano, N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto and M. Kuzuhara, Appl. Phys. Exp. **3**, 121003 (2010).
2011	.23 .51	.51 .86	N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto and Kuzuhara, Jpn. J. Appl. Phys. **50**, 100202 (2011).
2013	.15	.40	T. Nanjo, A. Imai, Y. Suzuki, Y. Abe, T. Oishi, M. Suita, E. Yagyu and Y. Tokuda, IEEE T. Electron. Dev. **60**, 1046 (2013).
2014	.60	1.0	N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto, H. Tokuda and M. Kuzuhara, Electron. Lett. **50**, 211 (2014).

Prior work:

- Begun to address critical issues for UWBG semiconductors, such as Ohmic contact, trends in breakdown, high Temp I_{DS}-V_{DS}, …
- No prior research aimed at AlGaN alloys aimed at maximizing AlGaN *LFOM*

HEMT Structure and Geometry

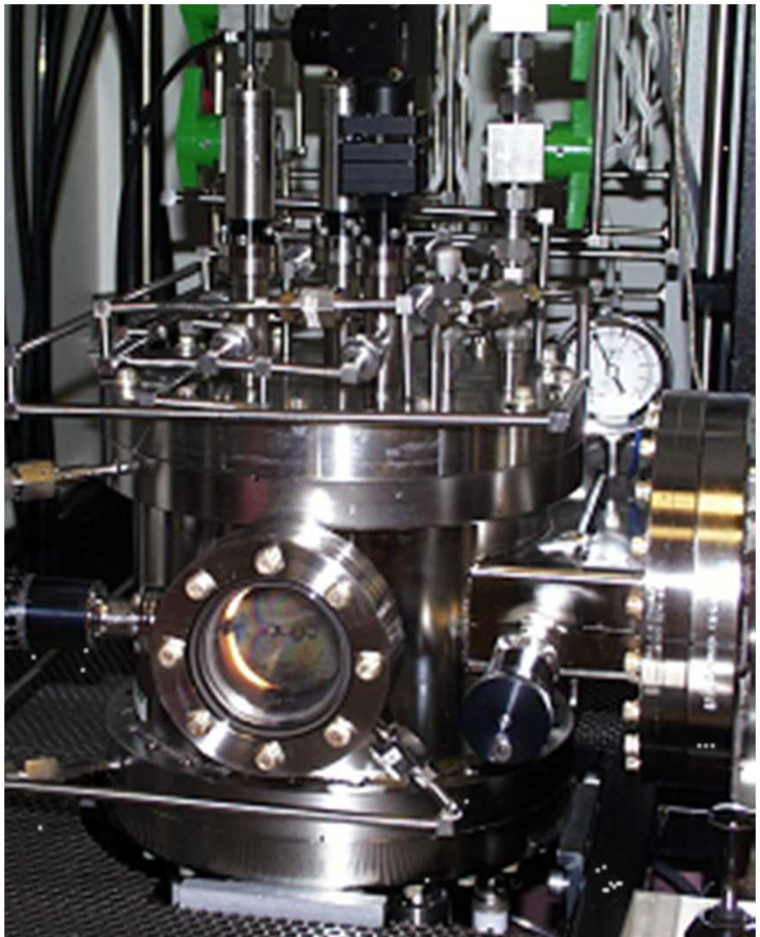




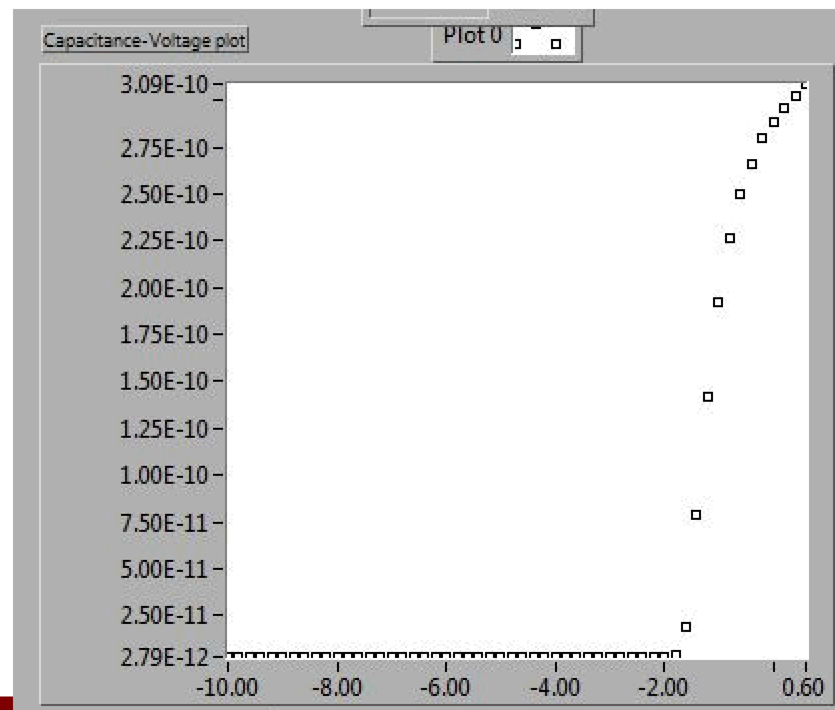
Circular Geometry:
(edge effects unimportant)

$Al_{0.85}Ga_{0.15}N$-Channel HEMT Growth and Characterization

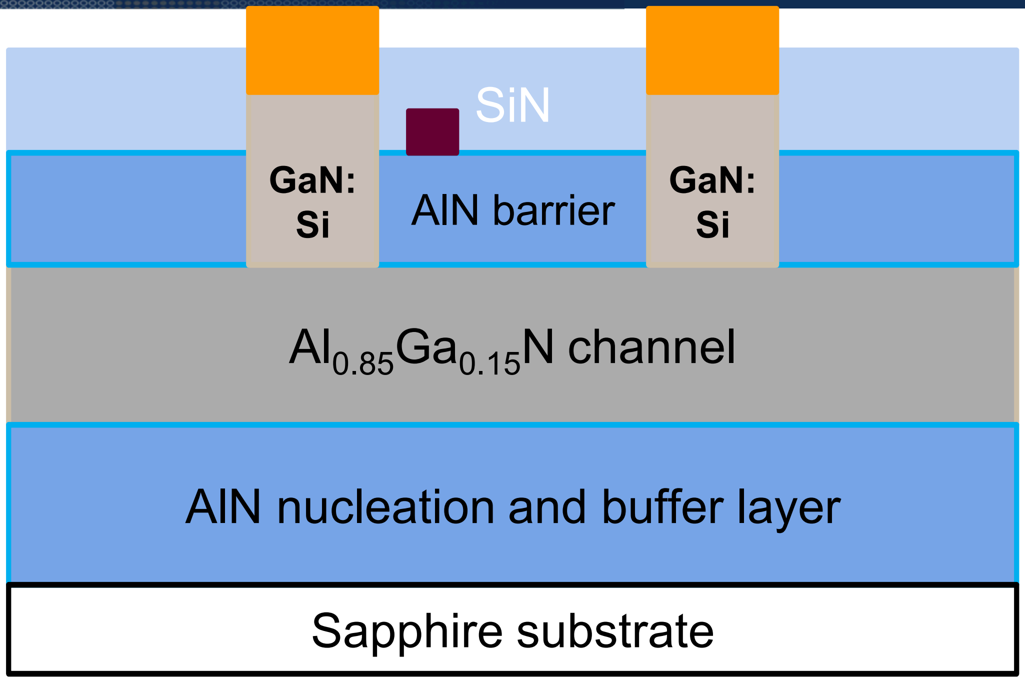
Veeco D125 MOCVD



- Sheet Resistance, $\boldsymbol{R_{sh} = 4200\,\Omega/\square}$
- $\boldsymbol{V_p = -1.8\,V}$ (from C-V)
- Inferred mobility **μ = 250 $cm^2V^{-1}s^{-1}$**



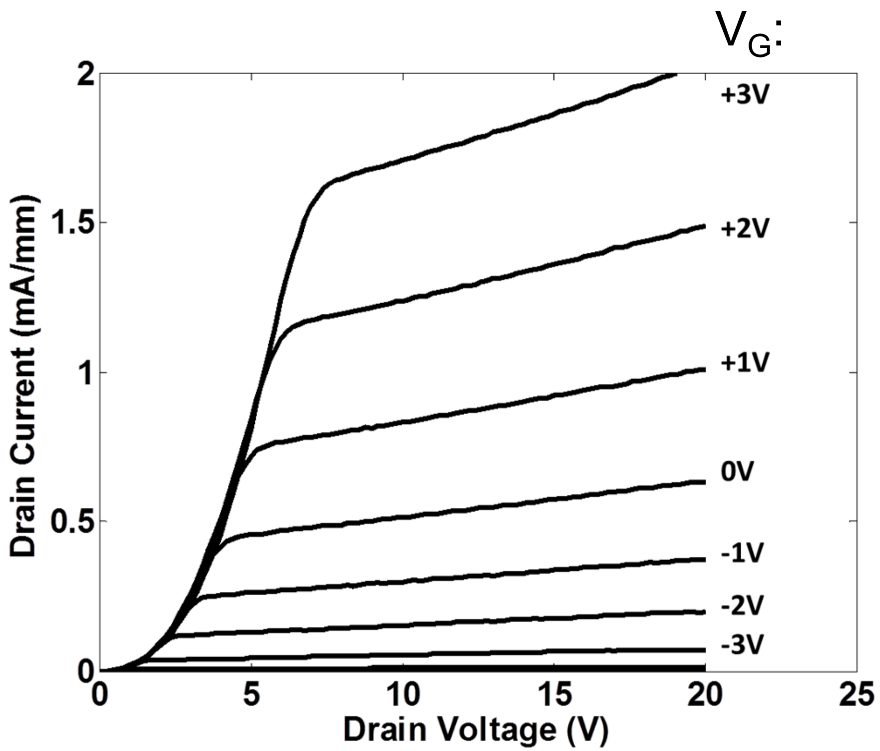
HEMT Fabrication

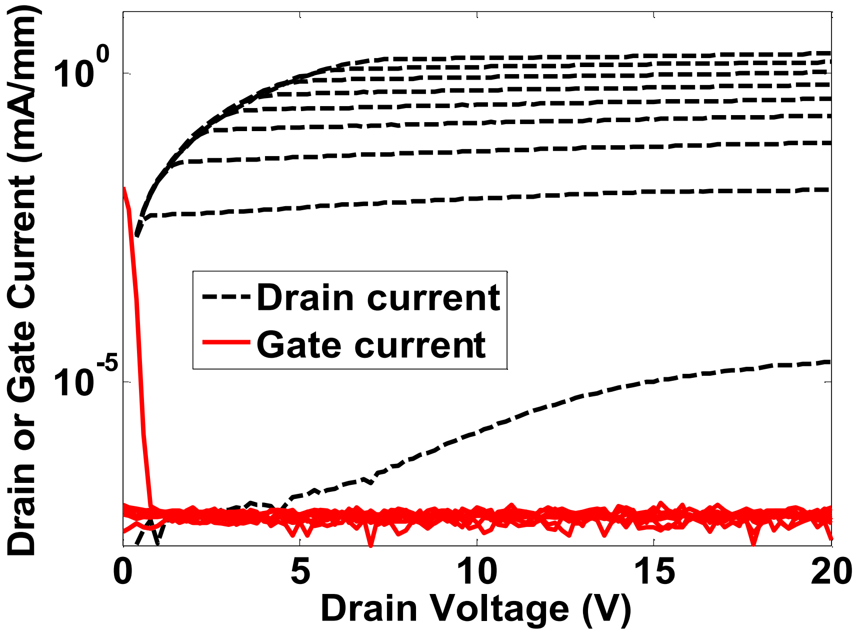


Process Steps:

1. SiN deposition, photolithography, SiN etch, AlN etch, PR removal, GaN:Si regrowth, SiN removal
2. Photolithography, ohmic metal deposition, litoff, RTA
3. Gate photolithography, evaporation, liftoff
4. SiN deposition, photolithography, SiN etch (pads)

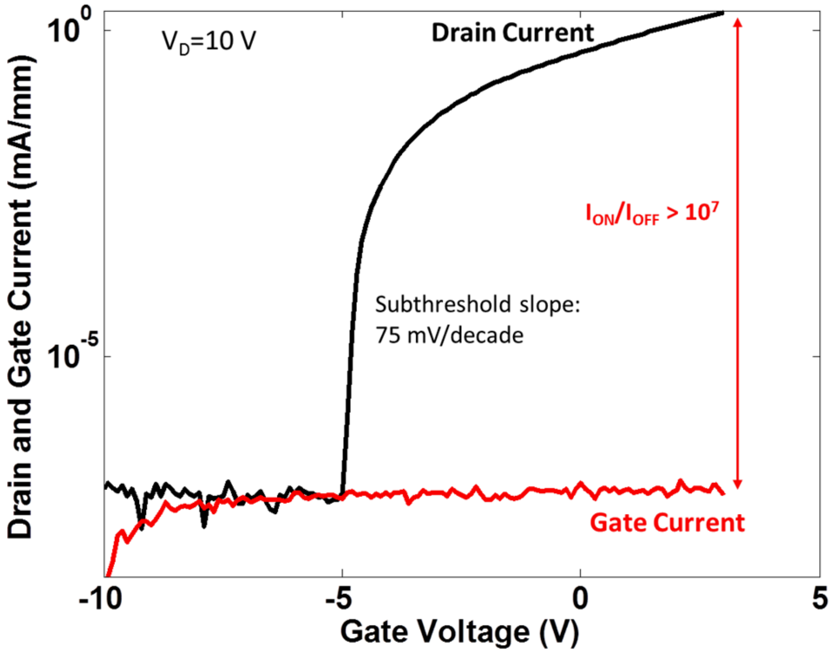
$Al_{0.85}Ga_{0.15}N$-Channel HEMT Shows Good Gate Control

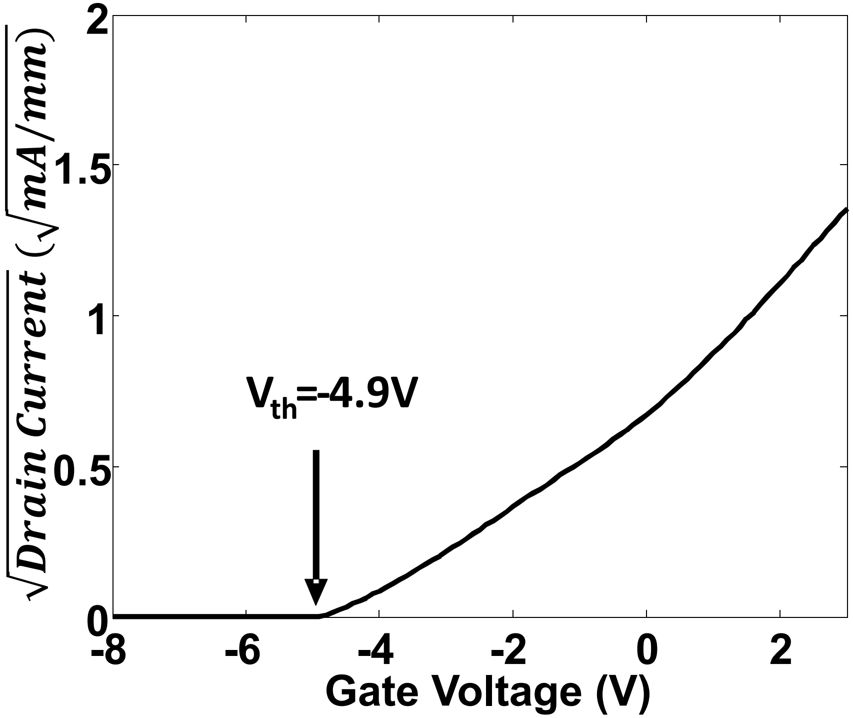




- Operates like Field Effect Transistor
  - Good pinchoff
  - Knee voltage linear with gate voltage
  - Low drain and gate leakage currents
- Not Ideal in some Aspects
  - Hysteresis in forward and reverse Gate sweeps
  - Source and drain contacts more rectifying than Ohmic
  - Large output conductance

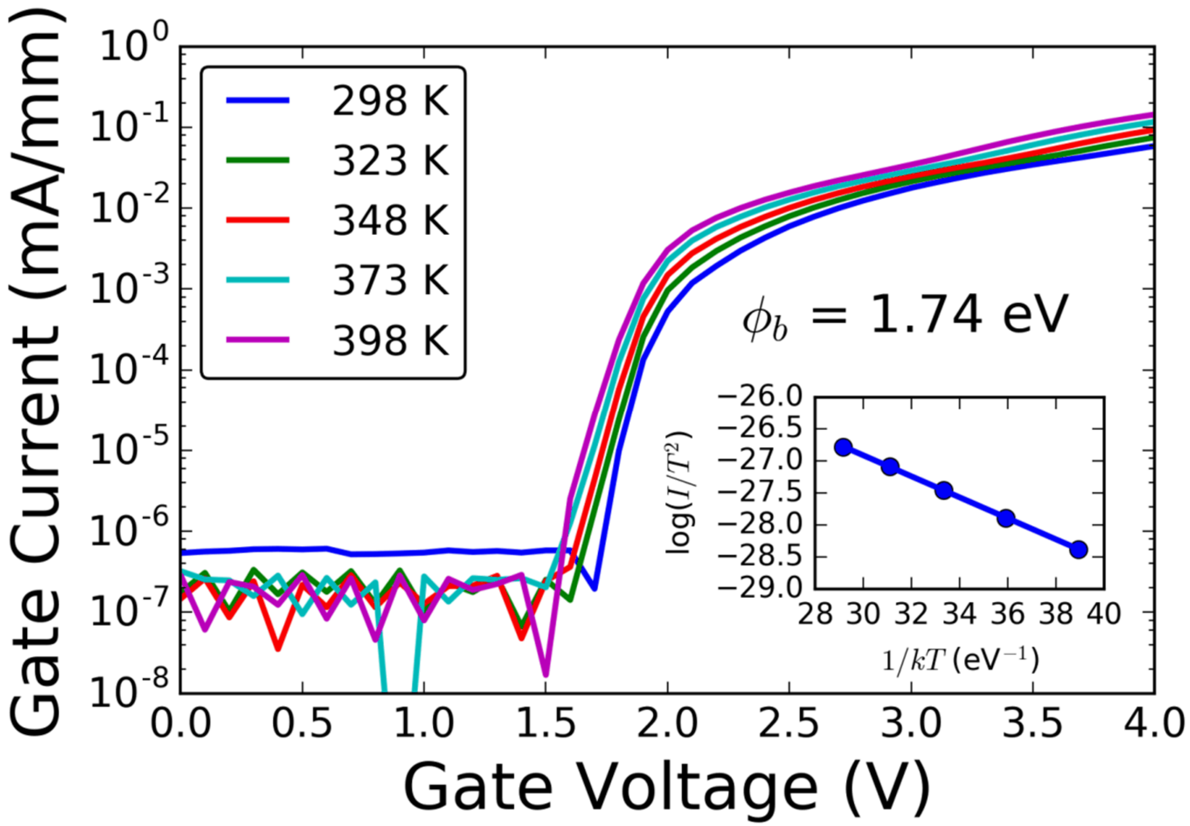
$Al_{0.85}Ga_{0.15}$N-Channel HEMT Shows Excellent Leakage and off-state Characteristics





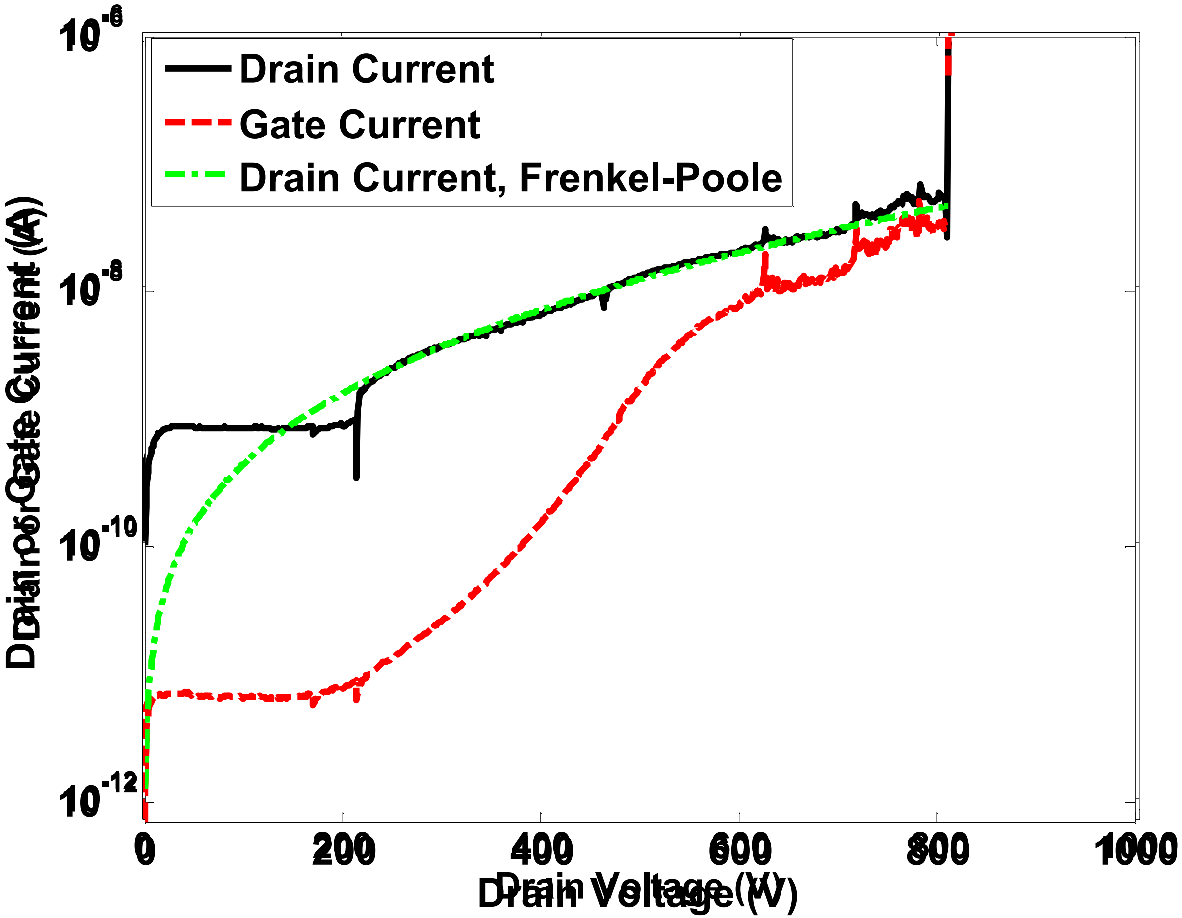
- Leakage current near measurement limit
  - Similarly low gate leakage in $Al_{0.25}Ga_{0.75}$N/GaN requires insulated gate (high interface state density)
  - Excellent subthreshold slope, 75 mV/decade
  - Excellent I_{ON}/I_{OFF} ratio $>10^7$
- Leakage current near measurement limit

$Al_{0.85}Ga_{0.15}N$-Channel HEMT: Large Schottky Barrier



- Using Method in Z. Lin, Appl. Phys. Lett. **82**, 4364 (2003)
- Comparison to Ni/$Al_{0.25}Ga_{0.75}N$/GaN:
  - Φ_b = 0.99 eV (A. C. Schmitz, Semicond. Sci. Technol. **11** (1996) 1464–1467)

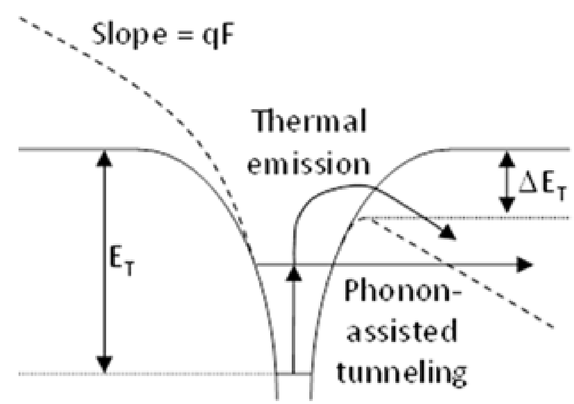
$Al_{0.85}Ga_{0.15}N$-Channel HEMT Shows Promising Breakdown Voltage



- Standard gate – no fieldplate, 10 μm g-d spacing
  V_{br} = 810 V
- Frenkel-Poole emission

$$I = AVe^{BV}$$

- Good fit with A=1.1x10^{12} V^{-1},
  B= 5.0x10^{-4} V^{-1}



- Compare against β-Ga_2O_3 FET: gate-connected fieldplate, 10 μm g-d spacing (M. Higashiwaki, APL **103**, 123511 (2013).
  V_{br} = 370 V

Limitation of $Al_{0.85}Ga_{0.15}N$-Channel HEMT (Source and Drain contacts)

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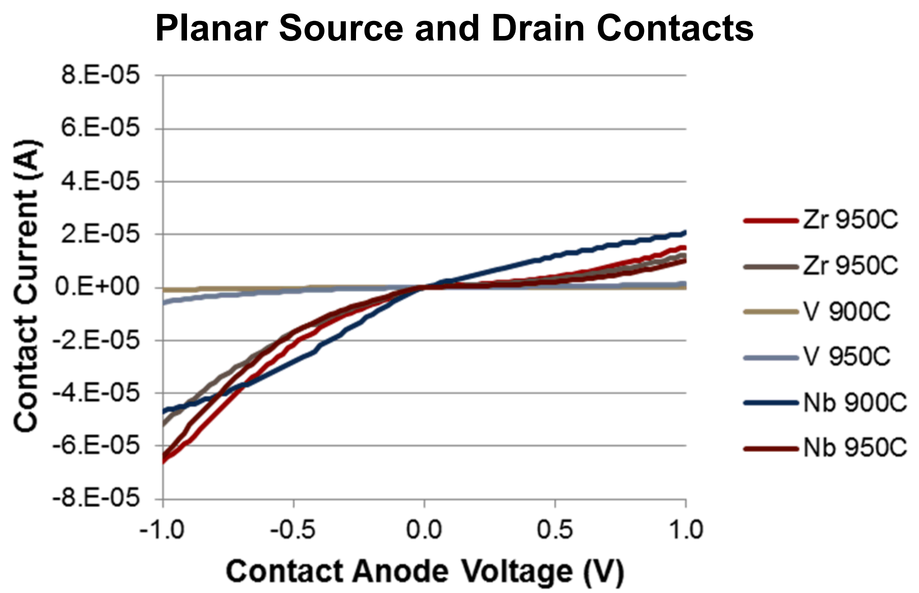
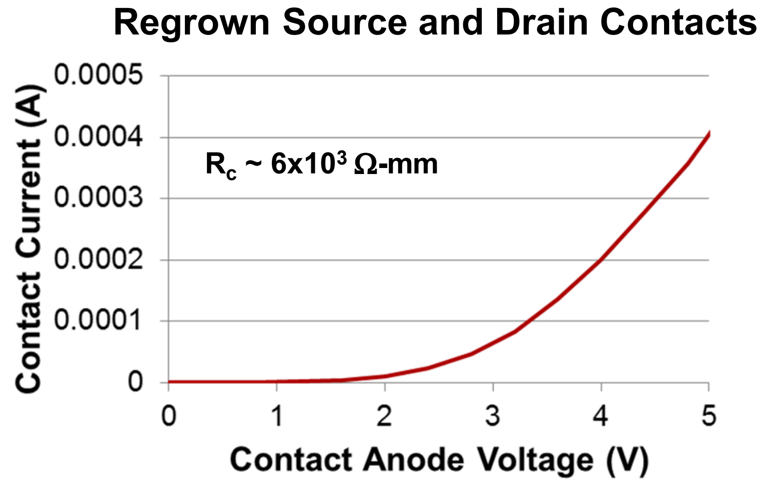
Planar Source and Drain Contacts

Sample	Metal	Anneal
1	Zr/Al/Mo/Au 15/120/35/50 (nm)	900°C
2	Zr/Al/Mo/Au 15/120/35/50 (nm)	950°C
3	V/Al/V/Au 15/80/20/100 (nm)	900°C
4	V/Al/V/Au 15/80/20/100 (nm)	950°C
5	Nb/Ti/Al/Mo/Au 20/20/100/40/50 (nm)	900°C
6	Nb/Ti/Al/Mo/Au 20/20/100/40/50 (nm)	950°C

Regrown Source and Drain Contacts

Sample	Metal	Anneal
1	Ti/Al/Ni/Au 25/100/15/50 (nm)	850°C





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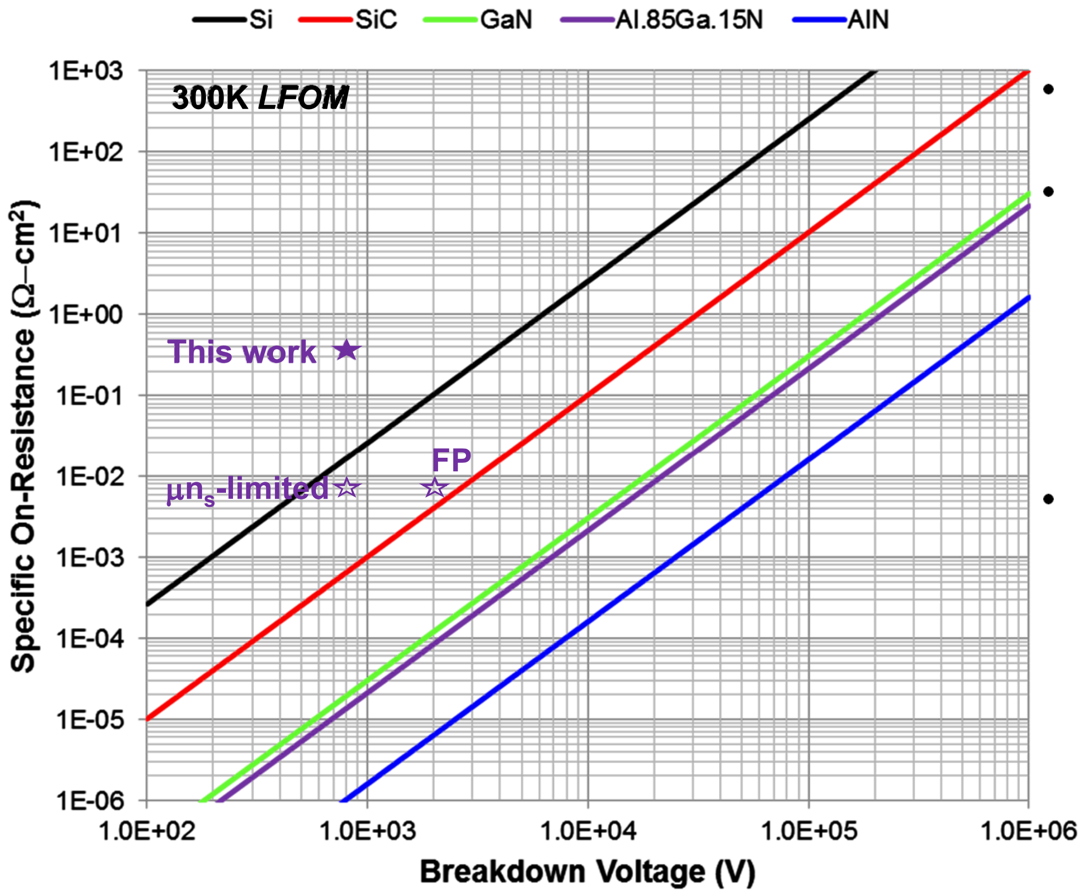
Significance of $Al_{0.85}Ga_{0.15}N$-Channel HEMT



- Standard gate – no fieldplate, 10 μm gate-drain spacing
- 1st HEMT is above Si line
  - Expect 2.5x improvement from implementing fieldplate
  - 42x improvement based on improved Ohmic contact and R_{sh}~4200 Ω/□
- To approach AlGaN line:
  - 2x further improvement by increasing n_s
  - Improve V_{br} with sophisticated electric field management or reduce gate-drain spacing

* FP = Field Plate

Summary

- Demonstrated the first $AlN/Al_{0.85}Ga_{0.15}N$ HEMT
- Extended the Al-composition and Bandgap Range for $Al_xGa_{1-x}N$-channel HEMTs to encompass the lateral figure of merit's maximum value for $Al_xGa_{1-x}N$ alloys
- Established the rationale for UWBG $AlN/Al_{0.85}Ga_{0.15}N$ high-temperature superiority over AlGaN/GaN
- Demonstrated AlGaN-channel HEMT with:
  - HEMT Breakdown Voltage of 810 V
  - Excellent Drain Leakage Current and subthreshold Slope (75 mV/decade)
  - Excellent Gate Leakage Current and Φ_b (1.74 eV)
- Modeled Drain Leakage Current with Frenkel-Poole Conduction