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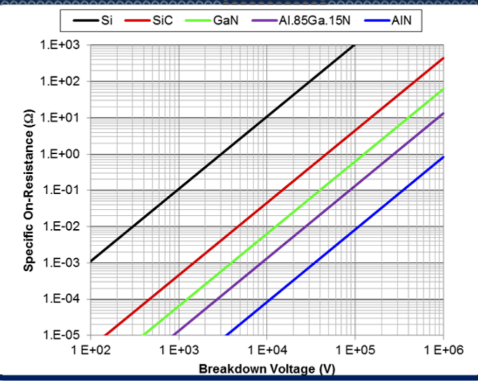

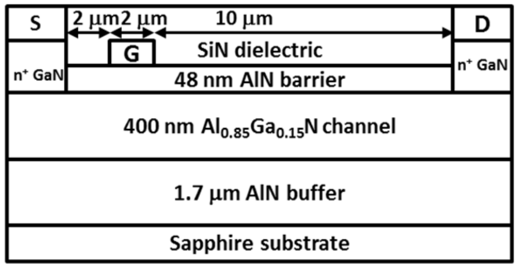

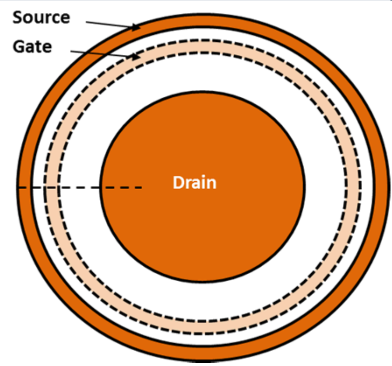

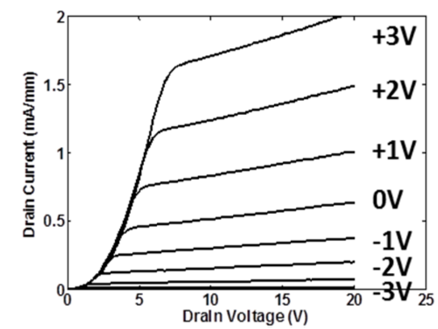

Device Characteristics of an $AlN/Al_{0.85}Ga_{0.15}N$ High Electron Mobility Transistor with A Regrown Ohmic Contact

ULTRAWIDE BANDGAP POWER ELECTRONICS

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

Lester Eastman Conference on High Performance Devices

August 3, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

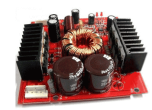
- **Motivation**
- **Extending the Lateral Figure-of-Merit with Ultra-Wide Bandgap Semiconductors (UWBG)**
- **Prior AlGaN-channel HEMT Results**
- **HEMT Structure, Fabrication and Characterization**
- **HEMT Electrical Characteristics and Analysis**
- **HEMT Roadmap toward the Lateral Figure of Merit**
- **Summary**

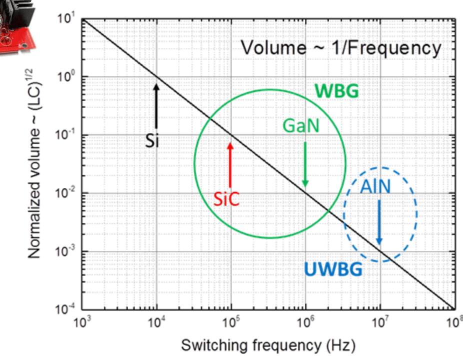
Motivation: Power switching, rf Power Amplifiers and rf Switches

Power Conversion Applications

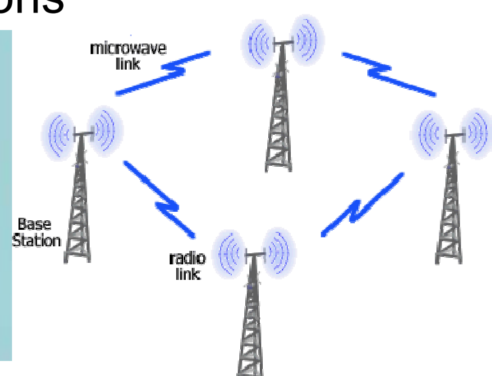
UWBG materials and devices may enable *another order-of-magnitude reduction* in power converter size and weight!

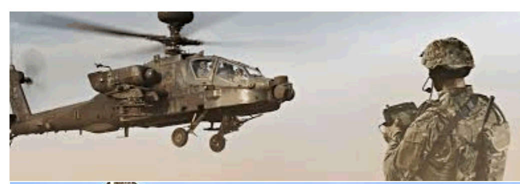
UWBG

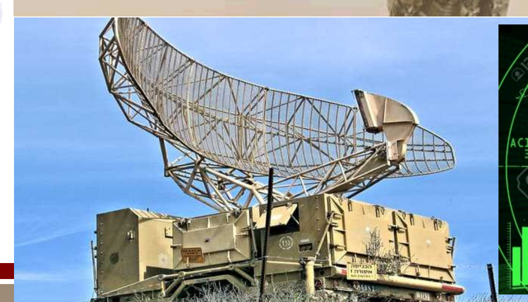


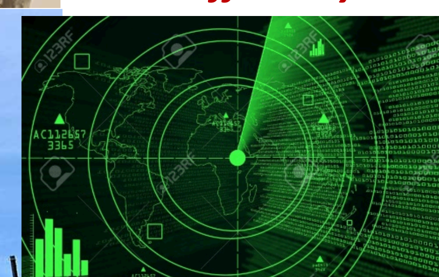


rf Power Applications









UWBG may enable *improved power and efficiency*

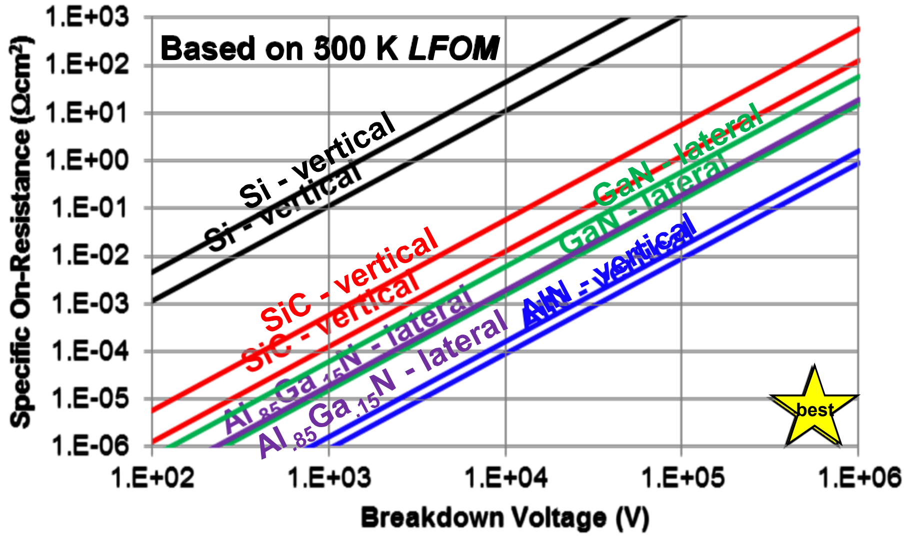
Comparison of Materials Using Lateral Figure of Merit (based on conduction loss)

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

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

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	**1000**	**9.7**	**2.9**	**2.0×10^{12}**	**3.4×10^6**
GaN	**1590**	**9.5**	**3.4**	**1.0×10^{13}**	**3.7×10^6**
$Al_{0.85}Ga_{0.15}N$	**120**	**8.35**	**5.78**	**1.0×10^{13}**	**1.4×10^7**
AlN	**1390**	**8.5**	**6.2**	**1.0×10^{13}**	**1.7×10^7**

Model the Mobility across the AlGaN Composition Range

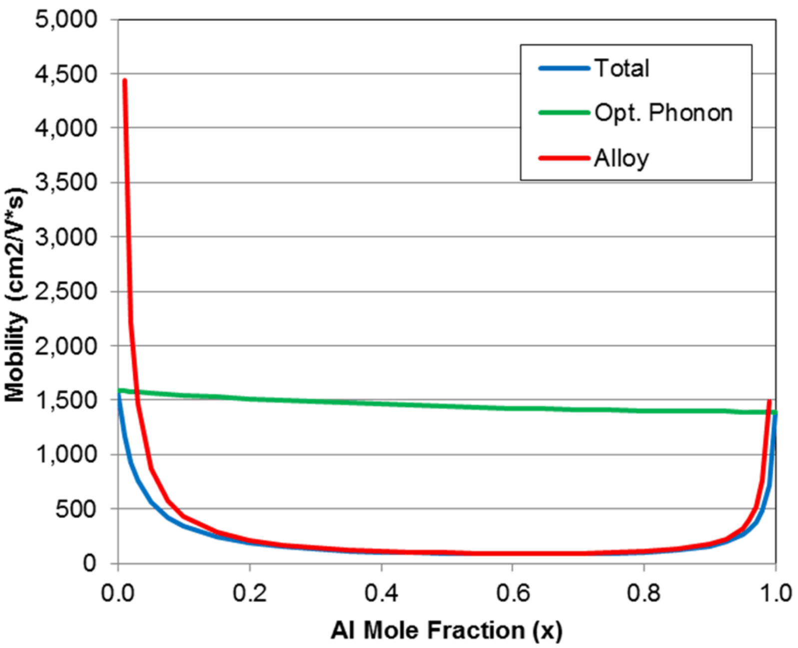
Mobility is related to the average carrier-relaxation time $\langle\tau\rangle$, $\mu = \frac{q\langle\tau\rangle}{m^*}$

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

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

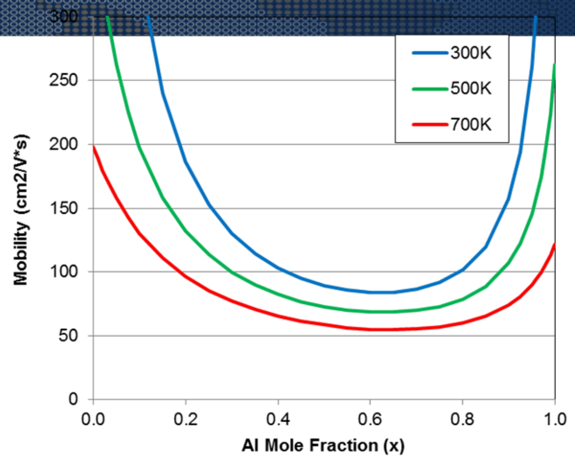
Alloy scattering: $\mu_A = \frac{q\hbar^3}{m_{eff}^2(\Delta V_O)^2\Omega_O x(1-x)} \cdot \frac{16}{3b}$

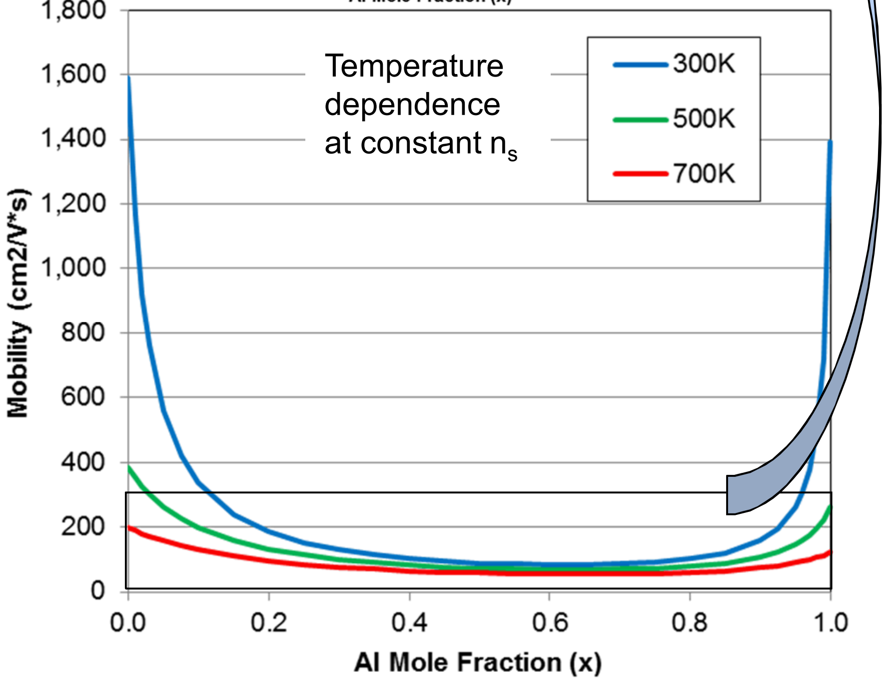
Polar optical phonon scattering: $\mu_{PO} = \frac{2k_O\hbar^2 F\epsilon_O\epsilon_P}{qm_{eff}^2\omega_O N_B(T)G(k_O)}$

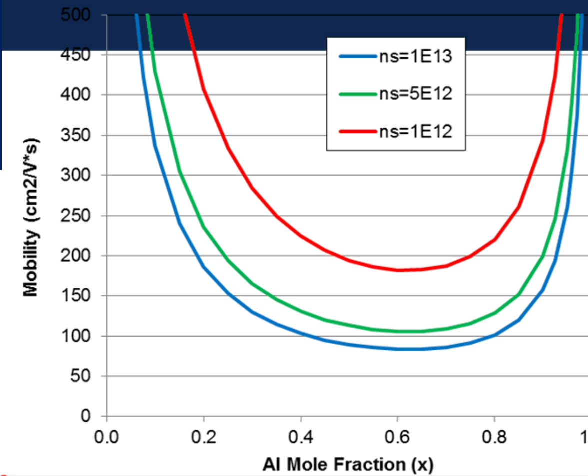


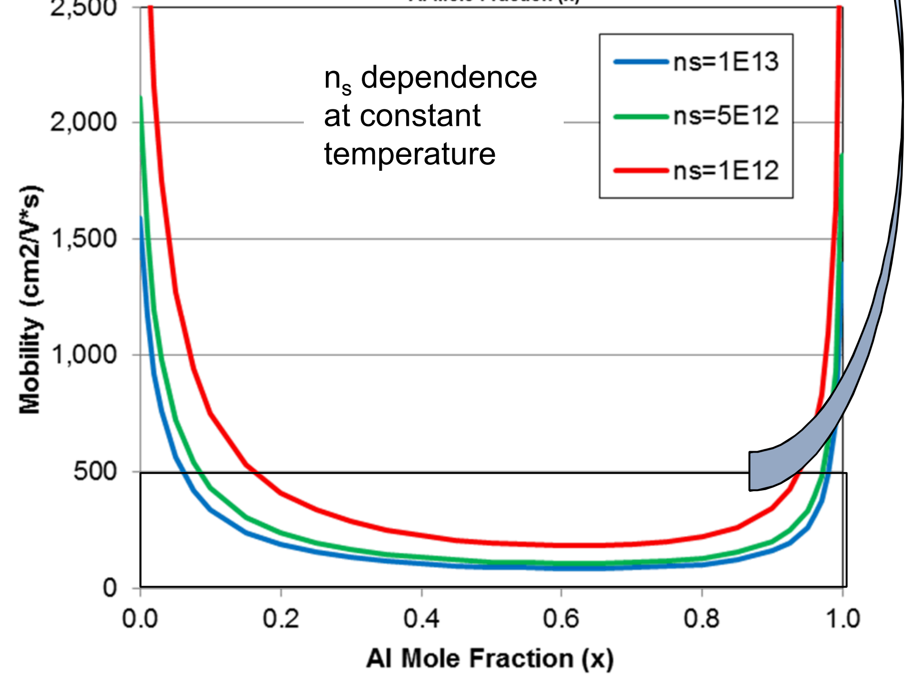
Mobility for AlGaN Alloys

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



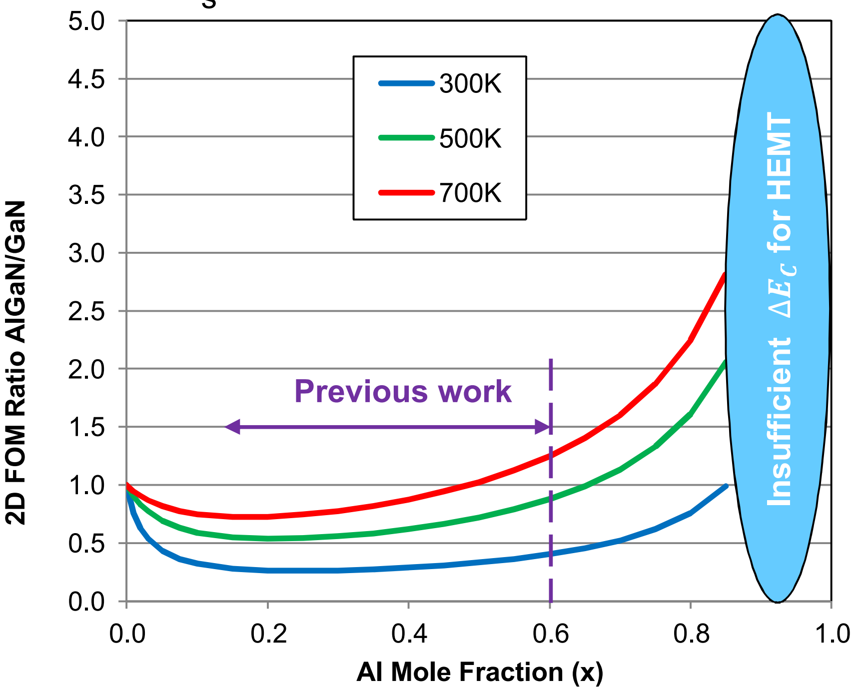




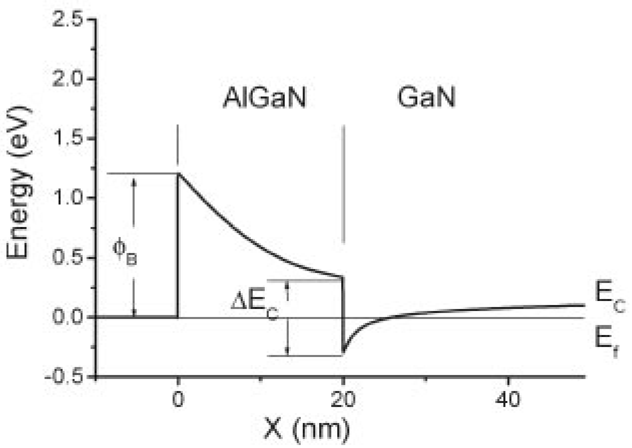


Normalized Lateral Figure of Merit for AlGaN Alloys

n_s=1e13



Constant n_s=1e13 requires a substantial ΔE_C

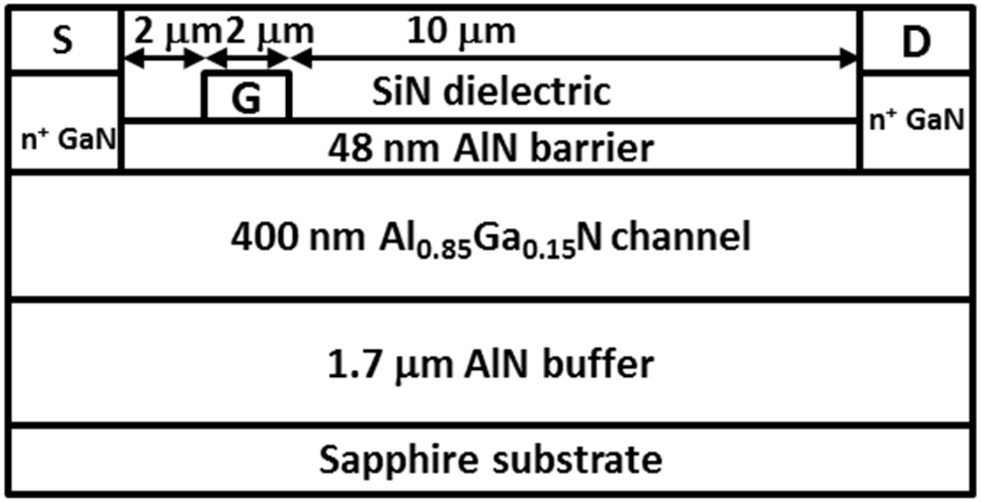


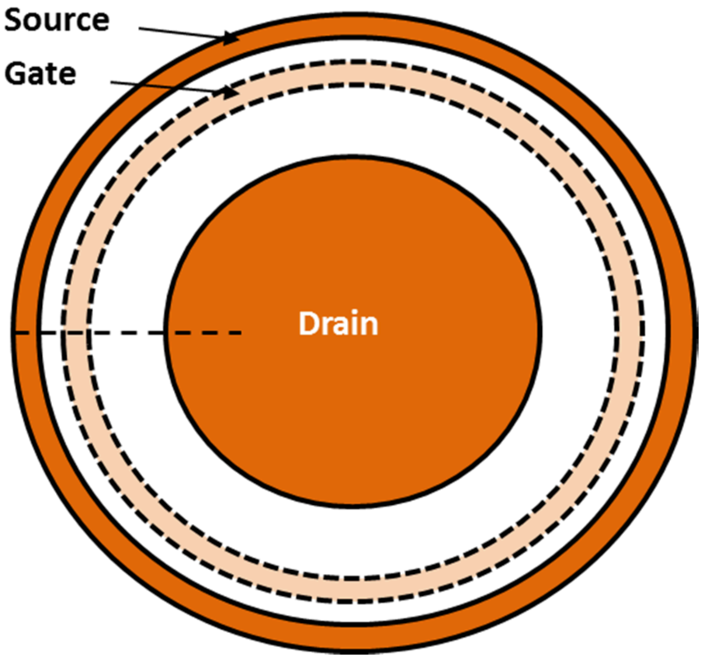
- AlGaN-channel HEMTs offer meaningful LFOM advantage over wide bandgap semiconductors at *elevated temperatures*, but not at room temperature

Largest Bandgap in a Transistor Channel

Material	x =	y =	E_g	citation
$Al_yGa_{1-y}N/Al_xGa_{1-x}N$	.85	1.0	5.84	This presentation and A.G. Baca, A.M. Armstrong, A.A. Allerman, E.A. Douglas, C.A. Sanchez, M.P. King, M.E. Coltrin, T.R. Fortune, and R.J. Kaplar, Appl. Phys. Lett. **109**, 033509 (2016)
$Al_yGa_{1-y}N/Al_xGa_{1-x}N$	.6	1.0	5.23	N. Yafune, S. Hashimoto, K. Akita, Y. Yamamoto, H. Tokuda and M. Kuzuhara, Electron. Lett. **50**, 211 (2014)
β-Ga_2O_3	n/a	n/a	4.3	M. Wong, K. Sasaki, A. Kuramata, S. Yamakoshi, and M. Higashiwaki, Electron. Dev. Lett. **37**, 212 (2016)
Diamond	n/a	n/a	5.5	Promising material, but no transistor

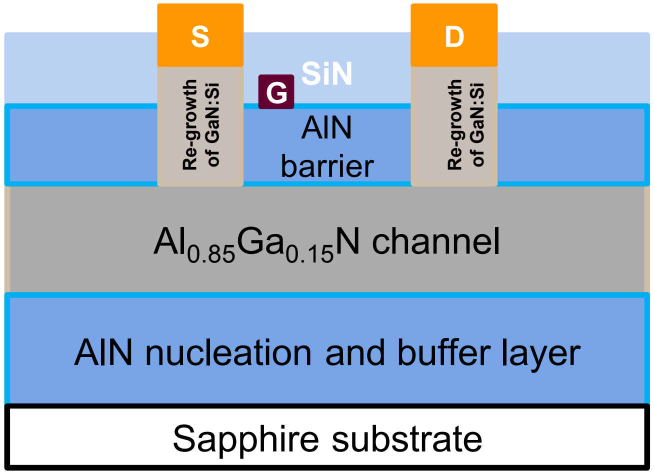
HEMT Structure and Geometry



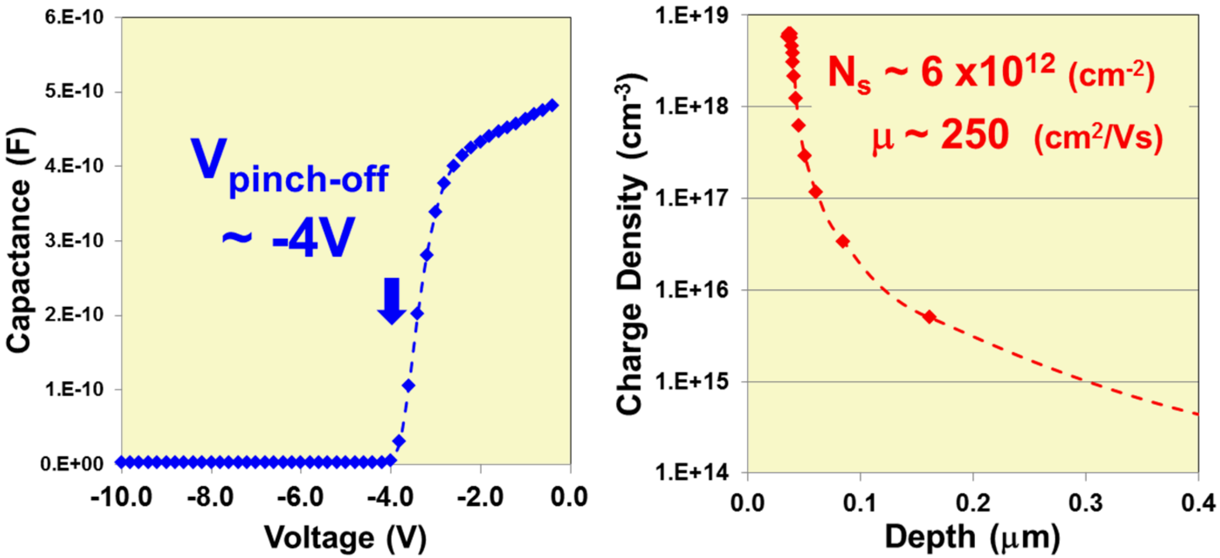


Circular Geometry:
(edge effects unimportant)

HEMT Material Characterization and Fabrication



CV Characterization

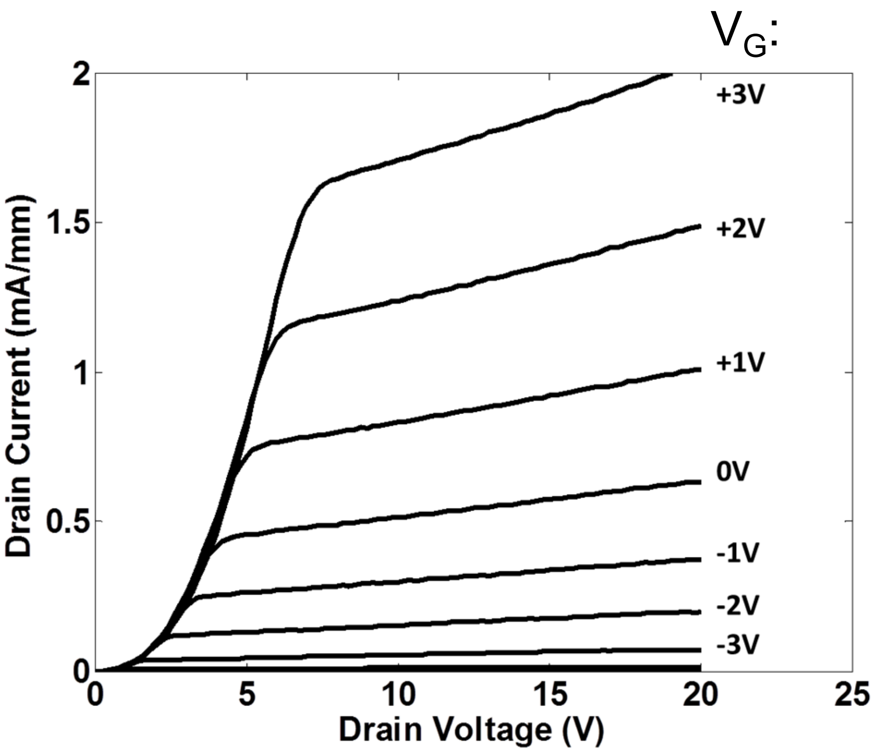


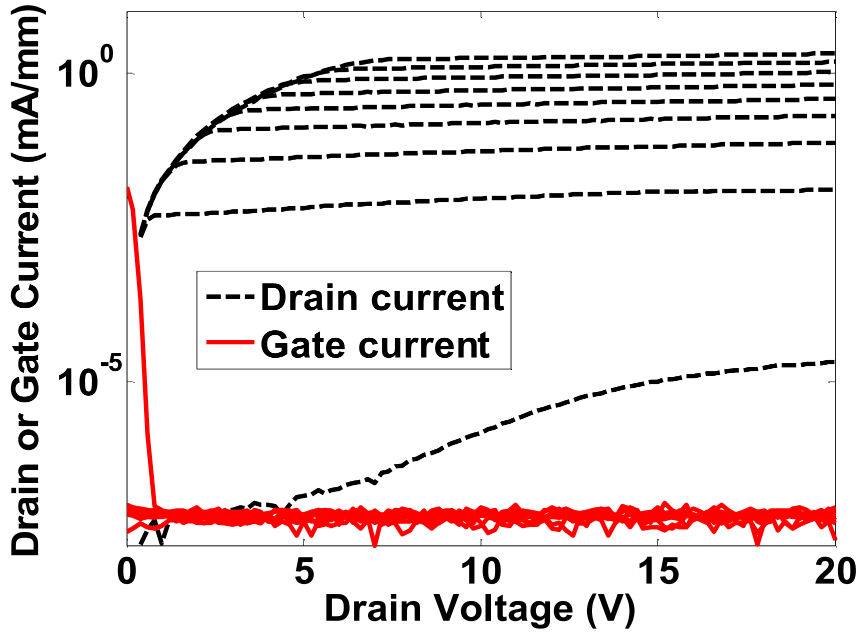
Process Steps:

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)

- **Sheet resistance: 4200 Ω/□**
- **Pinch-off voltage: -4 V**
- **Sheet charge density: 6×10^{12} cm^{-2}**
- **Inferred mobility: 250 cm^2/Vs**

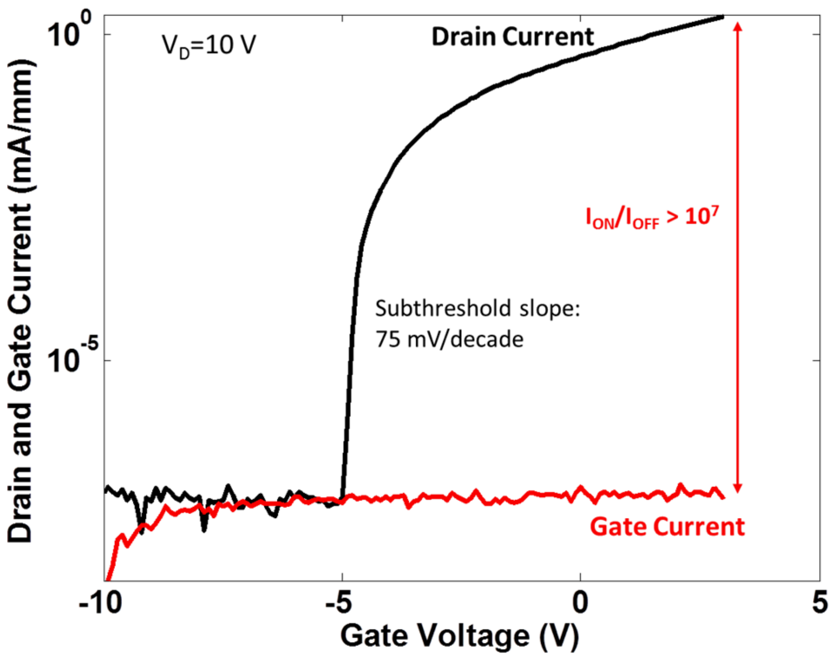
$Al_{0.85}Ga_{0.15}N$-Channel HEMT Shows Good Gate Control

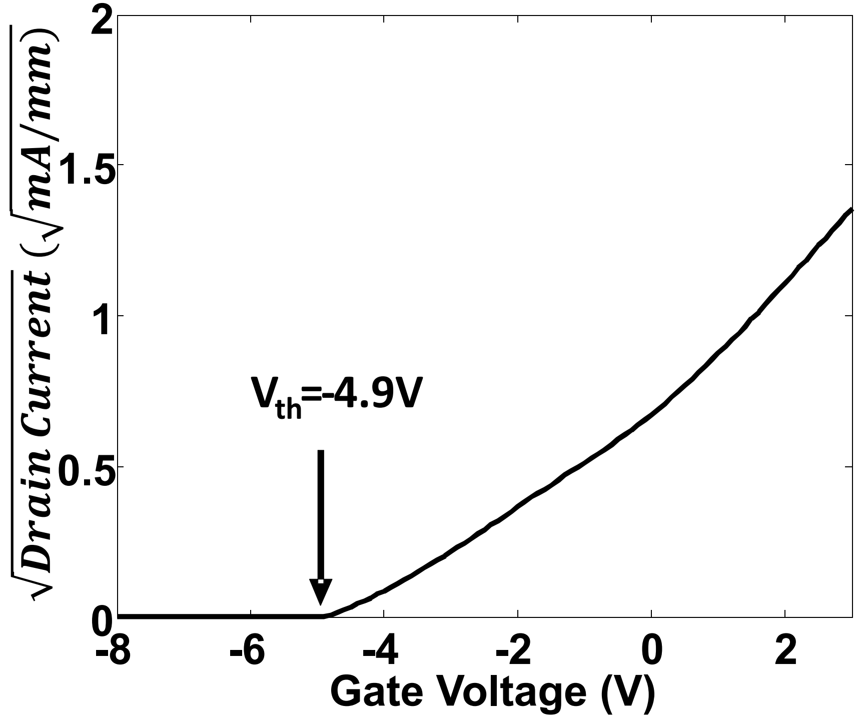




- Operates like Field Effect Transistor
  - Good pinchoff
  - Knee voltage linear with gate voltage
  - Low drain and gate leakage currents
- Not Ideal in some Aspects
  - Hysteresis in forward and reverse Gate sweeps
  - Source and drain contacts more rectifying than Ohmic
  - Large output conductance

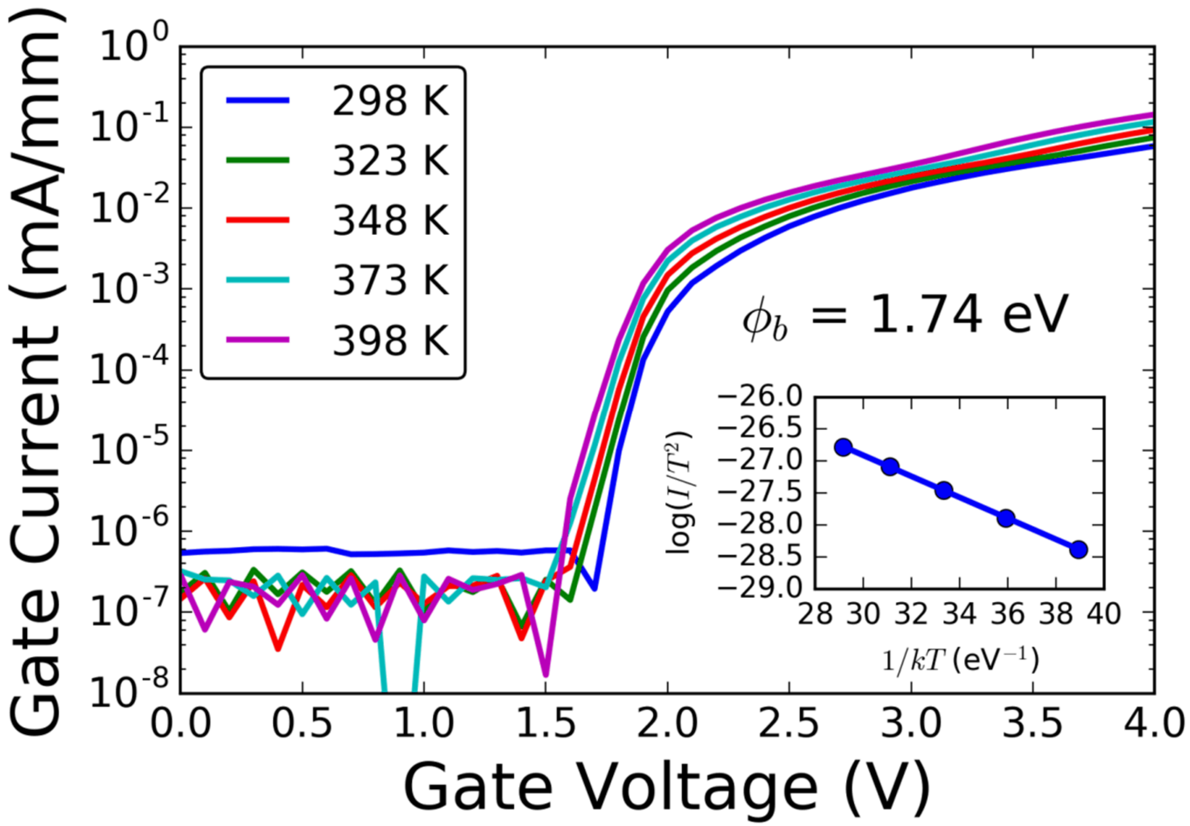
$Al_{0.85}Ga_{0.15}N$-Channel HEMT Shows Excellent Leakage and off-state Characteristics





- 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

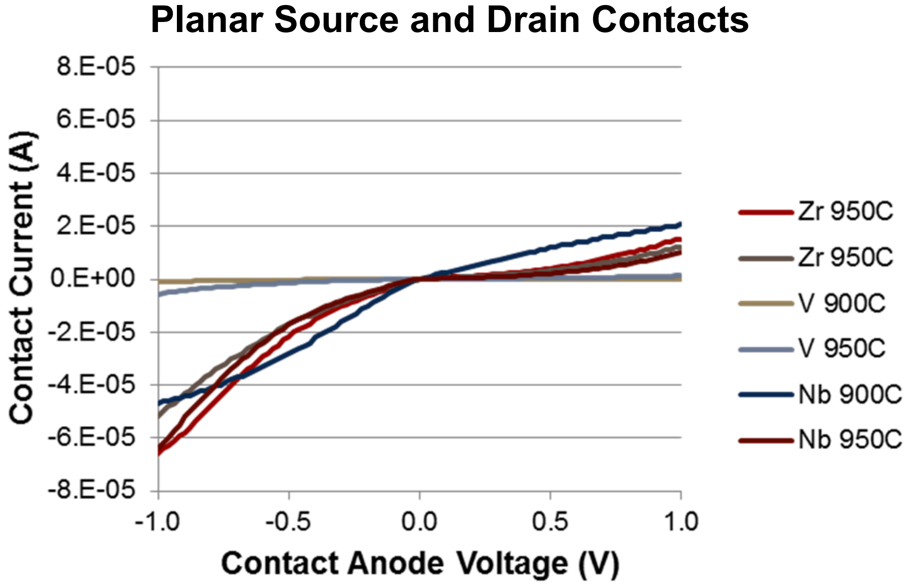


- Using Method in Z. Lin, Appl. Phys. Lett. **82**, 4364 (2003)
- Comparison to Ni/$Al_{0.25}Ga_{0.75}$N/GaN:
    - Φ_b = 0.99 eV (A. C. Schmitz, Semicond. Sci. Technol. **11** (1996) 1464–1467)

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

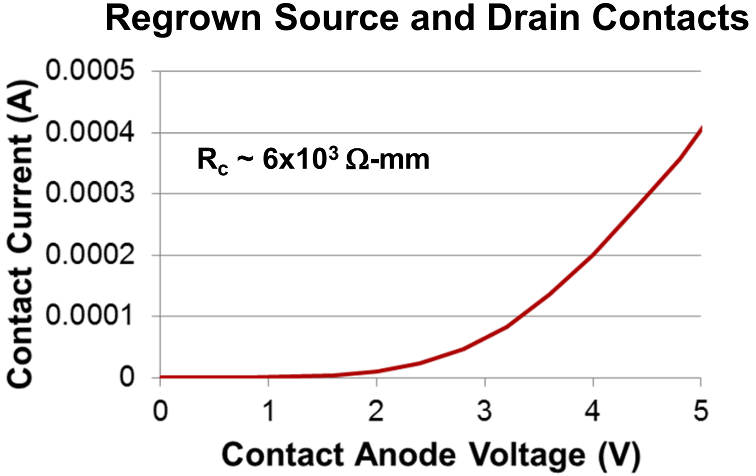
Planar Source and Drain Contacts

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

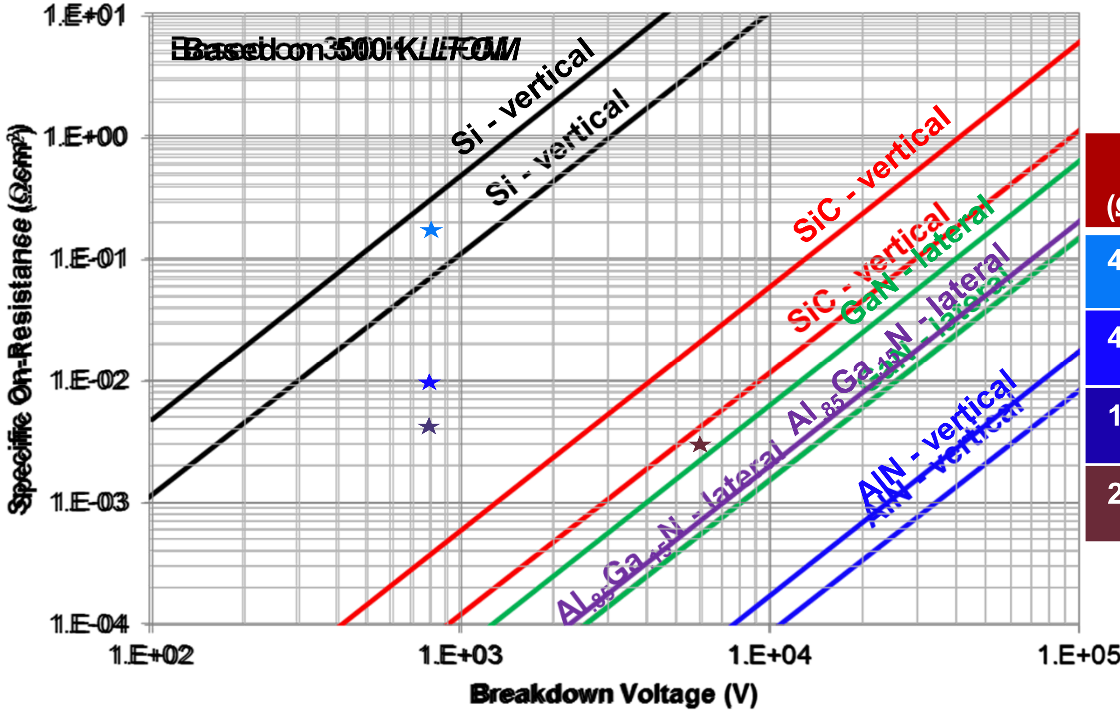


Regrown Source and Drain Contacts

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



Path to the Theoretical Line



ρ_s (Ω/□)	ρ_{ch} (Ω/□)	ρ_c (Ωcm²)	Effective E_{crit}	$R_{on,sp}$ (Ωcm²)	BV (V)
4200	4200	.0245	.06	.16	810
4200	4200	1×10^{-5}	.06	.0095	810
1800	1800	1×10^{-5}	.06	.0043	810
2650	~10^4	1×10^{-5}	.5	.003	5000

- **Don't get to the theoretical line for same reasons GaN won't:**
  - **Not at 100% Effective E_{crit}**
  - ***E-mode* channel has higher ρ_s than material limit**
  - **Contacts have finite size**

★ **Today's HEMT**
★ **Better contacts**
★ **Better epi**

★ **Electric field management, e-mode, aggressive lithography, 500K**

Summary

- Demonstrated the first $AlN/Al_{0.85}Ga_{0.15}N$ HEMT – Highest Bandgap in a Field Effect Transistor Channel
- 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 (and no field plate)
  - Excellent Drain & Gate Leakage Current, On/Off current ratio, and subthreshold Slope (75 mV/decade)
  - Excellent Gate Leakage Current and Φ_b (1.74 eV)
- Modeled Drain Leakage Current with Frenkel-Poole Conduction