SAND2020-10813C

The Outlook for Al-Rich AlGaN Transistors

Albert Baca, Brianna Klein, Andrew Armstrong, Andrew Allerman, Erica Douglas, and Robert Kaplar

Sandia National Laboratories
Albuquerque, NM USA

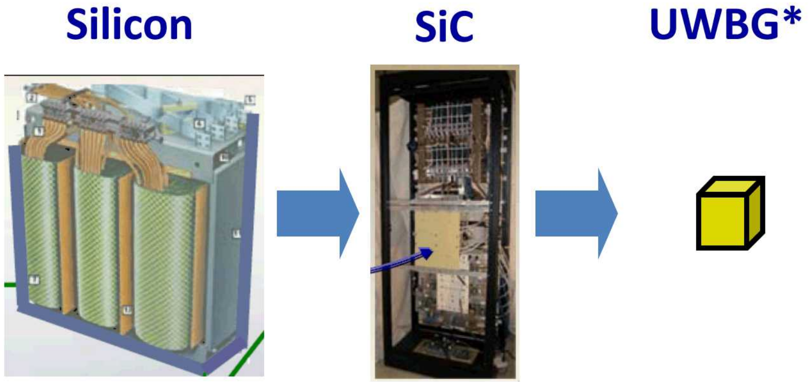
Presented at the Fall 2020 Electrochemical Society Meeting, Virtual, Oct. 2020

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the presentation do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Figure-of-Merit metrics for incumbent and emerging devices
- High current, high voltage devices in Al-rich AlGaN
- RF devices in Al-rich AlGaN
- Extreme temperature operation in Al-rich AlGaN
- Outlook for Al-Rich Transistors
- Summary

Emerging semiconductors for Power Electronics – I



Better Power Transistor Enables higher power and smaller volume

New Use Cases:

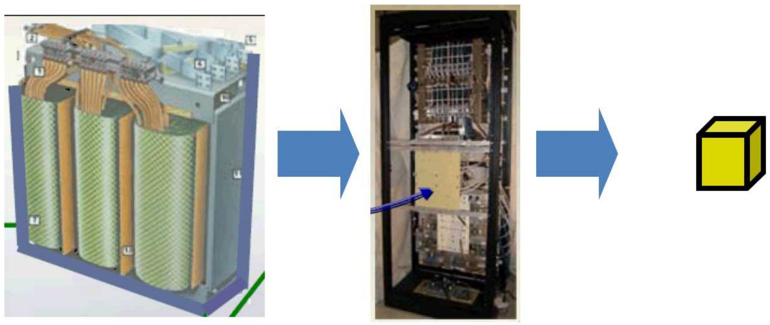
- Electrification of sensors or weapons, propulsion by electrical means, and more
- These applications demand higher power capability in a transistor
- Transistors must operate at higher voltage, power density, SiC or GaN, while managing thermal properties

Both vertical (primarily Si, SiC, but GaN emerging) and lateral (GaN, AlGaN) types of transistors have been investigated

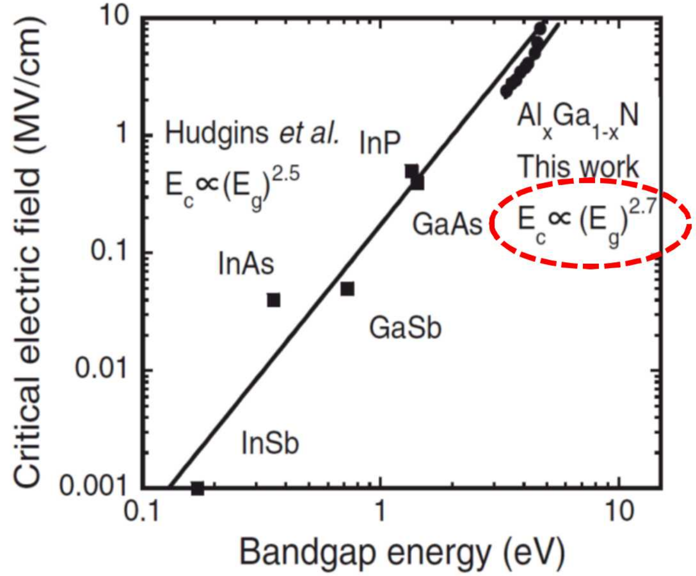
*UWBG refers to the ultra-wide bandgap semiconductors, those with a bandgap > E_G(GaN), 3.4 eV

UWBG semiconductors for Power Electronics – II

Silicon **SiC** **UWBG**



Hudgens *et al*. IEEE Trans. Power Electron. 18, 907 (2003)



Power Density comes with Challenges: Need greater efficiency from transistor, and those associated challenges

Key to a superior transistor is high critical electric field, E_{crit}, which scales exponentially with bandgap, $E_g^{2.7}$

For emerging technologies, we will make transistor comparisons using a conduction-loss based figure of merit

Material	E_{crit} (MV/cm)
Si	0.3
SiC	3.4
GaN	4.0
$Al_{0.3}Ga_{0.7}N$	7.3
β-Ga_2O_3	8
$Al_{0.7}Ga_{0.3}N$	12.7
AlN	17

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Figure-of-Merit metrics for incumbent and emerging devices
- High current, high voltage devices in Al-rich AlGaN
- RF devices in Al-rich AlGaN
- Extreme temperature operation in Al-rich AlGaN
- Outlook for Al-Rich Transistors
- Summary

Figure of Merit Differs for Lateral and Vertical Devices

Baliga FOM (Vertical)

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

Lateral FOM

$$\frac{V_{br}^2}{R_{on,sp}} = q\mu n_s E_{crit}^2$$

FOM derivations in Baca *et al.*, JVST A 38, 020803 (2020).

Basis for FOM: minimal conduction loss and greater voltage capability are good, but the latter requires lower doping and longer drift region, impacting the former

Figures of Merit differ **… *but* they are directly comparable by measuring** V^2/R

$$\frac{1}{4}\varepsilon E_{crit} \text{ compares to } qn_s$$

Vertical & Lateral FOMs can be numerically similar, *e.g. GaN:* depends on numerical values of n_s *and* E_{crit}

Numerical Comparison of GaN Lateral and Vertical Devices

Baliga FOM (Vertical):

$\varepsilon_o\ \varepsilon_r$ = (8.85 x 10^{-14})*(9) F/cm

μ = 1500 cm^2/Vs

Lateral FOM:

μ = 1500 cm^2/Vs

n_s = 1 x 10^{13} cm^{-2}

Both:

E_{crit} = 4 x 10^6 V/cm

$$\frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_{crit}^3 = 2 \times 10^{10}$$

$$\frac{V_{br}^2}{R_{on,sp}} = q\mu n_s E_{crit}^2 = 3.8 \times 10^{10}$$

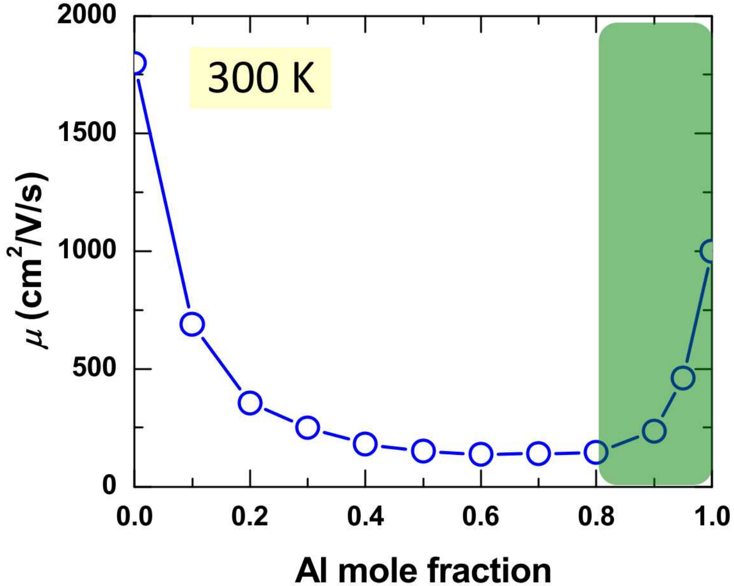
Numerically similar in spite of extra E_{crit} factor in BFOM

Future plots in this presentation show LFOM for (Al)GaN; other technologies show BFOM if the device implementation is a vertical device (Si, SiC) or LFOM if the device implementation is a lateral device (Ga_2O_3)

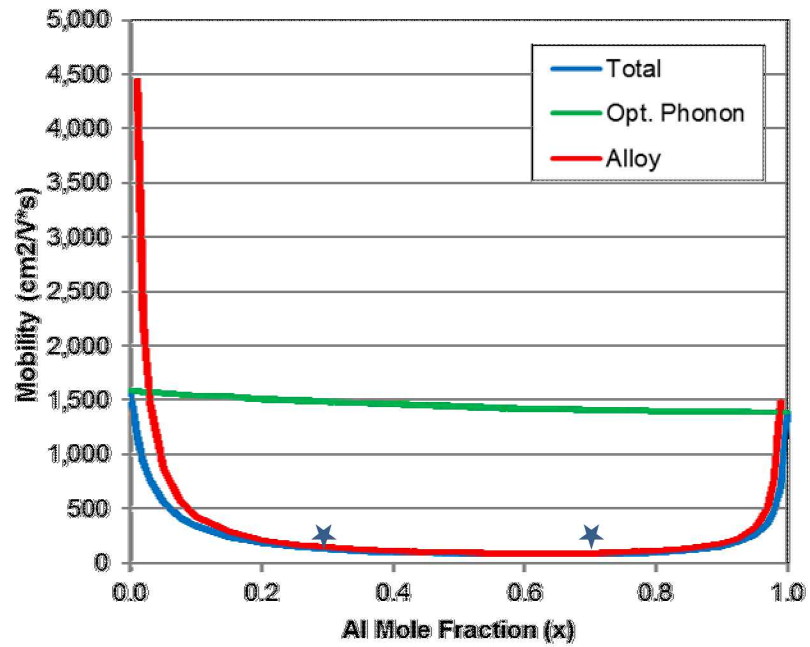
Ability of any device to approach the FOM is important for its maturation

AlGaN Alloy Mobilities are Smaller than Binary Alloys

AlGaN HEMT channel mobility



Bajaj *et al*. APL 105 263503 (2014)



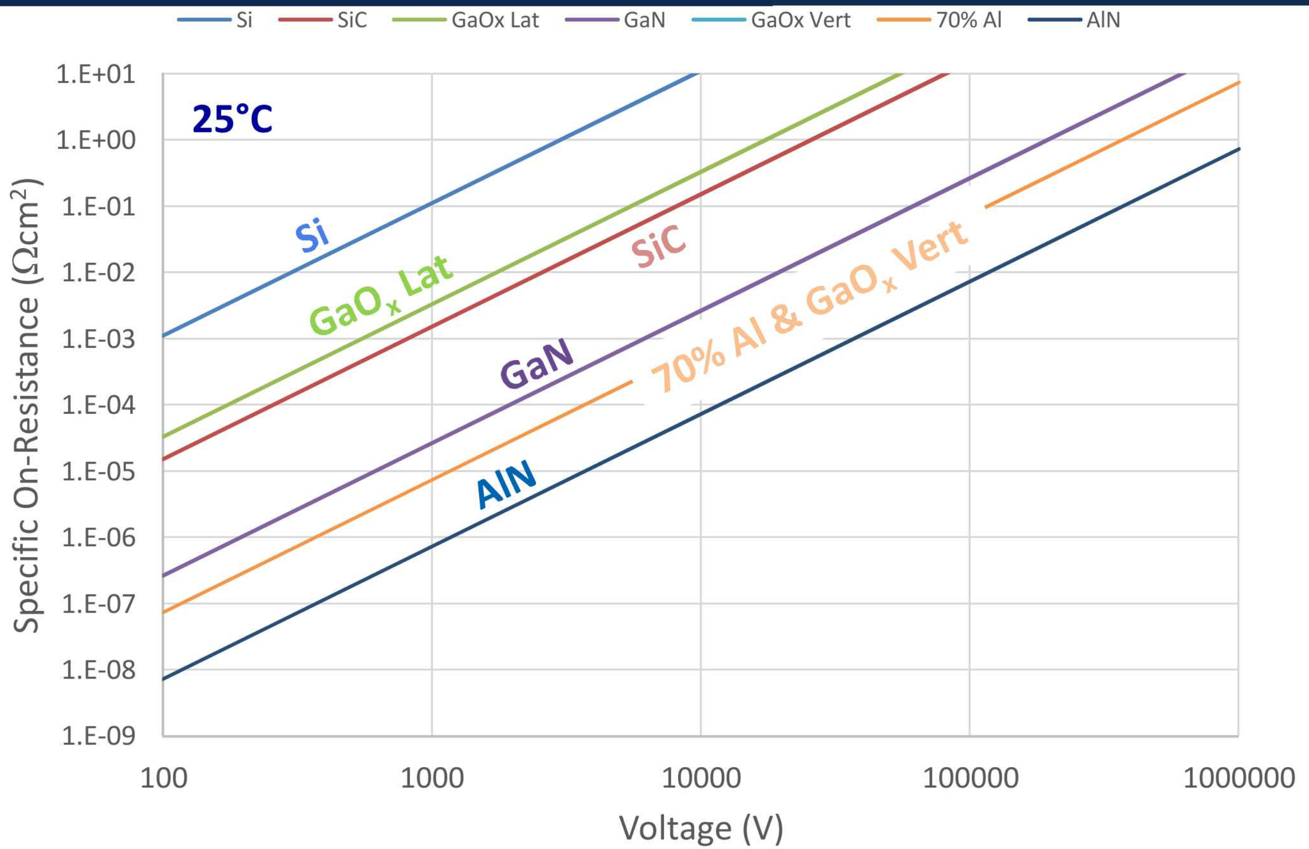
Coltrin *et al.*, JSST 6, S3114 (2017)

$Al_xGa_{1-x}N$ mobility increases markedly at x > 0.9

$Al_xGa_{1-x}N$ mobility is dominated by alloy scattering

Binary alloy mobility drops markedly with temperature, while ternary alloys are less T-dependent, because alloy scattering has a lesser temperature dependence than optical phonon scattering

25°C Figure of Merit for WBG and UWBG Devices

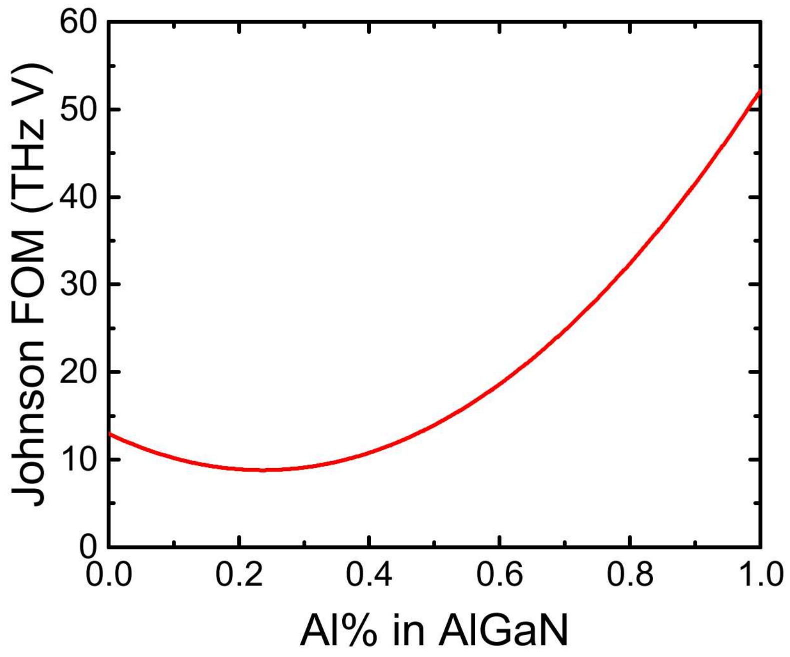


- ***Al-rich AlGaN can be a high performing technology***
- ***Si: incumbent technology; SiC & GaN are well represented in current research***
- ***Ga_2O_3 FOM is marginally competitive as a lateral device – is there a path to vertical?***
- ***Everything beyond SiC and GaN is immature***
  - ***Al-rich lateral devices – this presentation***
  - ***AlN – doping & conductivity issues***

Albert Baca - agbaca@sandia.gov

Johnson FOM (RF)

$$JFOM = V_B f_T = \frac{E_{crit} v_{sat}}{2\pi}$$



- **With parity in v_{sat} (not yet demonstrated), Al-rich AlGaN may exceed AlGaN/GaN in RF performance due to an up to 4x advantage in E_{crit}**
- **A source region of minimal dimensions (due to low mobility) will be required**
- **Ohmic contacts are presently an issue for RF performance**

Research Institutions in $Al_xGa_{1-x}N$ Channel Transistors

High Voltage, High Current Transistors*

- Mitsubishi, 2007-2013
- University of Tokyo Institute of Technology, 2007-2013
- Fukui University, 2010-2014
- Sharp, 2010
- Sumitomo, 2010-2014
- Ohio State University, 2014-
- Sandia, 2016-
- University of South Carolina , 2017-
- University of Florida, 2018-
- Penn State University, 2018-

RF Transistors*

- Ohio State University, 2018-
- University of South Carolina , 2018-
- Sandia, 2019-

A growing group of institutions, often with complementary capabilities

BUT … industry is on the sidelines for now

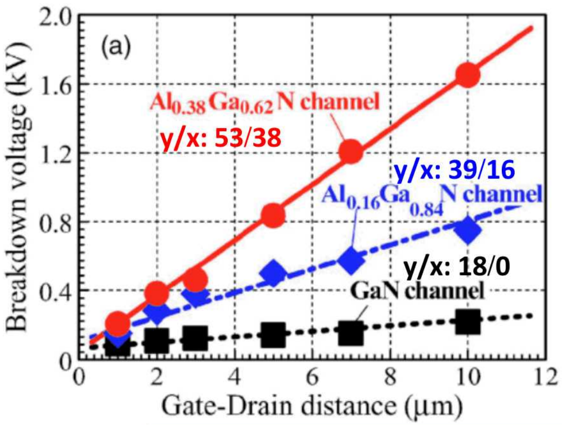
*based on the bibliography compiled for this presentation

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Figure-of-Merit metrics for incumbent and emerging devices
- High current, high voltage devices in Al-rich AlGaN
- RF devices in Al-rich AlGaN
- Extreme temperature operation in Al-rich AlGaN
- Outlook for Al-Rich Transistors
- Summary

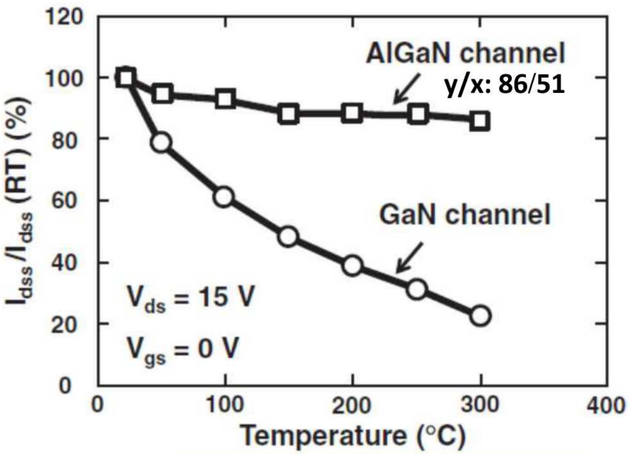
D-mode HEMTs: $Al_yGa_{1-y}N/Al_xGa_{1-x}N$ Heterostructures, y/x

"Remarkable Voltage Enhancement"



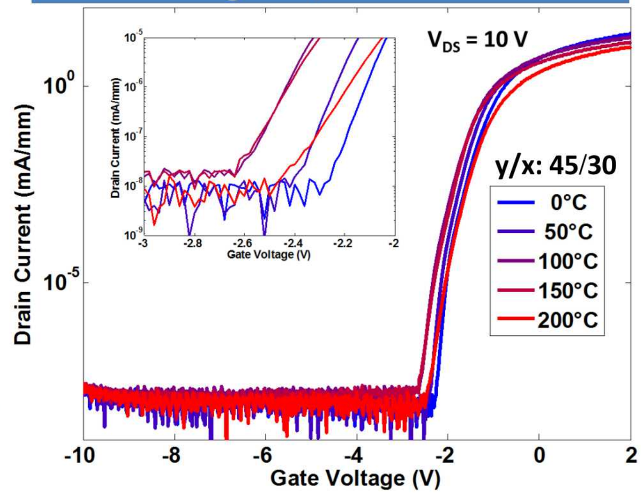
Nanjo *et al*. APL 92, 263502 (2008).

Drain Current vs T



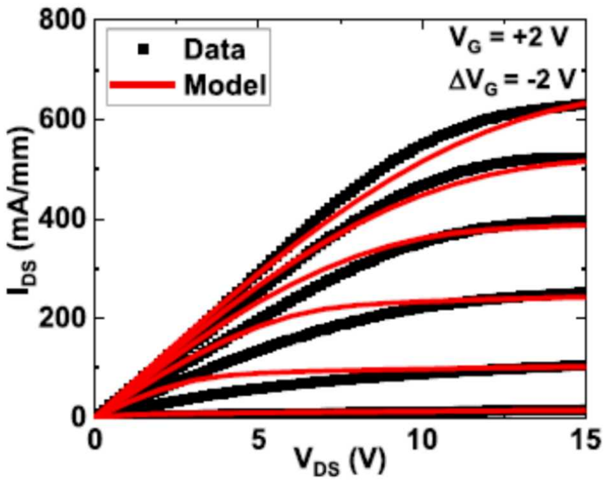
Tokuda *et al*. APE 3, 121003 (2010).

High On/Off Ratio



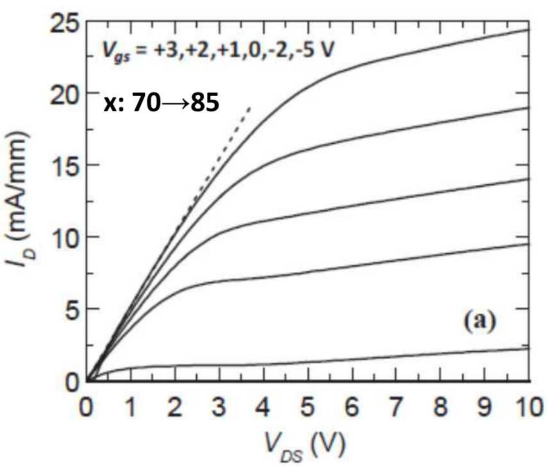
Baca *et al*. JSSST 6, S3010 (2017).

High Current Density



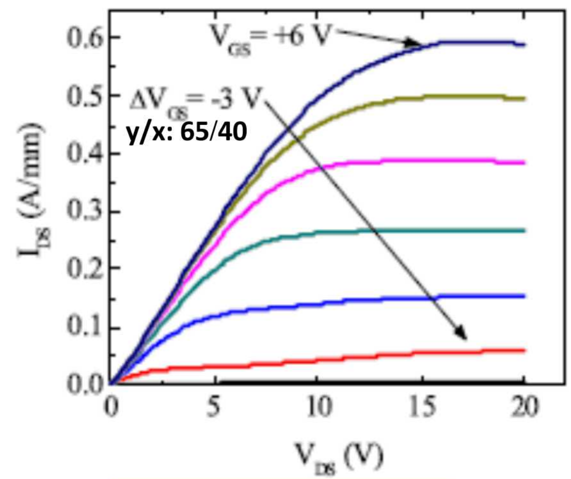
Xue *et al*. APL 115, 043502 (2019).

Polarization Doping "PolFET"



Armstrong *et al*. JJAP 57, 074103 (2018).

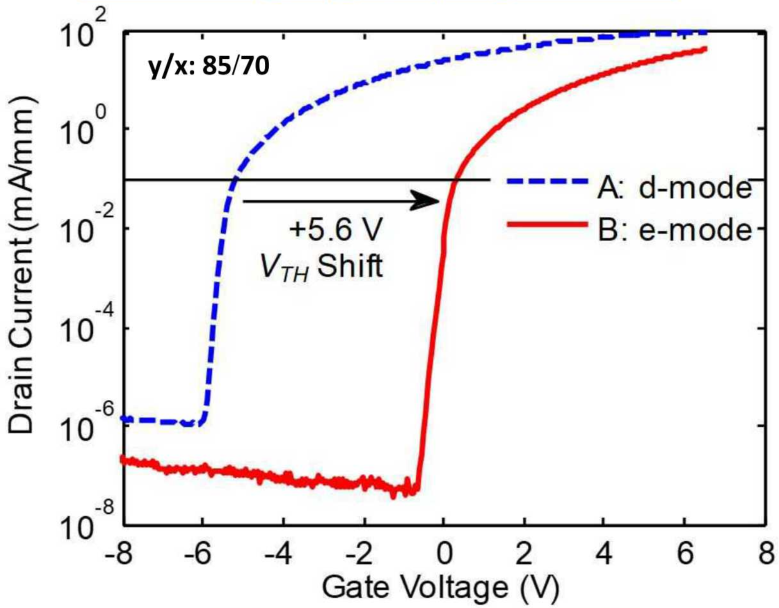
MOSHFET



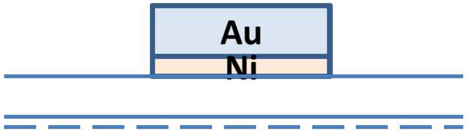
Hu *et al*. EDL 39, 1568 (2018).

Enhancement-mode HEMTs

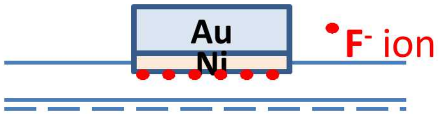
F-RIE Treatment with $Al_{.85}Ga_{.15}N/Al_{.7}Ga_{.3}N$



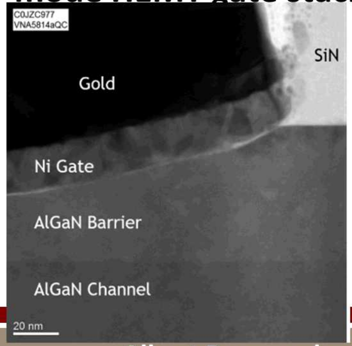
Klein *et al*. APL 114, 112104 (2019).



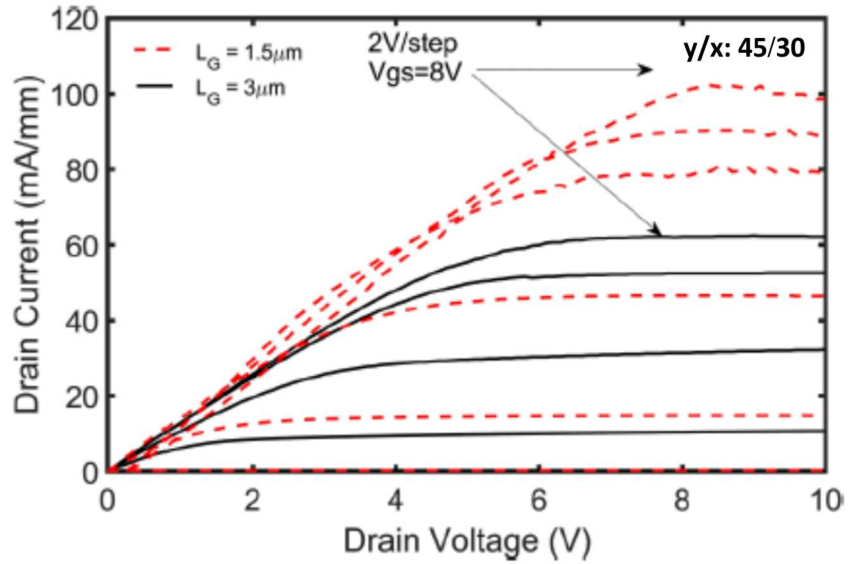
D-mode HEMT gate stack



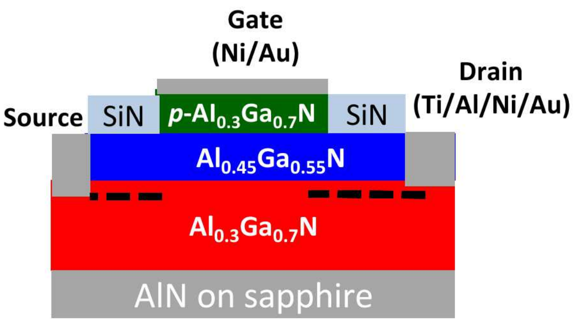
D-mode HEMT gate stack



p+ gate (p- $Al_{.45}Ga_{.55}N$) with $Al_{.45}Ga_{.55}N/Al_{.3}Ga_{.7}N$



Douglas *et al*. JVST B 37, 021208 (2019).



Breakdown-Voltage in AlGaN Channel HEMTs

Al% x or y/x or x→y	Device Type	Break-down voltage (V)	L_G (μm)	L_{GD} (μm)	Break-down field (MV/cm)	Reference
53/38	HEMT	1650	1	10	1.65	Nanjo, 2008
53/38	HEMT	463	1	3	1.54	Nanjo, 2008
39/16	HEMT	> 350	1	2	> 1.75	Nanjo, 2008
86/51	HEMT	1800	9	15	1.2	Tokuda, 2010
40/15	HEMT	1700	1	10	1.7	Nanjo, 2013
70	MOSFET, Al_2O_3	620	1	1.7	3.65	Bajaj, 2018
70	MOSFET, Al_2O_3	224	0.7	1.1	2.04	Bajaj, 2016
85/70	HEMT	510	2	4	1.28	Baca, 2017-2
85/70	HEMT	495	2	2.0	2.48	Baca, 2019
85→70	PolFET	554	2	3.2	1.73	Armstrong, 2018
100→60	PolFET	620	2	3.0	2.07	Armstrong, 2019

AlGaN/GaN HEMTs: 1 MV/cm is a typical breakdown field (average)

AlGaN channel transistors: multiple reports showing greater than 1 MV/cm

Bodes well for AlGaN channel transistors

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Figure-of-Merit metrics for incumbent and emerging devices
- High current, high voltage devices in Al-rich AlGaN
- RF devices in Al-rich AlGaN
- Extreme temperature operation in Al-rich AlGaN
- Outlook for Al-Rich Transistors
- Summary

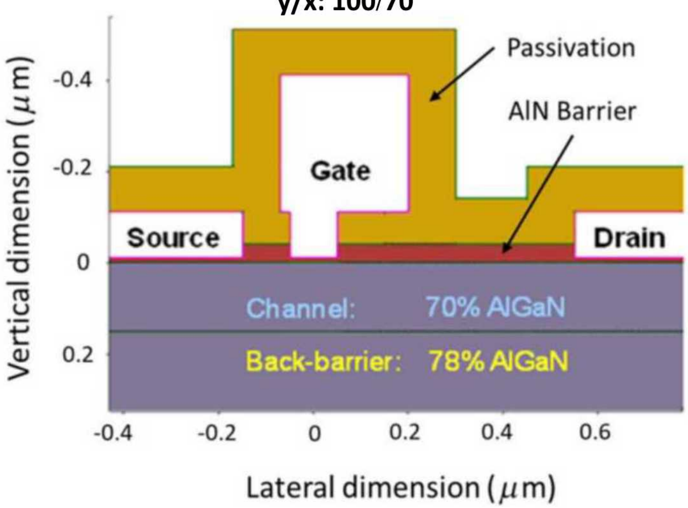
Al-Rich AlGaN Transistor: RF Comparisons

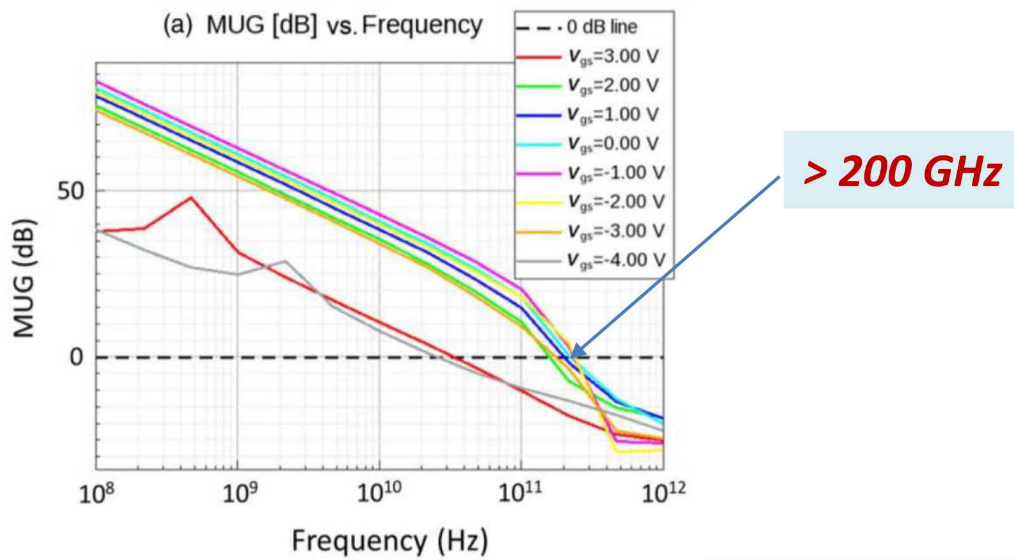
Al% y/x or x or x→y	Tran-sistor Type	f_T (GHz)	f_{MAX} (GHz)	I_{MAX} (mA/mm)	V_D (@I)	V_G (@I)	L_G (mm)	L_{SD} (mm)	r_c ($W\cdot cm^2$)	I_{ON}/I_{OFF}	Freq. (GHz)	P_{MAX} (W/mm)	PAE (%)	Ref.
82→65	PolFET	5.4	14.2	265	20	2	.8	3.7	-	10^3	-	-	-	Razzak, 2018
.7	MES-FET	8.8	24	440	15	0	.25	1.3	~ 10^{-4}	10^6	-	-	-	Hu, 2018
85/70	HEMT	28.4	18.5	160	10	10	.08	2.6	~ .01	10^9	3	.38	11	Baca, 2019
75/60	HEMT	40	56	460	10	2	.13	1.2	~ 10^{-4}	10^4	10	1.8	22	Xue, 2019

These are the initial RF reports: f_{max} approaching 60 GHz, L_{SD} approaching 1 μm

Improvement in Ohmic contacts are needed to push to the next level of performance

Simulations can estimate the true potential of the technology



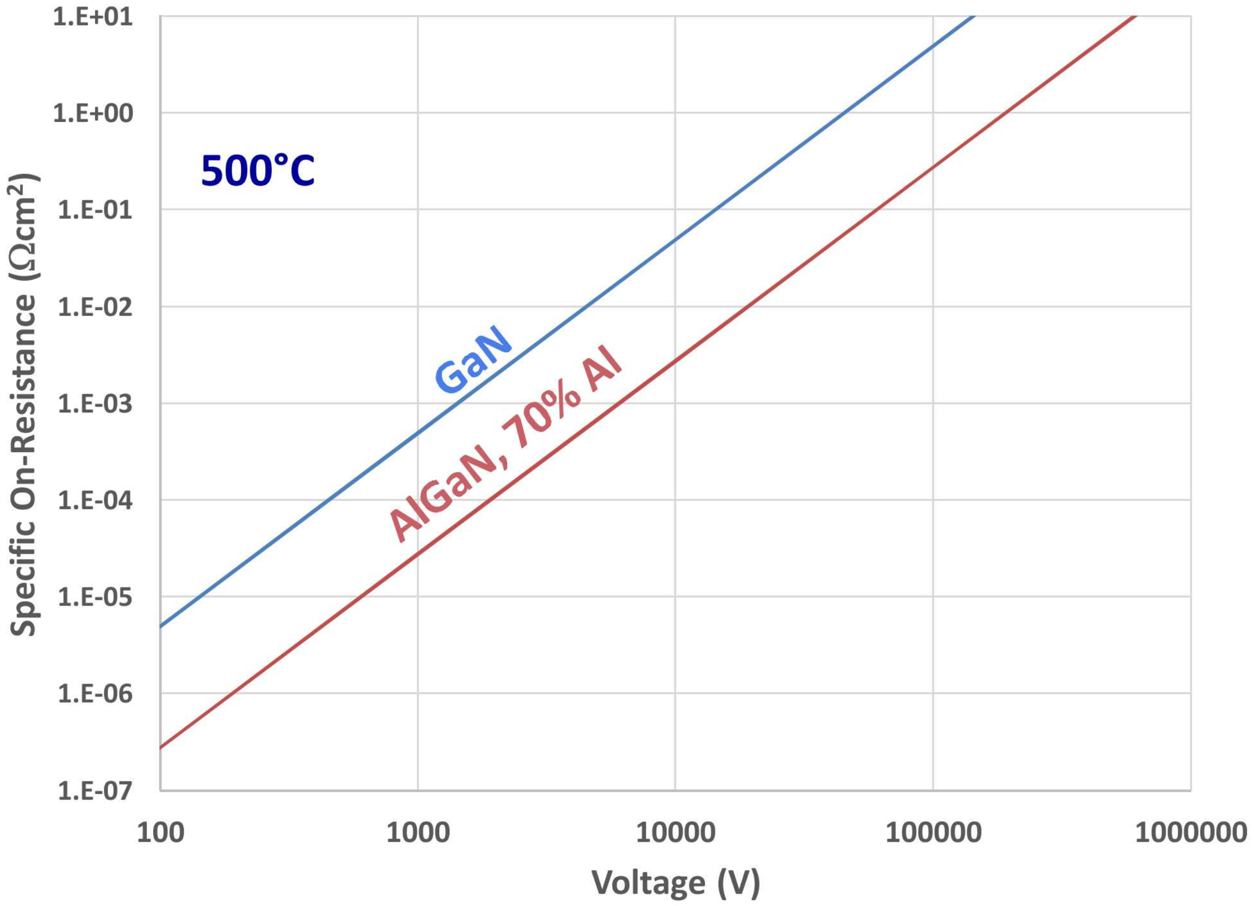


Reza *et al*. JJAP 58, 19 (2019).

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Figure-of-Merit metrics for incumbent and emerging devices
- High current, high voltage devices in Al-rich AlGaN
- RF devices in Al-rich AlGaN
- Extreme temperature operation in Al-rich AlGaN
- Outlook for Al-Rich Transistors
- Summary

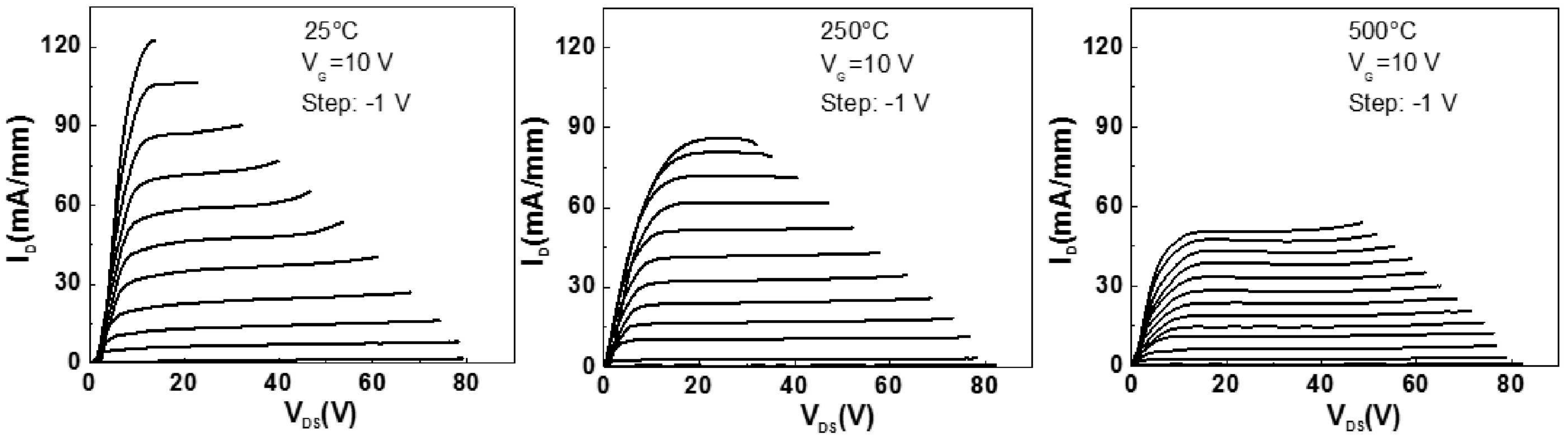
Extreme Temperature Figure of Merit for GaN & 70% AlGaN



FOM for Al-rich HEMT is 16x superior to that for GaN at 500°C

Later in the presentation, we'll show that GaN may lack a true off-state characteristic at 500°C

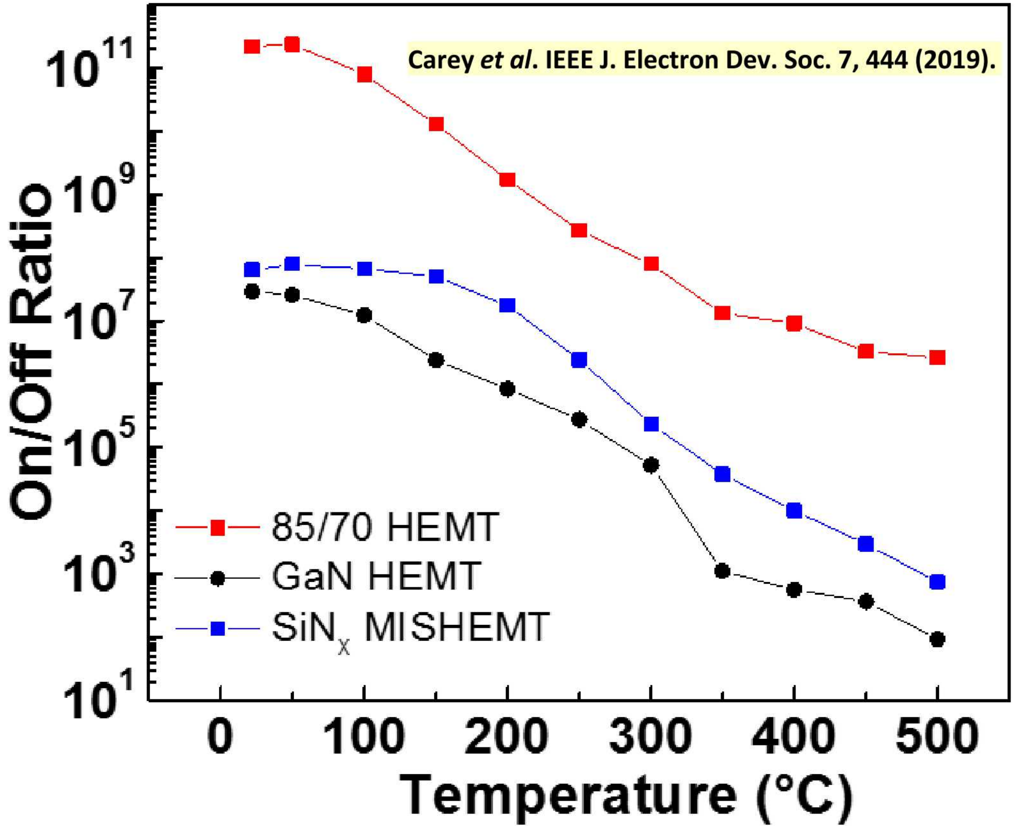
Extreme Temperature Operation of D-mode "85/70" HEMT



Carey *et al*. IEEE J. Electron Dev. Soc. 7 444 (2019).

Retain excellent current modulation and over 50 mA/mm current density across the entire temperature range 25 - 500°C

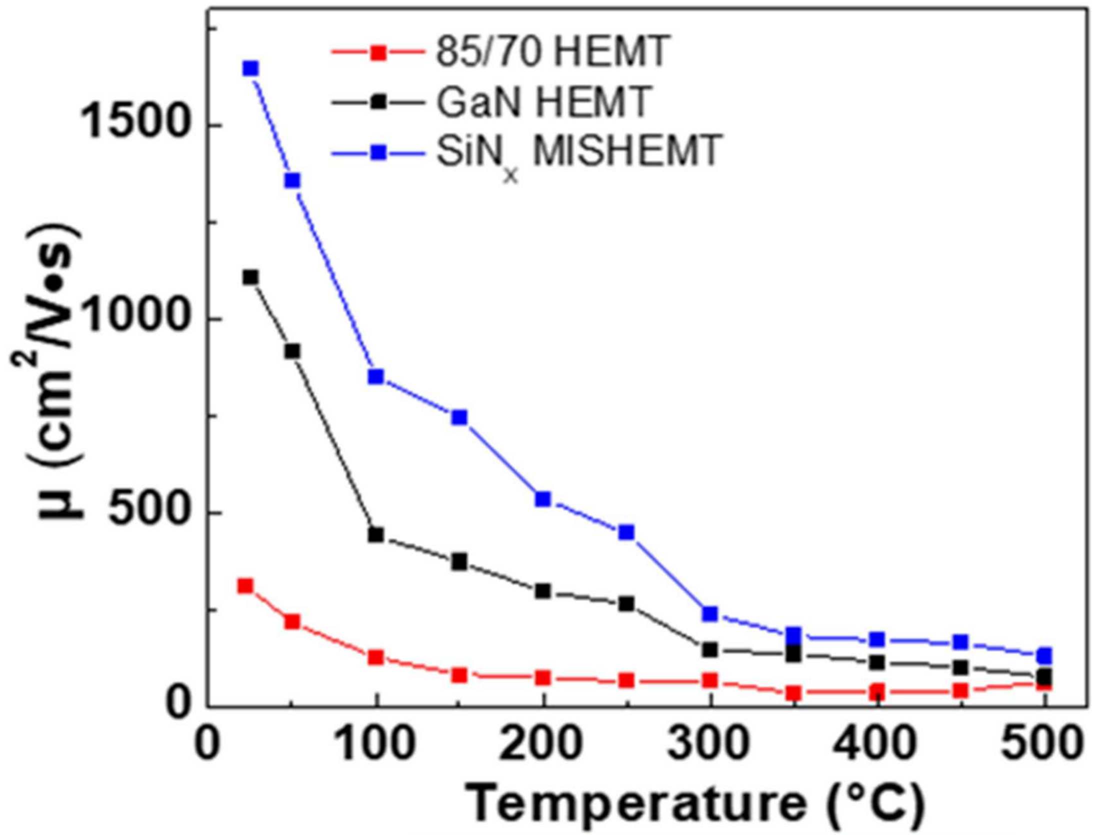
On/Off Ratio of D-mode "85/70" HEMT is Favorable at Extreme Temperature Operation



The Al-rich HEMT maintains an excellent I_{On}/I_{Off} ratio at 500°C and GaN doesn't

A low leakage OFF-state capability is extremely difficult at these temperatures in any technology, but looks viable in AlGaN technology – how much higher can they operate?

Mobility Trend over wide Temperature Range in (Al)GaN-channel HEMT



Carey *et al*. IEEE J. Electron Dev. Soc. 7, 444 (2019).

500°C: Mobility for Al-rich HEMT reaches near parity with GaN HEMT

500°C: Mobility is fairly flat from 200-500°C suggests relaxed cooling requirement for Al-rich transistors

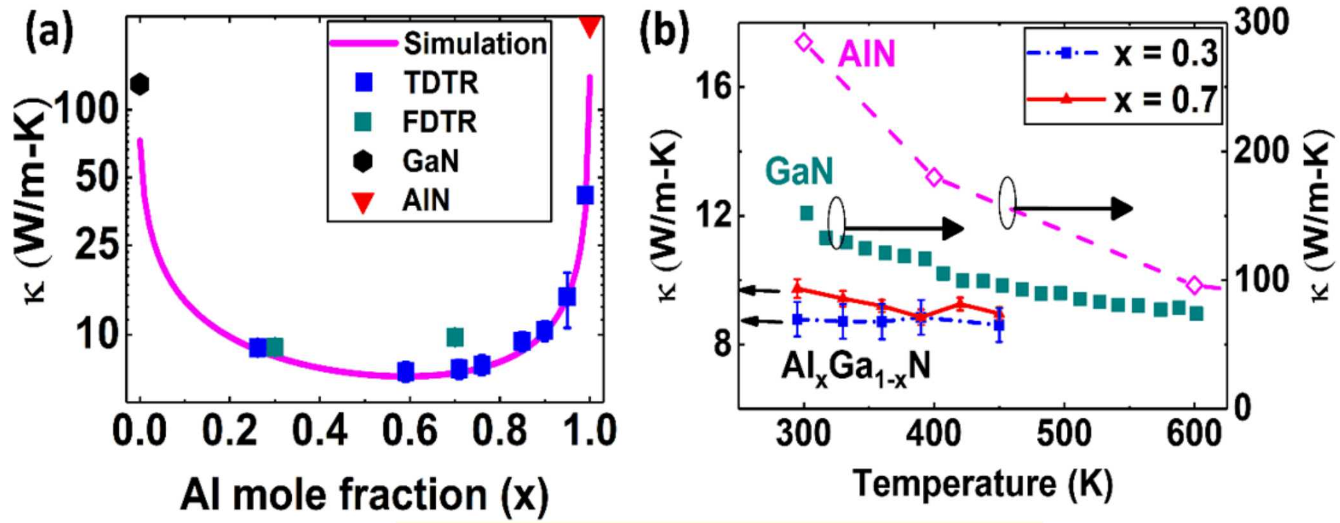
Compilation of Temperature Characterization in D-mode HEMTs

(Al%) y/x	Temperature range (°C)	I_{ON}/I_{OFF} change	Saturation current change	Reference
25/0	25 to 300		61% reduction	Hatano, 2010
51/24	25 to 300		37% reduction	Hatano, 2010
45/30	-50 to 200	$10^8 \rightarrow 10^8$	63% reduction	Baca, 2017-1
65/40	25 to 250	$5x10^7 \rightarrow 5x10^4$	~25% reduction	Hu, 2018
85/70	25 to 500	$> 2x10^{11} \rightarrow 3x10^6$	58% reduction	Carey, 2019
85/70	-50 to 200	$8x10^9 \rightarrow 5x10^7$	17% reduction	Baca, 2017-2
86/51	25 to 300		20% reduction	Tokuda, 2010
100/60	25 to 300		5% increase	Armstrong, 2019

Al-rich transistors: Multiple reports show excellent high temperature I_{ON}/I_{OFF} ratio

$I_D(T)$: Some reports show Al-rich transistors with moderated $I_D(T)$ compared to AlGaN/GaN

Thermal Conductivity *vs* T is Relatively Invariant



Chattergee *et al*. IEEE Electron Dev. Lett. 41 46 (2020).

Gaps exist above 450K (180°C), but thermal conductivity, $\kappa(Al_xGa_{1-x}N)$, appears temperature invariant – thermal management may not worsen at extreme temperature in contrast to GaN

Outline

- Motivation for Ultra-wide Bandgap AlGaN electronic devices
- Figure-of-Merit metrics for incumbent and emerging devices
- High current, high voltage devices in Al-rich AlGaN
- RF devices in Al-rich AlGaN
- Extreme temperature operation in Al-rich AlGaN
- Outlook for Al-Rich Transistors
- Summary

Challenges – Mobility

Detractors will not consider AlGaN transistors because of its low mobility, *BUT* …

The FOM is attractive for Al-content greater than 70% in power switching and for Al-content greater than 50% in RF

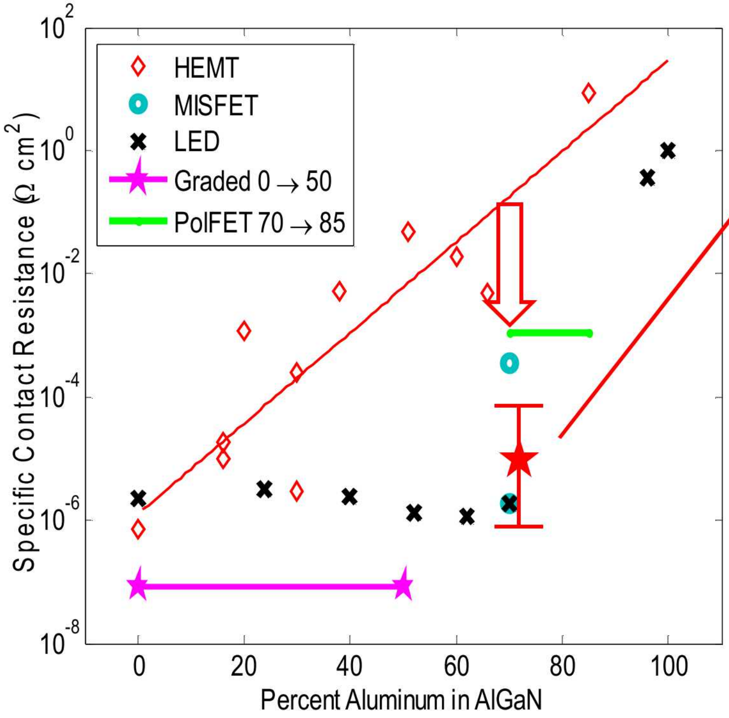
In RF applications, the effects of mobility are minimized by aggressively reducing the source-gate spacing in Al-rich transistors

In RF applications, the RF loadline is improved because knee-voltage is a smaller percentage of the breakdown voltage for Al-rich transistors

In spite of low mobility, Al-rich transistor may have low hanging fruit in “rugged” applications, such as extreme temperatures where other transistors struggle

Challenges – Ohmic Contacts

How will $Al_xGa_{1-x}N$ ever have good Ohmic contacts as x => 1?



A complex process integration with MBE-grown contacts and MOCVD grown heterostructures for a HEMT 2-DEG* has had mixed success but can be expected to improve over time

Bajaj *et al*. Appl. Phys. Lett. 109, 133508 (2016).

Xue *et al*. Appl. Phys. Lett. 115, 043502 (2019).

More innovation in Ohmic contacts is needed

*2-DEG, 2-dimensional electron gas

Challenges

- Ohmic contacts
- Substrates
- Dielectrics for high breakdown

Research is Advancing Along Many Fronts

- Transient characterization of AlGaN transistors
- F-ion stability in e-mode transistors
- Dimensional scaling of transistors
- Radiation performance of AlGaN transistors

Bibliography

Armstrong *et al*., Jap. J. Appl. Phys. 57, 074103 (2018).
Armstrong *et al*., Appl. Phys. Lett. 115, 052103 (2019).
Baca *et al*., ECS J. Solid-State Sci. Technol. 6, S3010 (2017).
Baca *et al*., ECS J. Solid-State Sci. Technol. 6, Q161 (2017).
Baca *et al.*, IEEE Electron Device Lett. 40, 17 (2019).
Baca *et al.*, JVST A 38, 020803 (2020).
Bajaj *et al*., Appl. Phys. Lett. 105, 263503 (2014).
Bajaj *et al*., Appl. Phys. Lett. 109, 263503 (2016).
Bajaj *et al*., IEEE Electron Device Lett. 39, 256 (2018).
Chattergee *et al*., IEEE Electron Dev. Lett. 41, 46 (2020).
Carey *et al*., IEEE J. Electron Dev. Soc. 7, 444 (2019).
Coltrin *et al.,* ECS J. Solid-State Sci. Technol. 6, S3114 (2017)
Douglas *et al*., J. Vac. Sci. Technol. B 37, 021208 (2019).
Hatano et al., CSMANTECH, 101 (2010).
Hudgens *et al*. IEEE Trans. Power Electron. 18, 907 (2003)
Hu *et al*., IEEE Electron Device Lett. 39, 1568 (2018).
Klein *et al*., Appl. Phys. Lett. 114, 112104 (2019).
Nanjo *et al*., Appl. Phys. Lett. 92, 263502 (2008).
Nanjo *et al*., IEEE Trans. Electron Dev. 60, 1046 (2013).
Reza *et al*., Jap. J. Appl. Phys. 58, 19 (2019).
Tokuda *et al*., Appl. Phys. Expr. 3, 121003 (2010).
Xue *et al*., Appl. Phys. Lett. 115, 043502 (2019).

Summary

- We can expect continued progress and increasing opportunities in Al-Rich tansistors
- Figures-of-Merit analysis suggests the payoff is appropriately large
- Research is advancing along many fronts
- Assuming a true need exists, extreme temperature operation is very exciting because demonstrating good transistor characteristics at > 500°C is non trivial
- Many obstacles are in the way and continued R&D is expected to address these