Wafer-scale GaN HEMT Performance Enhancement by Diamond Substrate Integration

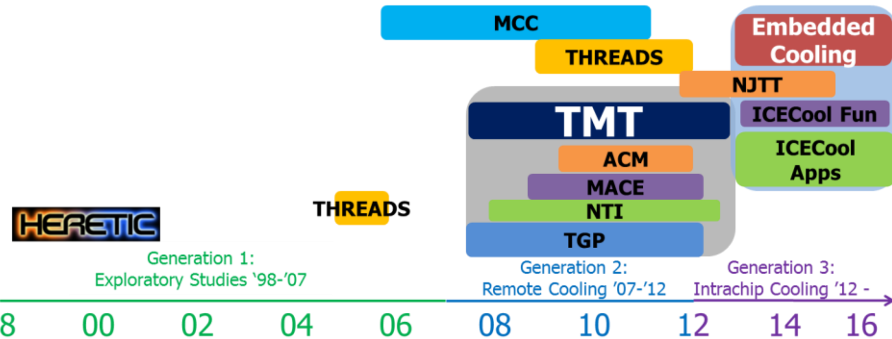
G.D. Via[1], J.G. Felbinger[2], J. Blevins[1], K. Chabak[1], G. Jessen[1],
J. Gillespie[1], R. Fitch[1], A. Crespo[1], K. Sutherlin[1],
B. Poling[3], S. Tetlak[3], R. Gilbert[3], T. Cooper[3],
R. Baranyai[4], J.W. Pomeroy[4], M. Kuball[4],
J.J. Maurer[2], A. Bar-Cohen[5]

[1] Air Force Research Laboratory, Dayton, OH
[2] Booz Allen Hamilton, Arlington, VA
[3] Wyle Labs, Dayton, OH
[4] Bristol University, Bristol, UK
[5] Defense Advanced Research Projects Agency, Arlington, VA

Briefing prepared for ICNS-10
August 27, 2013

The views, opinions, and/or findings contained in this article/presentation are those of the author/presenter and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.

Background



Heat Removal by Thermo-Integrated Circuits (HERETIC)

- 1998: DARPA PM Towe
- 2001: DARPA PM Radack
- 2002: HERETIC ends

Technologies for Heat Removal in Electronics at the Device Scale (THREADS)

- 2005-2006: DARPA PM Rosker
- 2009-2013: DARPA PM Albrecht

Micro Cryo Coolers (MCC)

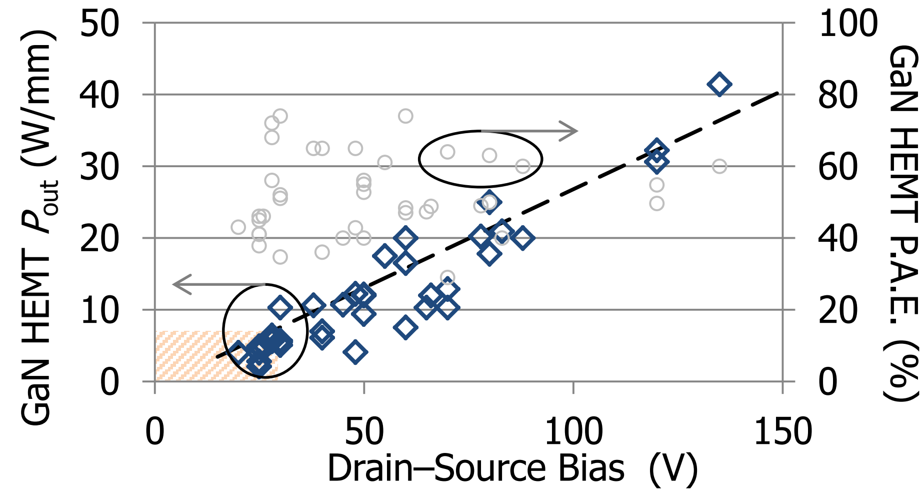
- 2006-2011: DARPA PM Dennis Polla

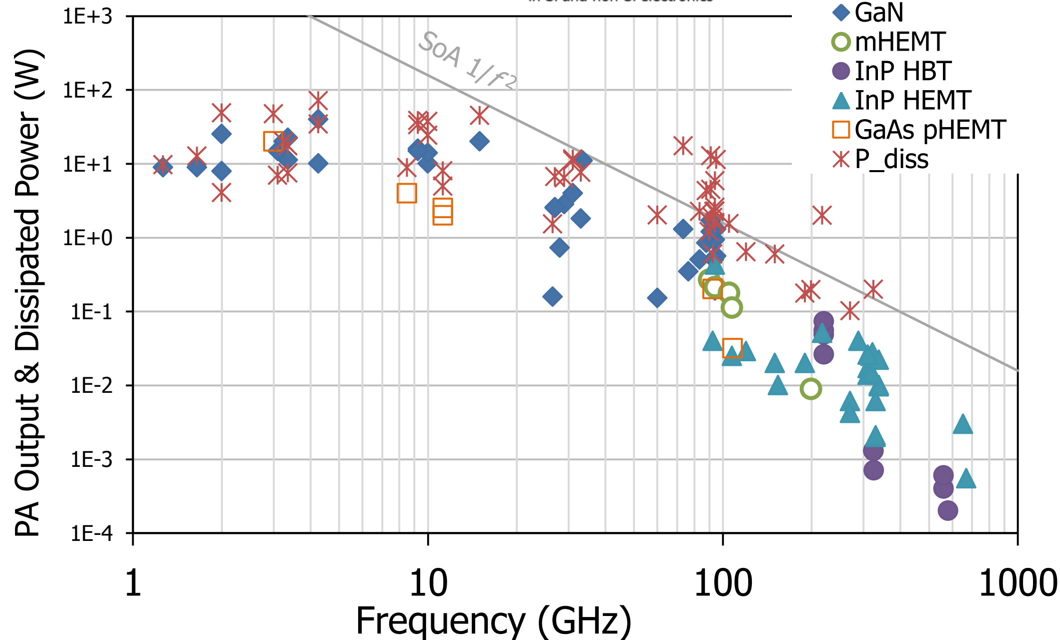
Thermal Management Technologies (TMT)

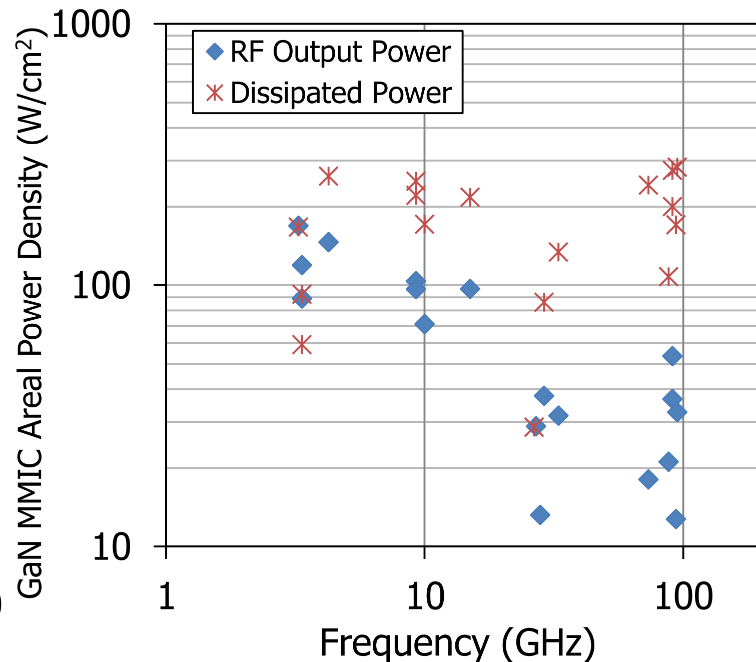
- 2007-2010: DARPA PM Kenny
- 2010-present: DARPA PM Bar-Cohen

Embedded Cooling (NJTT and ICECool)

- 2011 - 2015: DARPA PM Bar-Cohen
- NJTT and ICECool explore novel, disruptive, chip/package level – embedded - thermal technologies in Si and non-Si electronics

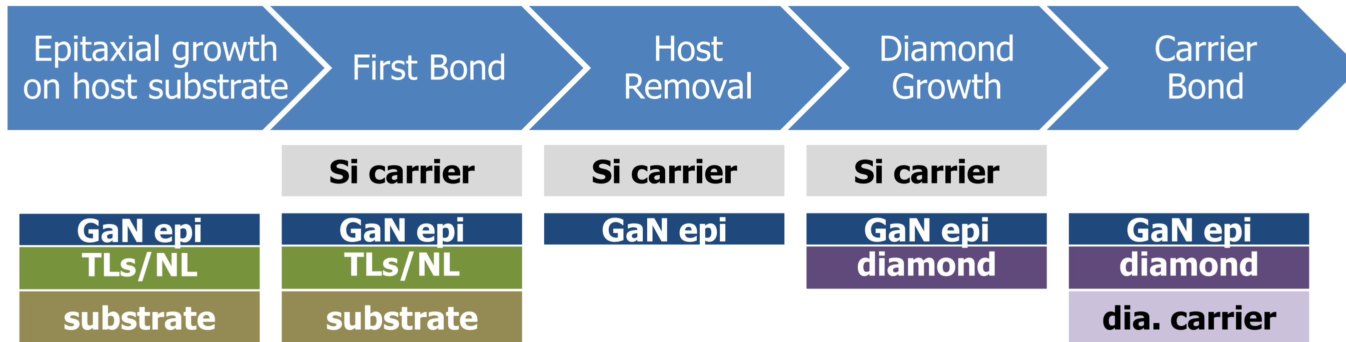




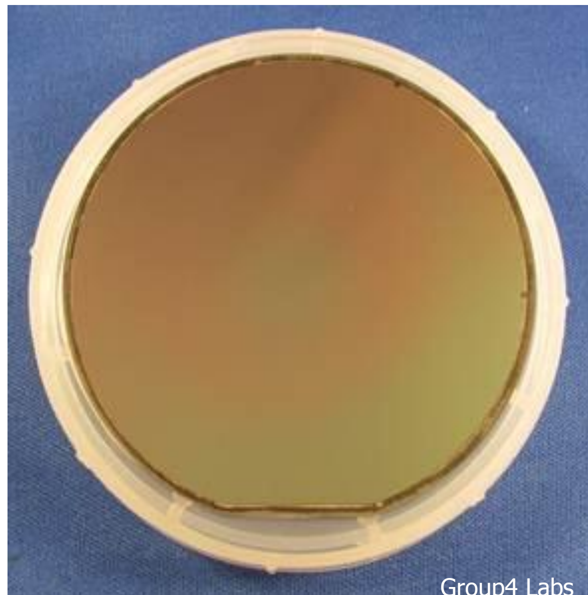


Distribution Statement A, Approved For Public Release, Distribution Unlimited

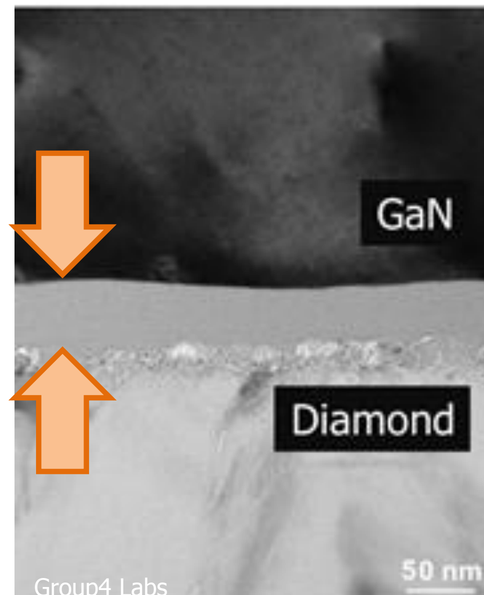
GaN-on-diamond Wafer Development

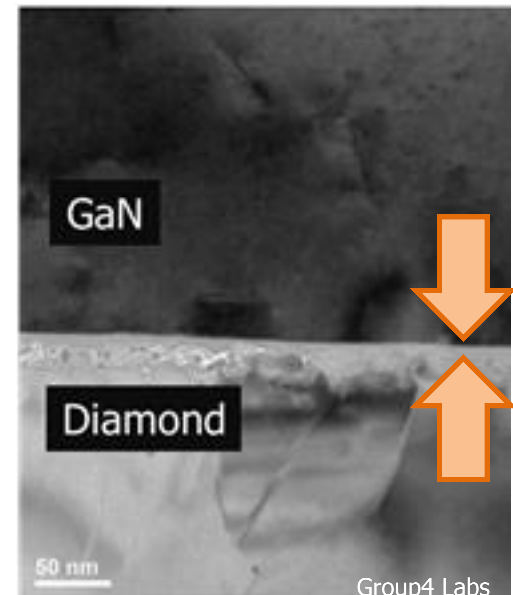


4" freestanding AlGaN/GaN-on-diamond from a Si substrate with optimized dielectric layer



Reduced dielectric layer thickness (7× shown) to achieve TBR consistent with 3× power handling at similar channel temperature





Distribution Statement A, Approved For Public Release, Distribution Unlimited

Objective

- Compare AlGaN/GaN/Si and AlGaN/GaN/Diamond device performance using nominally the same epitaxy and same device geometry
  - Materials characterization
  - PCM, DC, transient, small signal, large signal analysis
  - Thermal evaluation

Thickness	Composition
25 Å	GaN cap
200 Å	$Al_{0.26}Ga_{0.74}N$ barrier
0.8 μm	GaN buffer (thinned)
550 Å	Proprietary dielectric
116 μm	CVD diamond

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Fabrication Process Flow

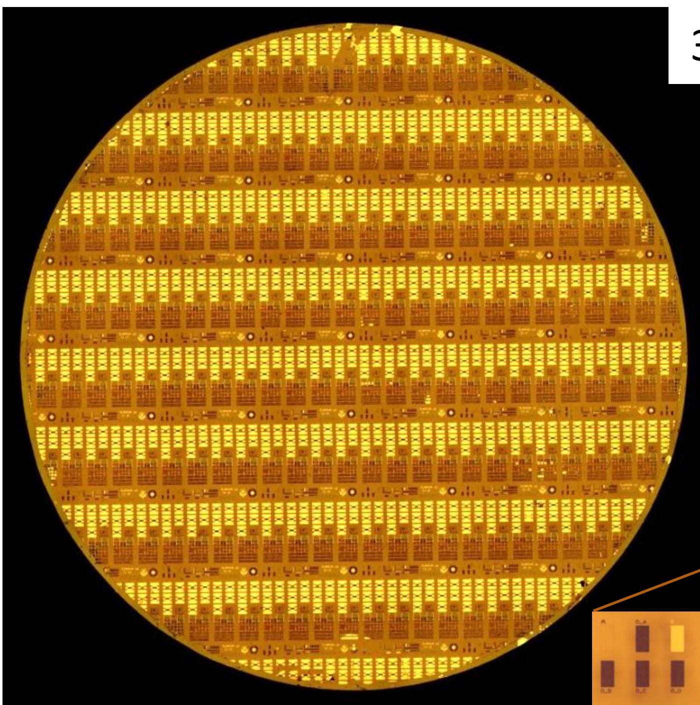
		G437C Diamond	G439C Si
Surface clean	Etch off protective Si_3N_4 layer; 7-min 49% HF, wait 24 hrs	X	
Mesa	Cl-based ICP etch ~80-nm deep	X	X
Ohmic	220-nm Ti/Al/Ni/Au 850C, 30s alloy in N2	X	X
PCM test	Rc, Rsh, isolation characteristics	X	X
T-gates	400-nm Ni/Au	X	X
Metal 1	500-nm Ni/Au	X	X
Passivation	100-nm PECVD Si3N4, 300C	X	X
PCM test	Passivated Rc, Rsh, isolation characteristics	X	X
dc/RF test	dc IV, small signal RF response	X	X

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Wafer Details

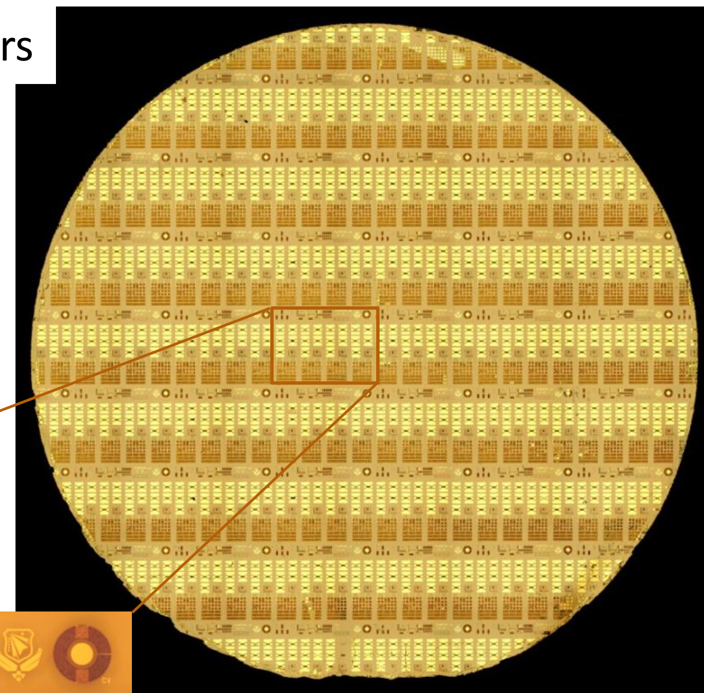
G437C (GaN/Diamond)

G439C (GaN/Si)

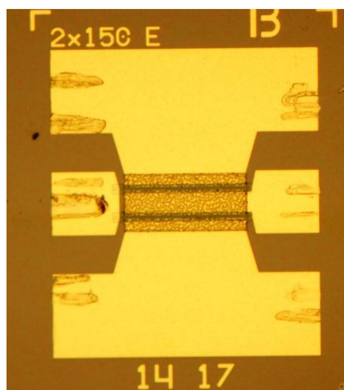


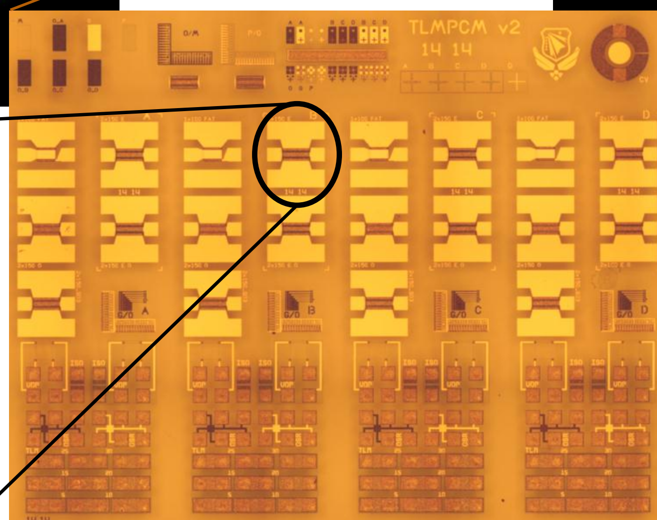
30 mm diameter wafers

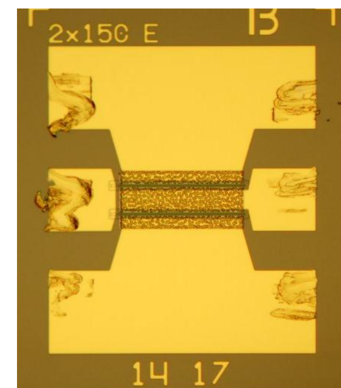
3.8 mm x 3.0 mm Retcile
(36 full reticles/wafer)



- Wg = 0.3 mm (2 x 150 µm)
- Lg = 0.15 µm
- S/D = 4.5 µm



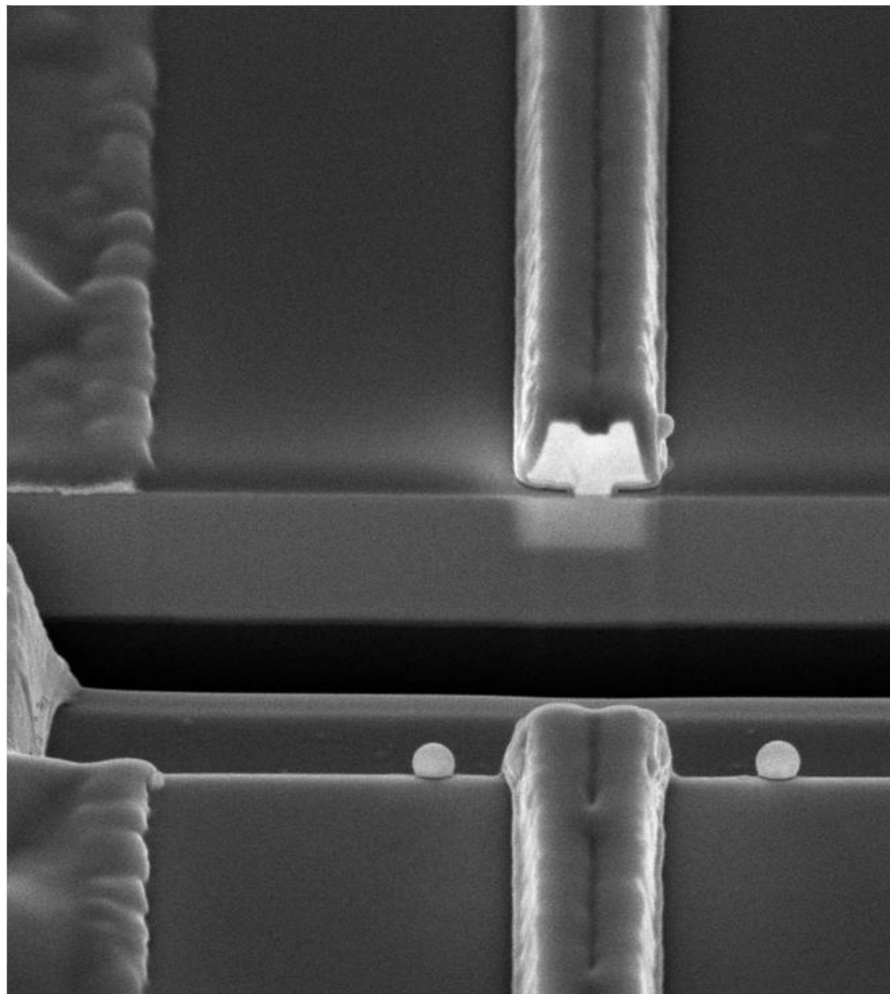


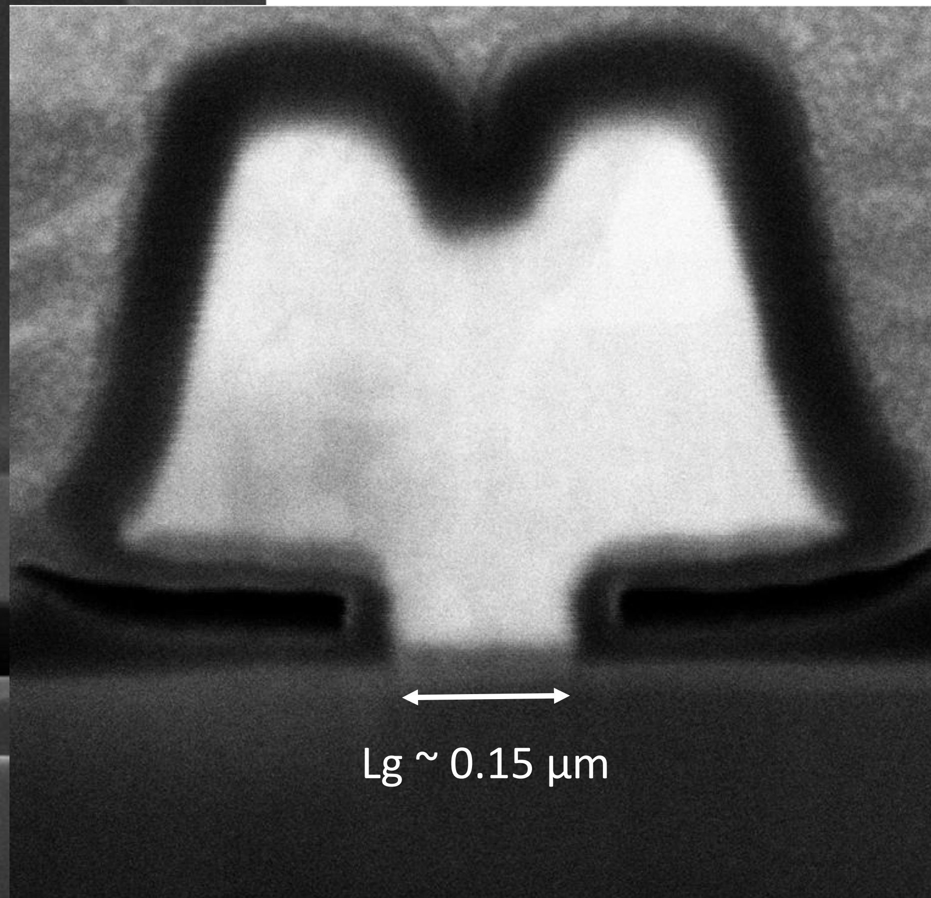


Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

AFRL

Nominal Device Cross-Section



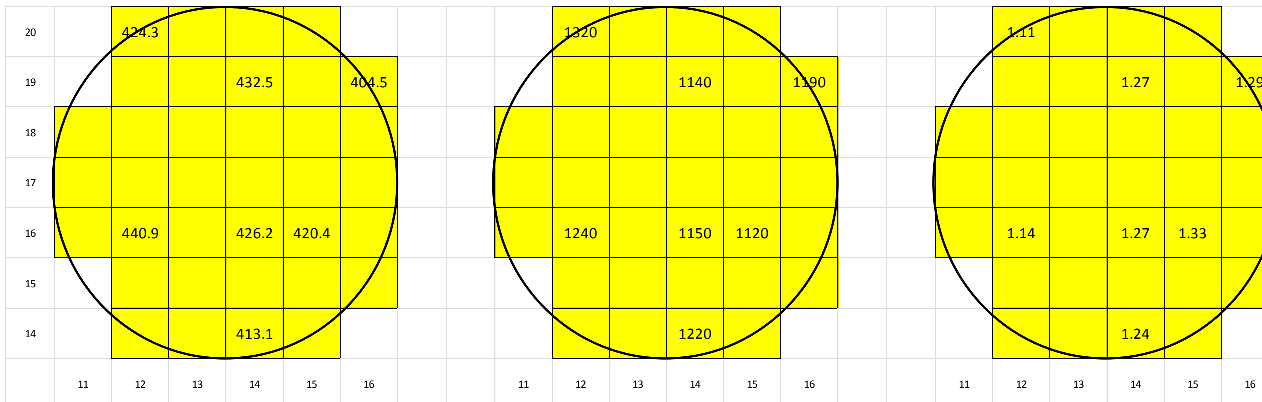


Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

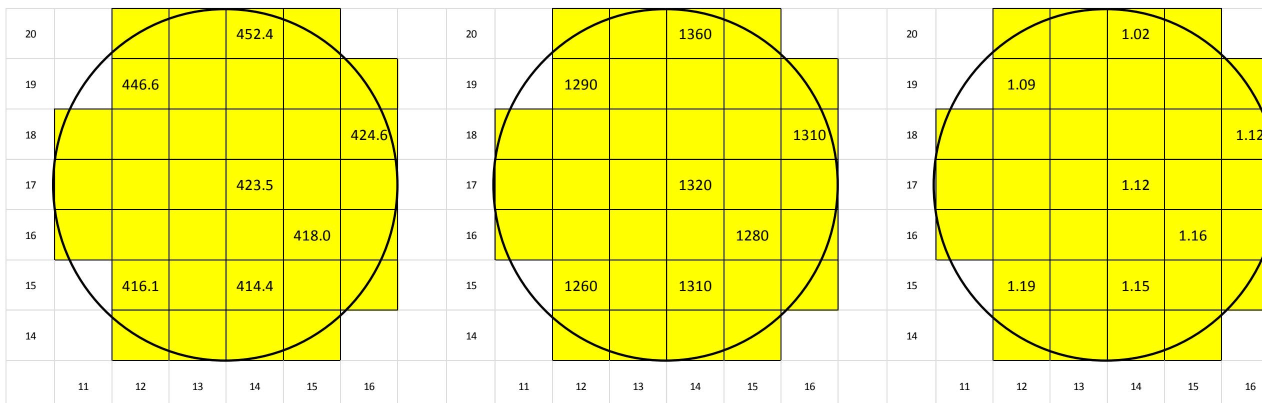
AFRL

Materials Characterization

G437C
GaN/Diamond



G439C
GaN/Si



	G437C (GaN/Diamond)			G439C (GaN/Si)		
	Rsh (Ω/sq)	μ (cm^2/V*s)	Ns (e13/cm^2)	Rsh (Ω/sq)	μ (cm^2/V*s)	Ns (e13/cm^2)
mean	423.1	1197	1.2	427.9	1304	1.1
st dev	12.0	69	0.1	15.3	32	0.1

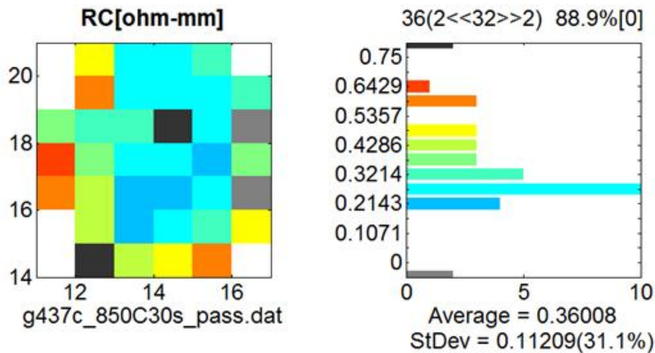
Sheet resistance identical, but GaN/Si shows higher mobility

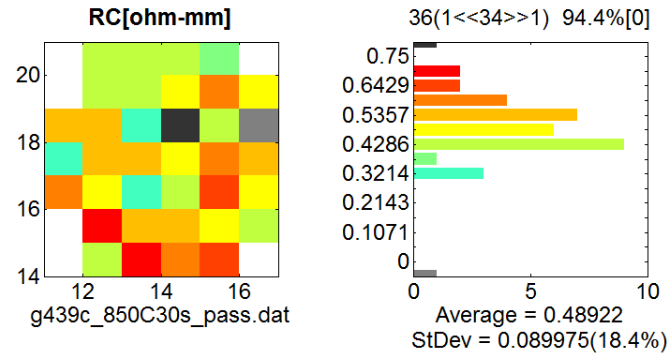
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Post-Process PCM Data

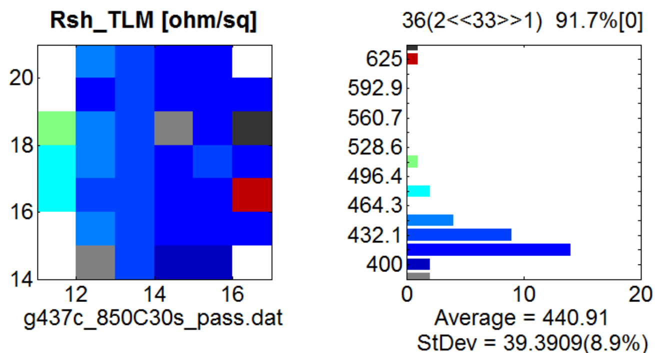
G437C (GaN/Diamond) — G439C (GaN/Si)

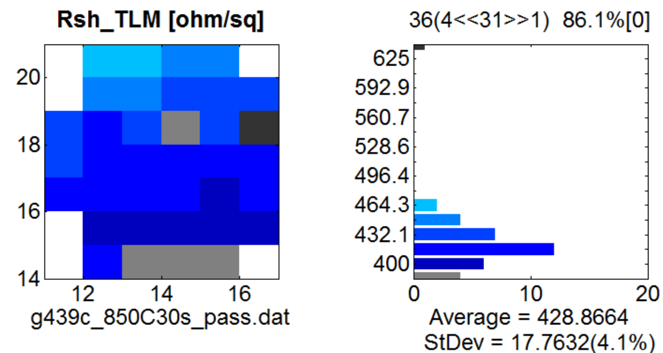
Contact Resistance



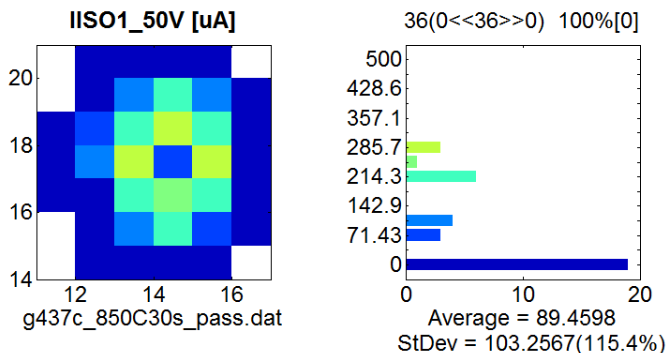


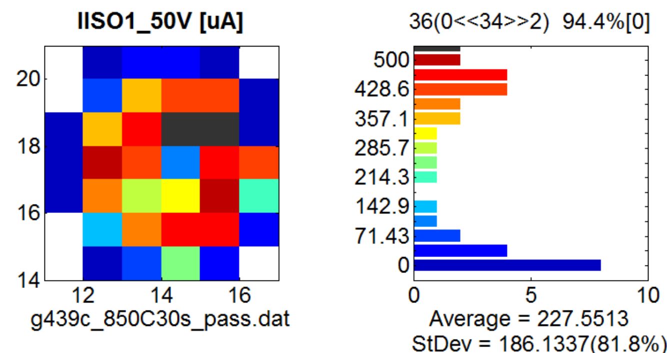
Sheet Resistance





Buffer Isolation





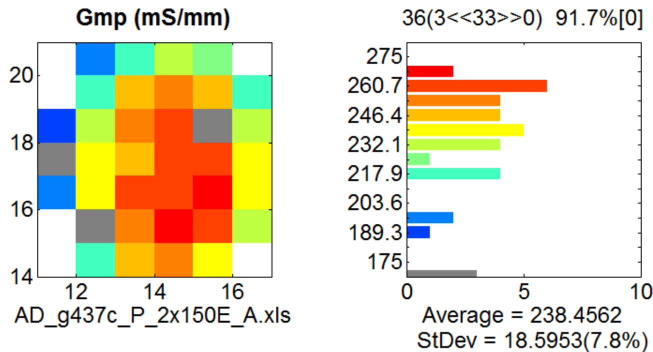
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

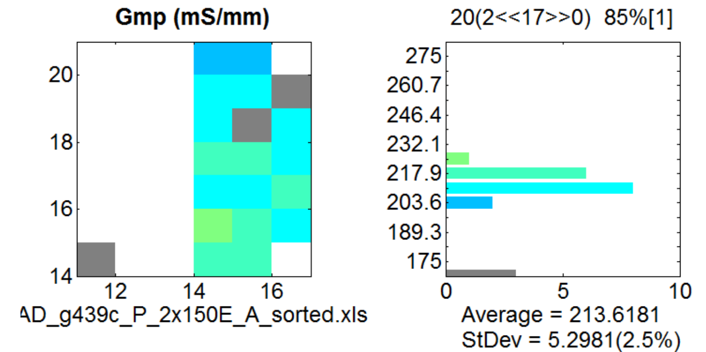
Passivated DC Device Results

G437C (GaN/Diamond) — G439C (GaN/Si)

Trans-conductance

$V_{DS} = 10V$

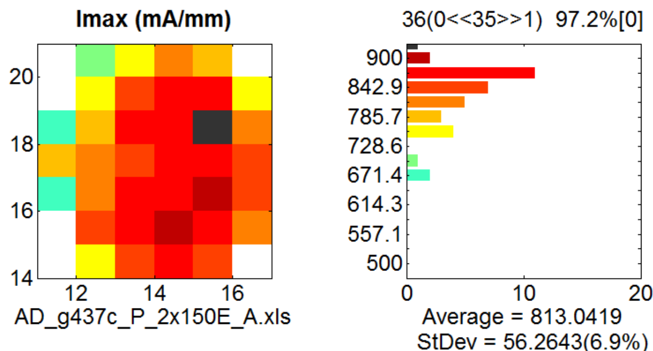


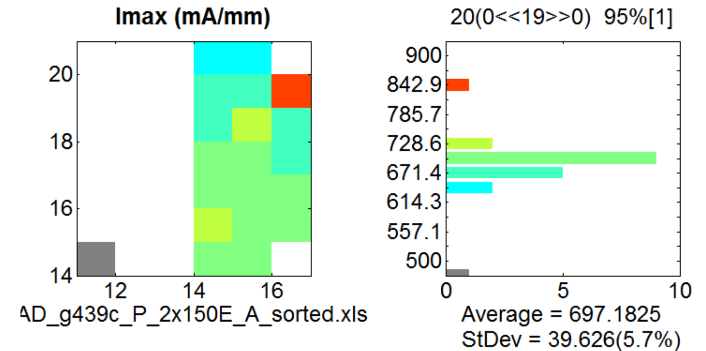


Maximum Drain Current

$V_g = +1V$

$V_d = 10V$

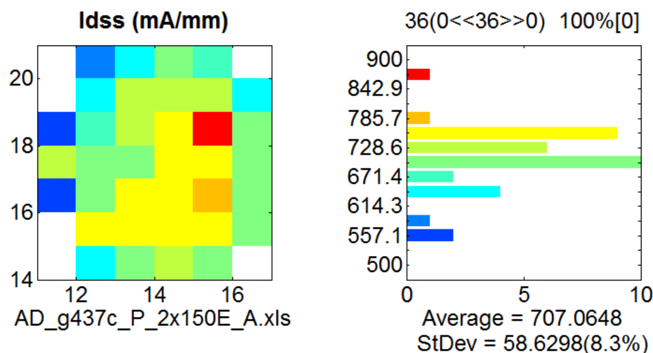


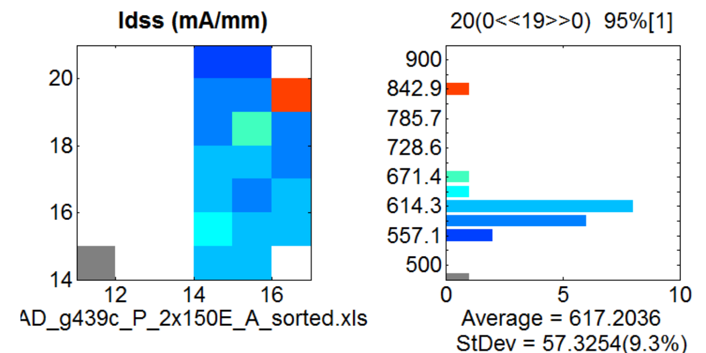


Saturated Drain-Source Current

$V_g = 0V$

$V_d = 10V$

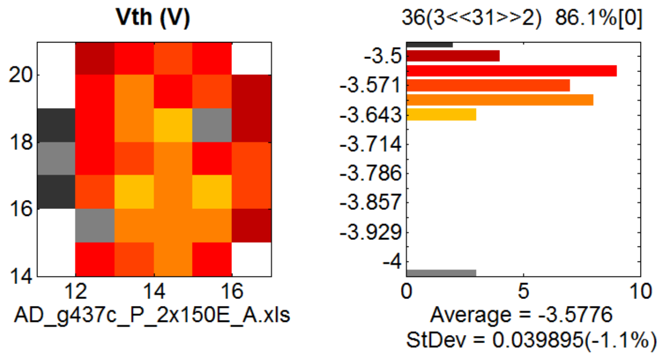




Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

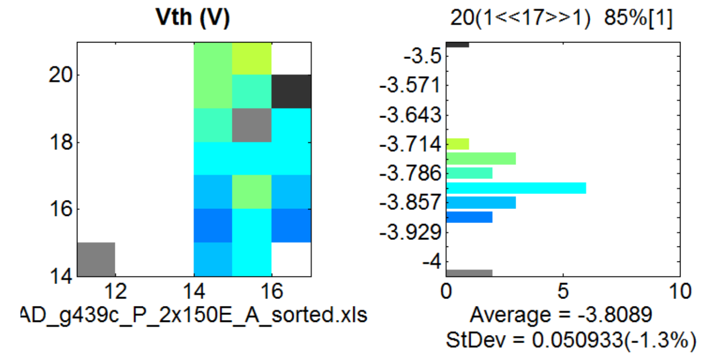
Passivated DC Device Results

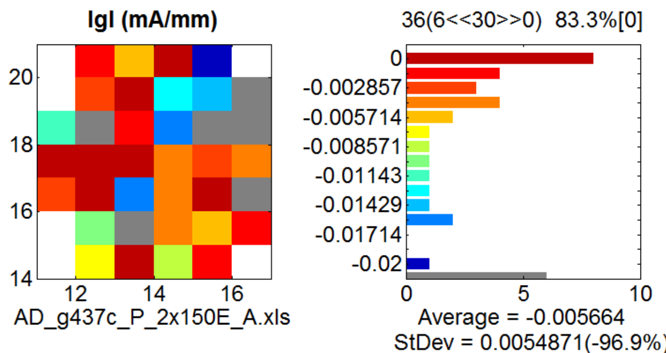
G437C (GaN/Diamond) — G439C (GaN/Si)



***Threshold* Voltage**

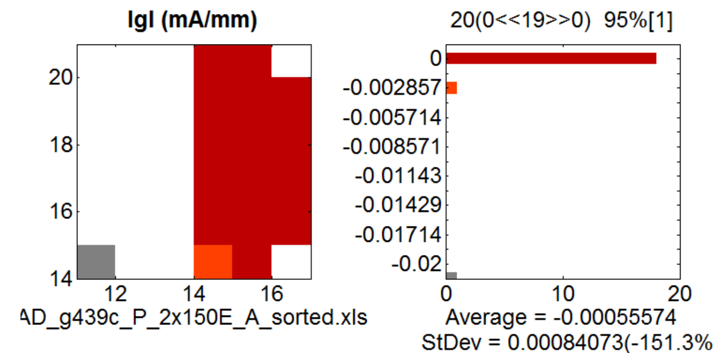
V_{DS} **= 10V**

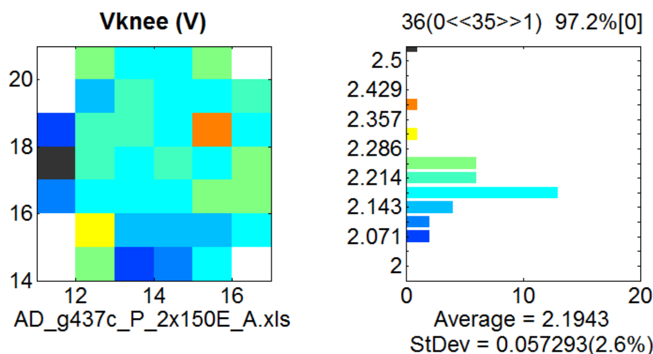




Gate Leakage

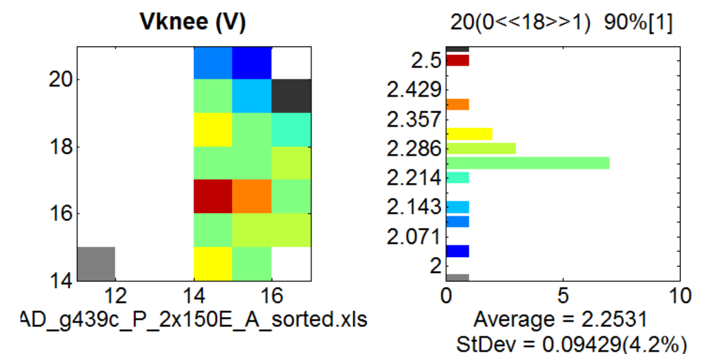
$V_G = V_{th} - 2V$





Knee Voltage

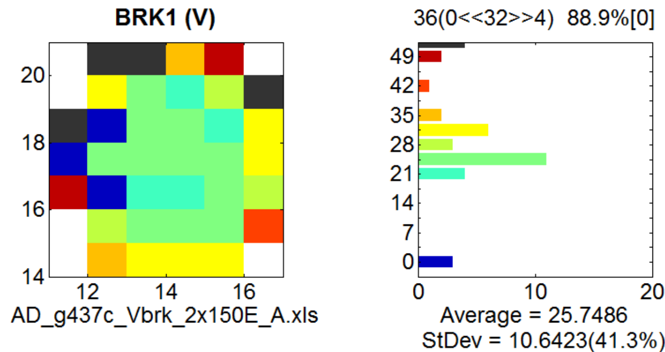
V_{DS} **= 10V**

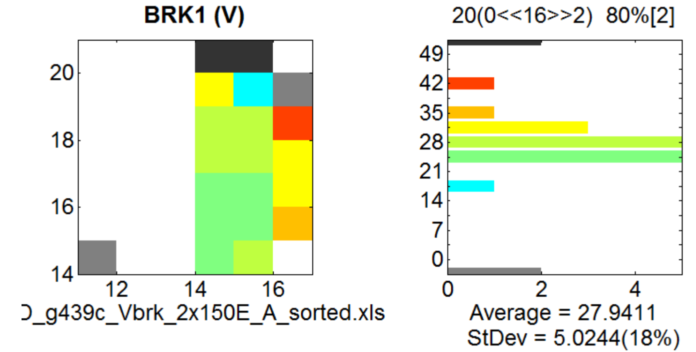


Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Passivated RF Device Results

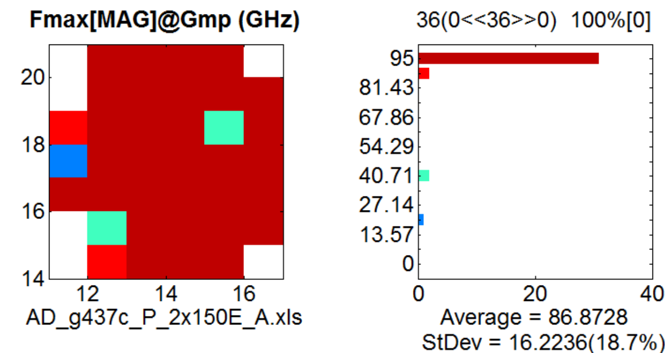
G437C (GaN/Diamond) G439C (GaN/Si)

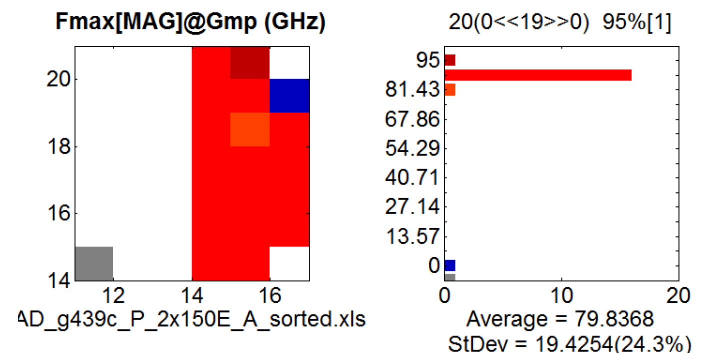




Breakdown

Ids= 1 mA/mm

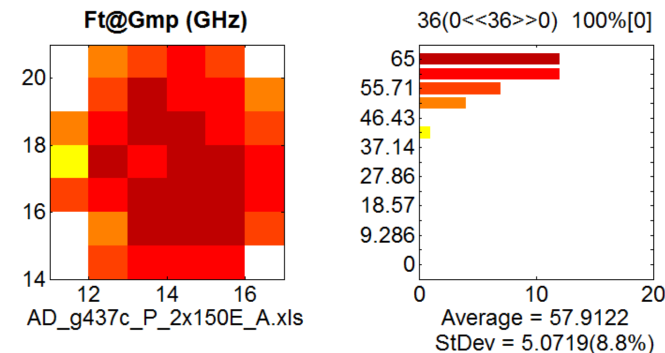


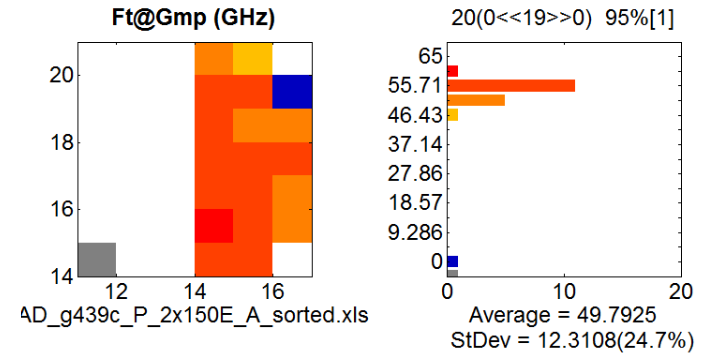


f_{max}(MAG)

Vd = +10 V

Vg = Gmp





f_t

Vd = +10 V

Vg = Gmp

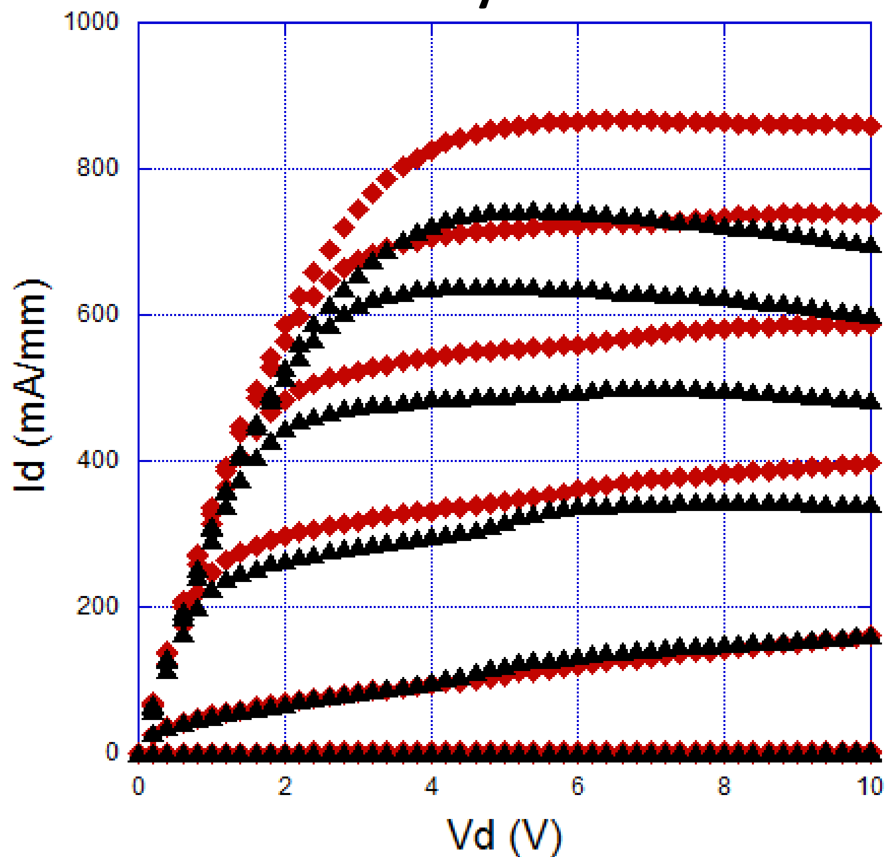
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Representative IV and Transfer Curves

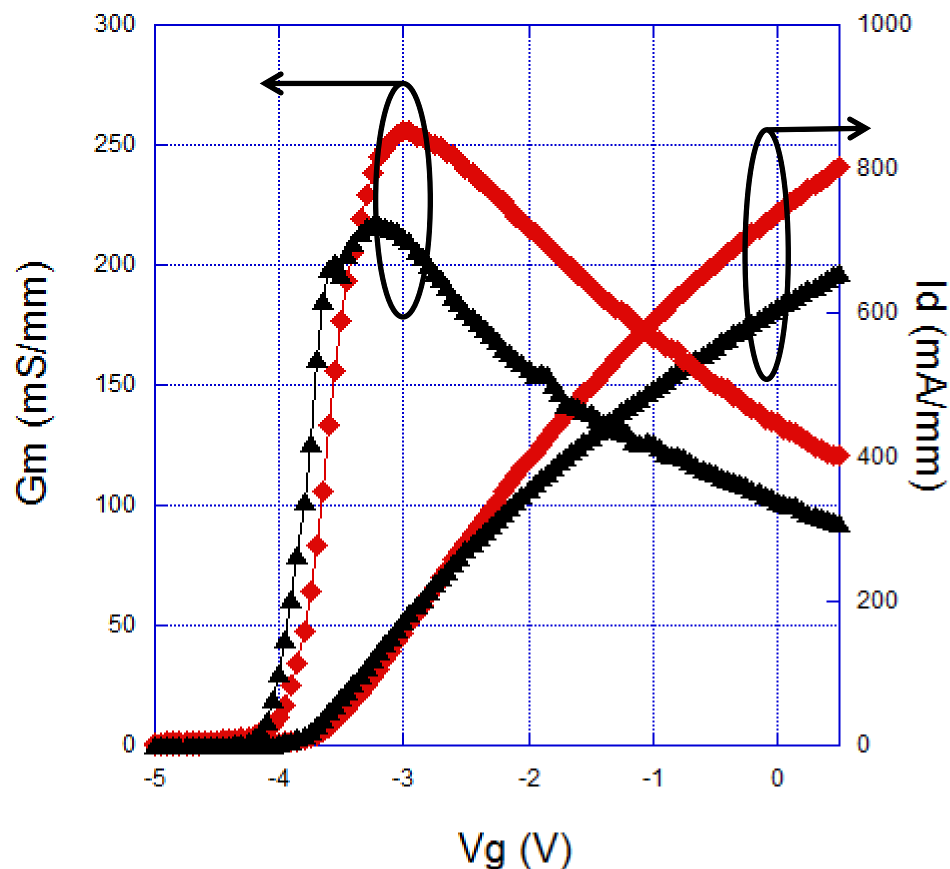
GaN/Diamond

GaN/Si

IV Family of Curves



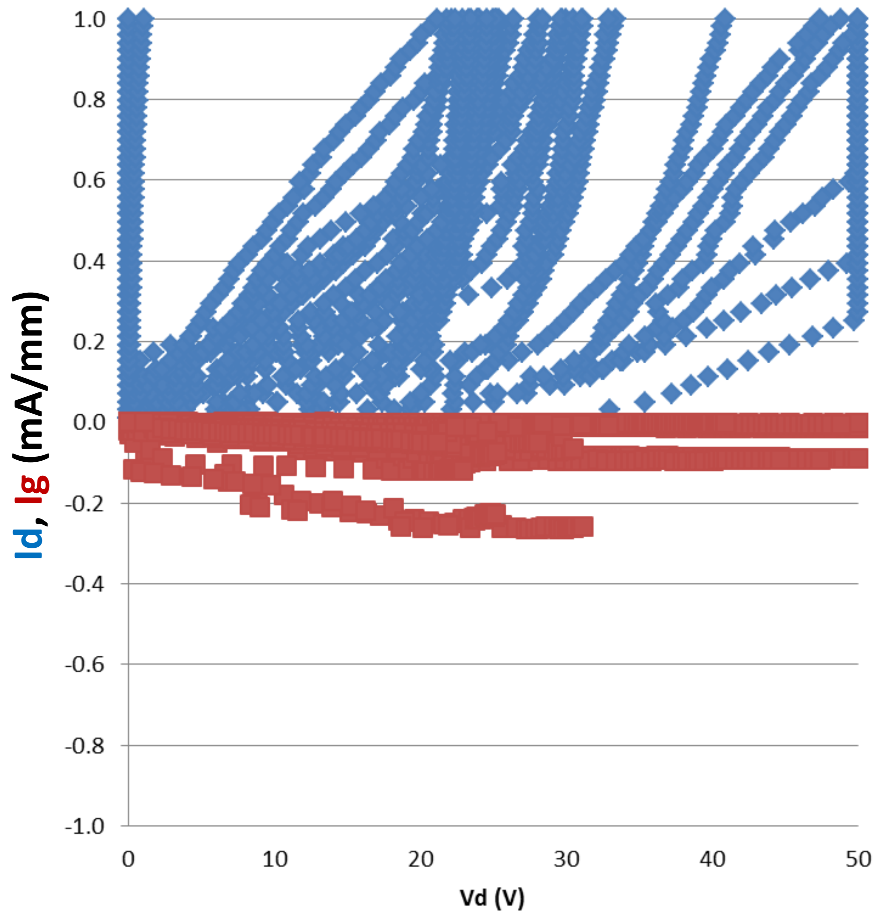
Transfer Curves



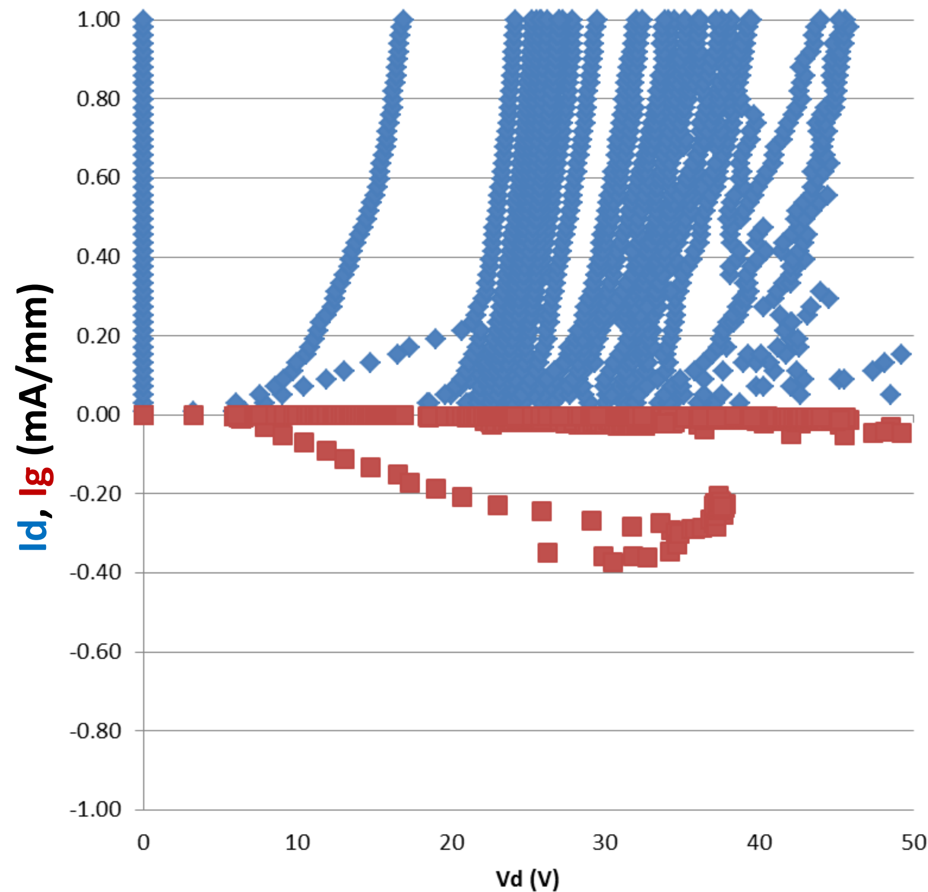
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Leakage Currents

G437C (GaN/Diamond)



G439C (GaN/Si)



Similar current leakage characteristics

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Data Summary

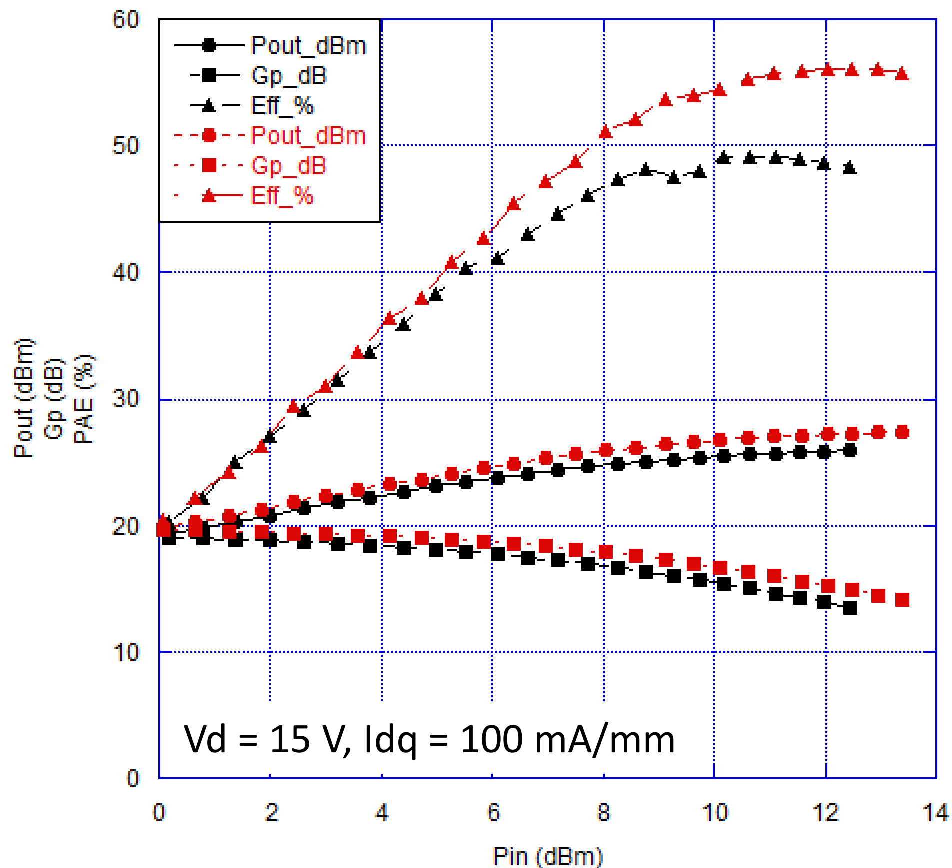
Parameter	GaN/diamond	GaN/Si
Rc (Ω-mm)	0.36 (0.11)	0.49 (0.09)
Rsh (Ω/sq)	441 (39.4)	429 (17.8)
IISO@50V (µA)	89 (103)	226 (186)
GmPeak (mS/mm)	238 (18.6)	214 (5.3)
Vth (V)	-3.58 (0.04)	-3.81 (0.05)
Imax (mA/mm)	813 (56.3)	697 (39.6)
Idss (mA/mm)	707 (58.6)	617 (57.3)
Igl (µA/mm)	-5.66 (5.49)	-0.56 (0.84)
Vbk (V)	25.75 (10.64)	27.94 (5.02)
GLag@5V (%)	7.9 (NA)	7.1 (NA)
DLag@5V (%)	10.0 (NA)	10.6 (NA)

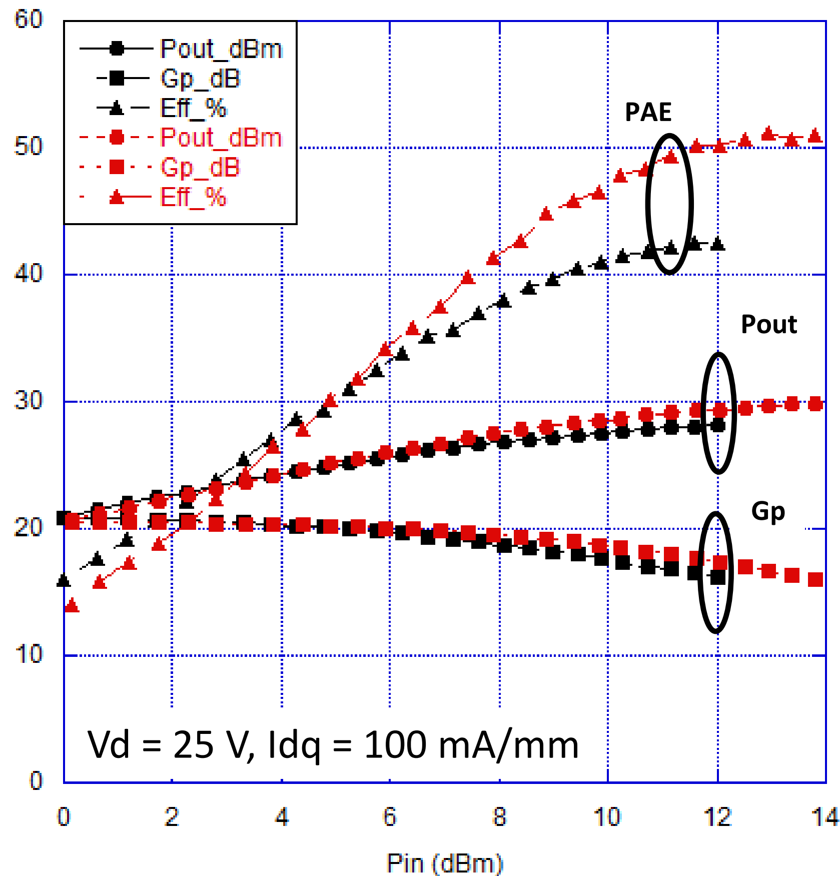
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

Load Pull Analysis

GaN/Si

GaN/Diamond





X-band large signal analysis shows GaN/Diamond devices perform better than GaN/Si under equivalent operating conditions

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

AFRL

Load Pull Analysis

Pout vs Vd

GaN/Si

GaN/Diamond

PAE vs Vd

Pout (dBm)

31
30
29
28
27
26

10
15
20
25
30

Vd (V)

PAE (%)

55
50
45
40
35
30

10
15
20
25
30

Vd (V)

Large signal trends consistent with increased self-heating in GaN/Si over GaN/Diamond

- lower output power for given drain bias

- greater roll off in power added efficiency with increasing drain bias

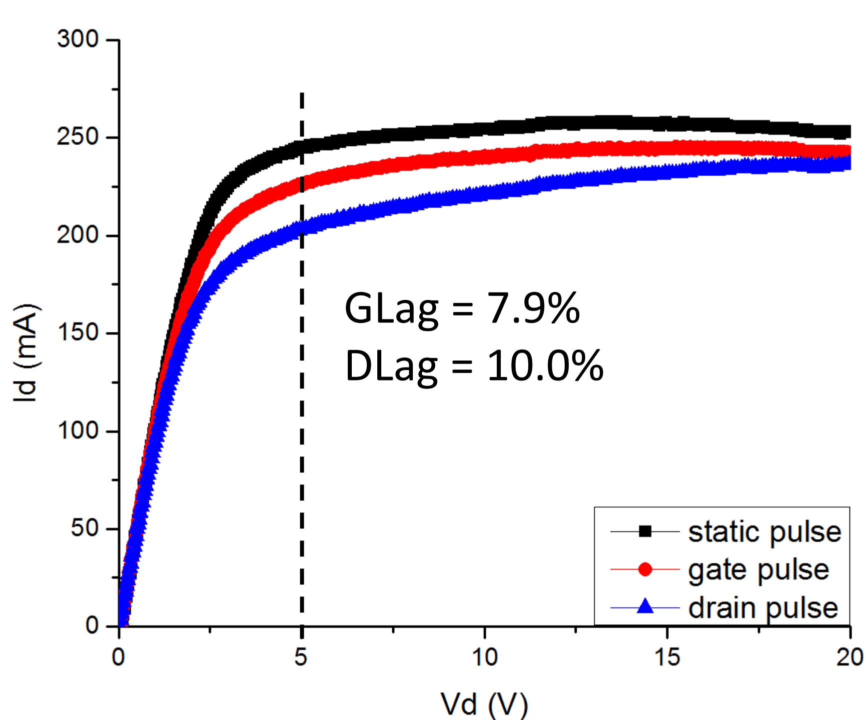
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

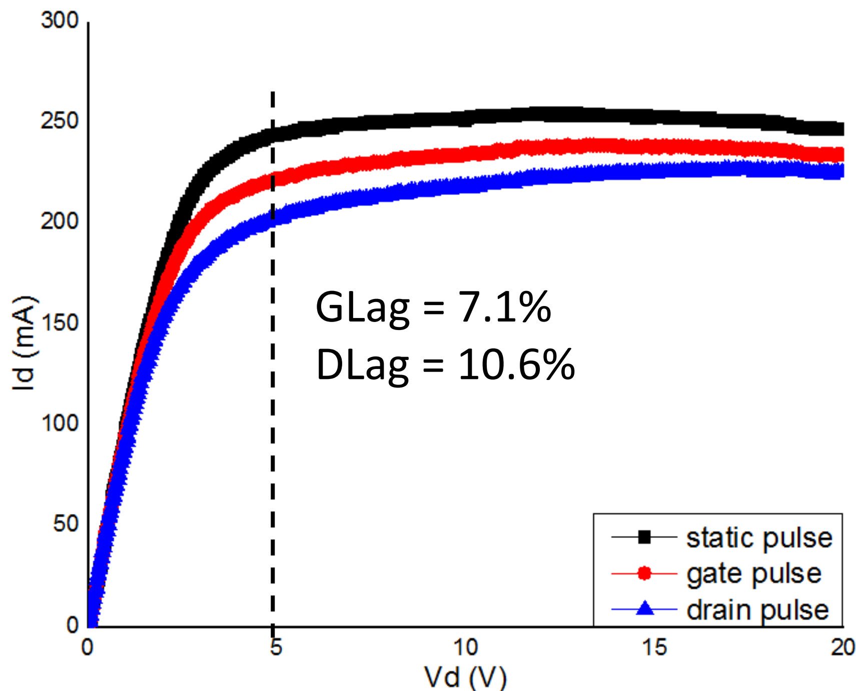
Pulsed IV Analysis

G437C (GaN/Diamond) G439C (GaN/Si)

Static pulse: Vd = 0V, Vg = 0V
Gate pulse: Vd = 0V, Vg = -6V (~ Vth – 2V)
Drain pulse: Vd = 20V, Vg = - 6V

GLag = 1 – (Gate pulse/Static pulse)
Dlag = 1 – (Drain pulse/Gate pulse)



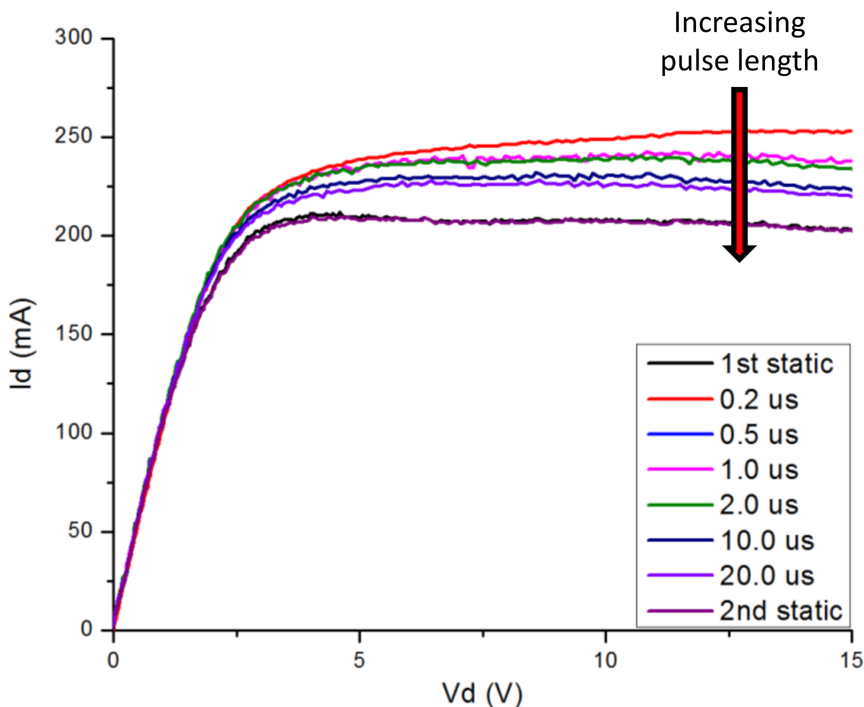


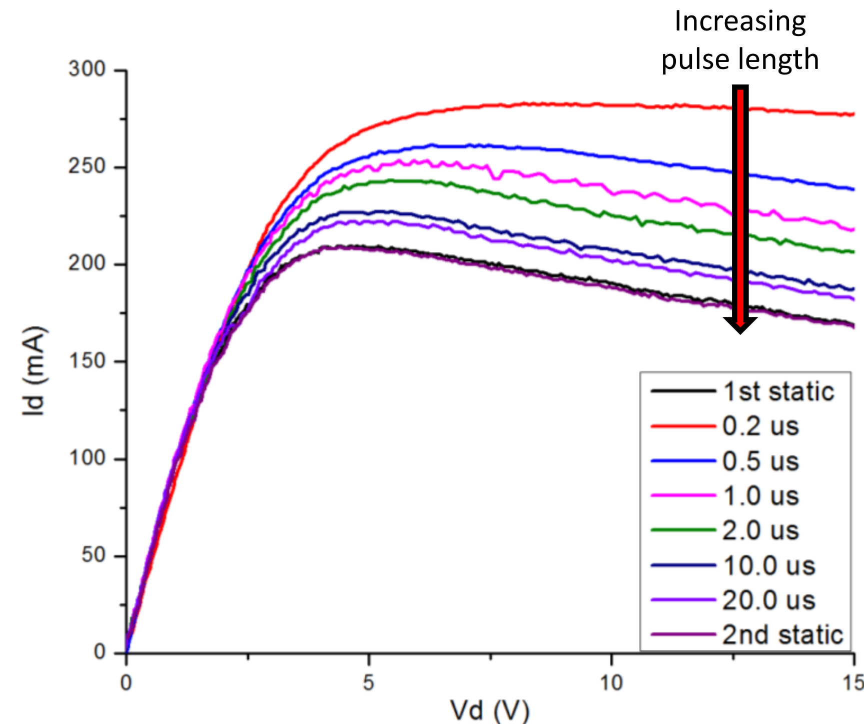
Little difference in dispersion characteristics between GaN/Si and GaN/Diamond

Pulse Length Analysis

G437C (GaN/Diamond) G439C (GaN/Si)

Current Droop Evaluation





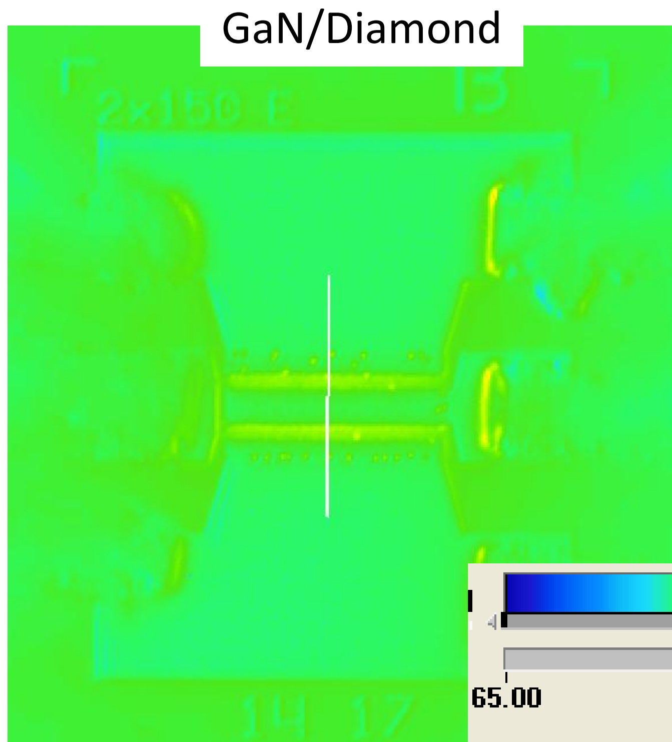
GaN/Si shows more current droop and is more sensitive to pulse length than GaN/Diamond due to increased self-heating

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

IR Analysis

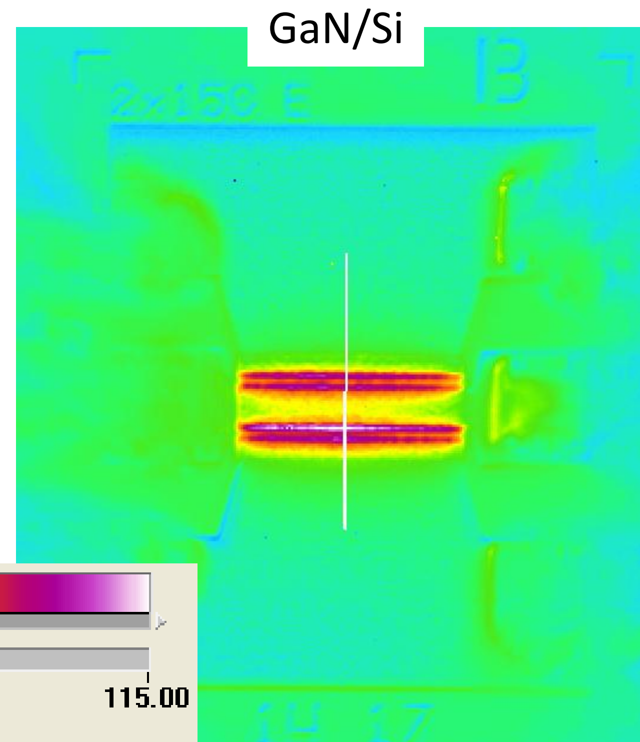
*Rth ~ (Tpeak – Tbase)/(Vd * Id)*

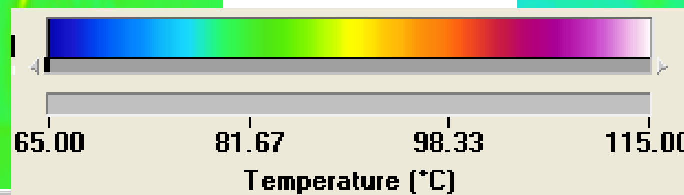
GaN/Diamond

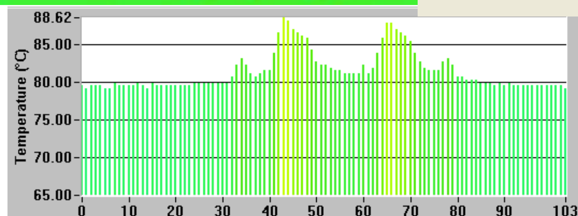


Vd = 25 V
Id = 130 mA

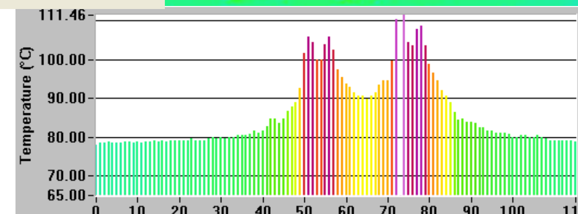
GaN/Si







Rth ~ 7.44 K/(W/mm)



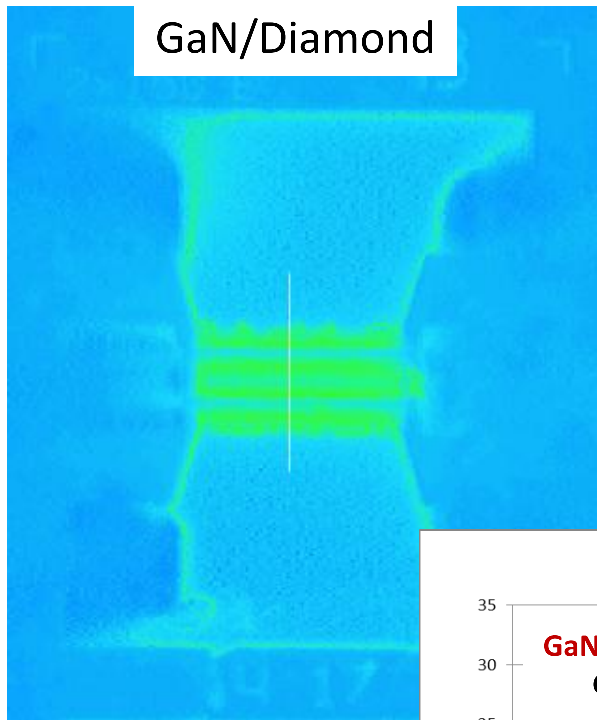
Rth ~ 16.6 K/(W/mm)

Rth for GaN/SiC ~ 11.5 K/(W/mm)

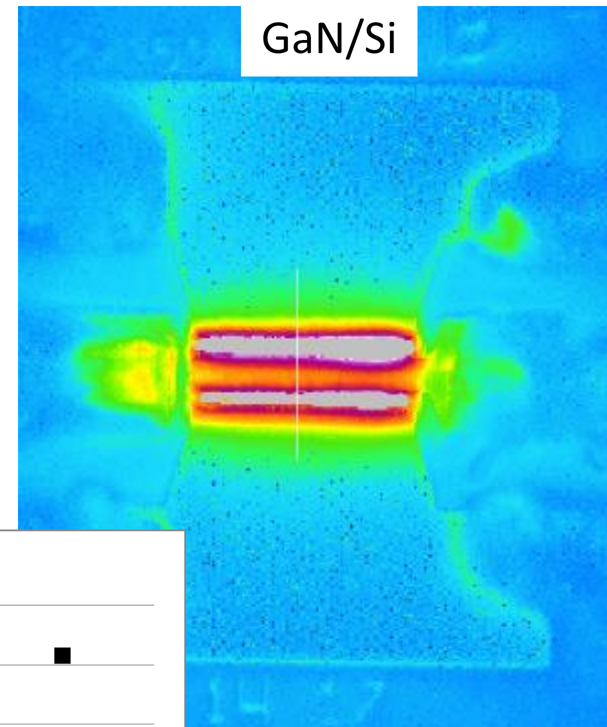
Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

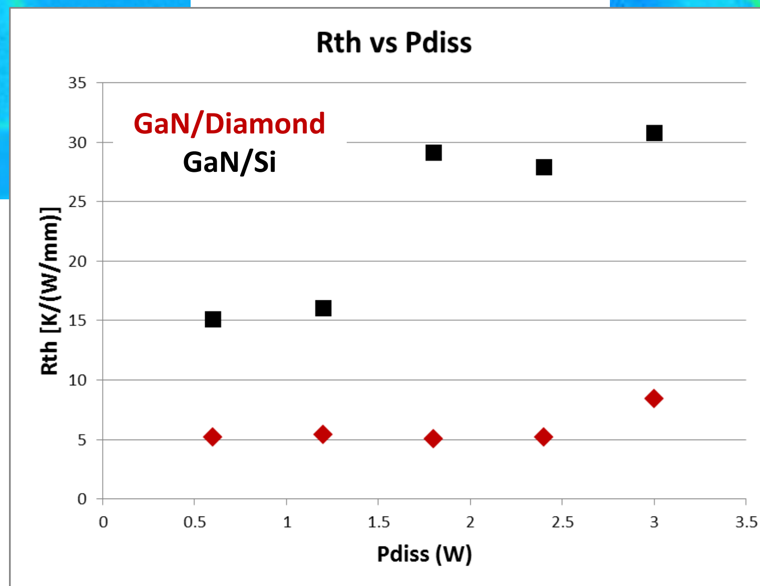
IR Analysis

*Rth ~ (Tpeak – Tbase)/(Vd * Id)*



Vd = 20 V
Id = 150 mA





Rth increases with Pdiss for GaN/Si while remaining fairly flat for GaN/Diamond

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

AFRL

µRaman Analysis

Si substrate
diamond substrate
edge of chip temperature on diamond substrate
AFRL
ΔT (K)
power (W)
8.0 K/(W/mm)

University of BRISTOL

Center for Device Thermography and Reliability

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).

AFRL

Conclusions/Remarks

- **Measureable differences between GaN/Diamond and GaN/Si samples**
- **Observed differences are consistent with improved thermal characteristics of GaN/Diamond relative to GaN/Si**
  - **Desirable drain current characteristic**
  - **Improvement in power added efficiency**
  - **Improvement in transient characteristics**
  - **Improved thermal resistance measured via IR & μRaman**
- **Some engineering challenges remain (μ, I_G, V_{br})**
- ***Manuscript on this work submitted to Physica Status Solidi***

Distribution Statement A: Approved for public release, distribution unlimited (88ABW-2013-3823).