“Tiny-but-Tough” Gallium Nitride Nanoelectronics for Extreme Harsh Environments

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IEEE International Conference on Wireless for Space & Extreme Environments (WiSEE)
Stanford University
12 December 2018

GaN for Future "Internet-of-Things" Devices

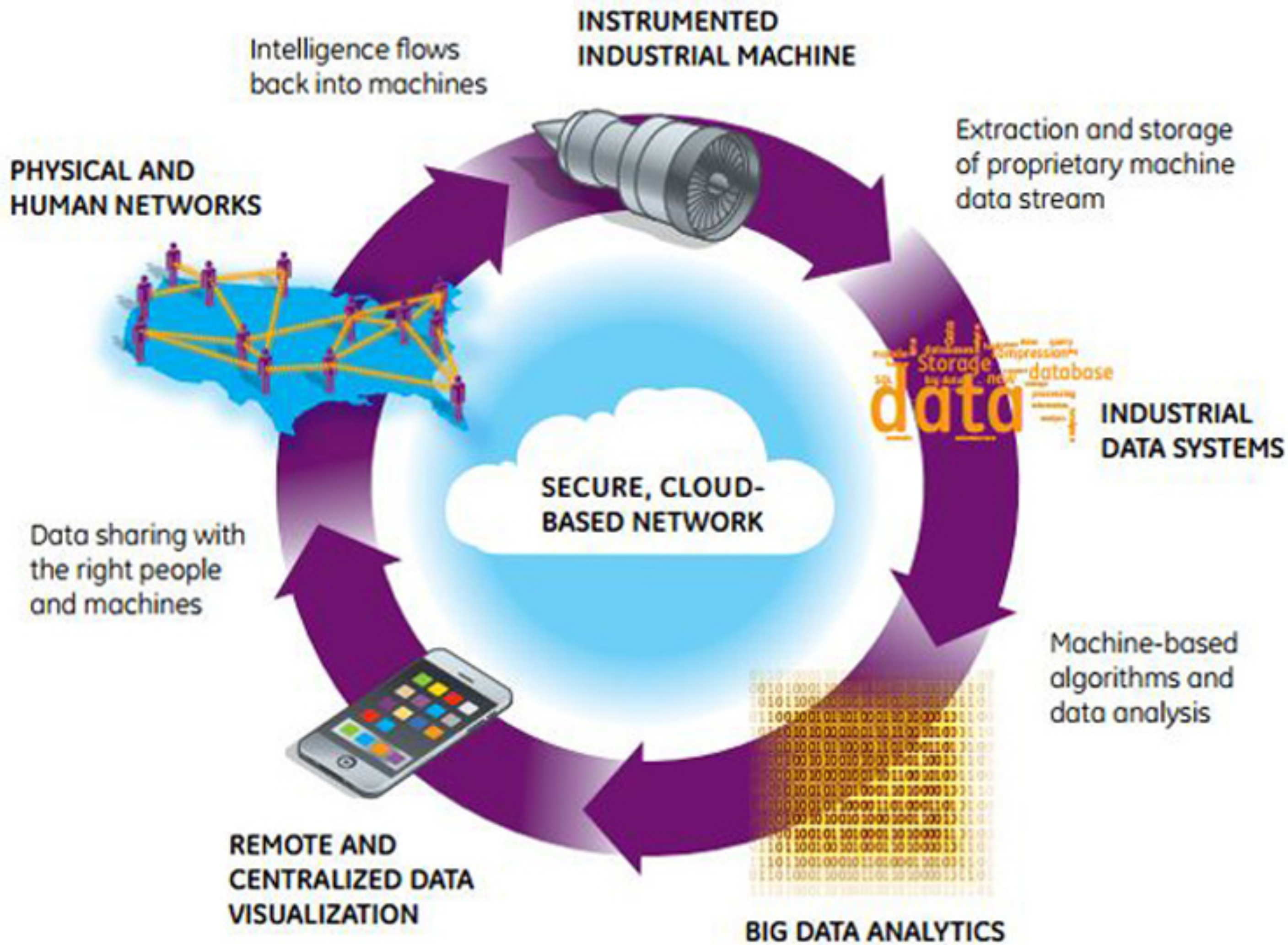


Image credit: General Electric

Harsh Environment Sensing

Energy Industries	Geothermal	Oil & Gas Exploration	Industrial Gas Turbines	Automotive Engines	Aircraft Engines
Minimum Sensing Temperatures					
Desired Sensing Measurands	Pressure Temperature H_2S Strain	Pressure Temperature Hydrocarbon Strain	Pressure Temperature Flame Speed Acceleration	Pressure Temperature Flame Speed O_2	Pressure Temperature Flame Speed Acceleration

- **"Harsh environment" includes extremes of pressure, temperature, shock, radiation and chemical attack.**
- **Sensing within harsh environments enables real-time monitoring of <u>subsurface environments</u>, <u>combustion</u> and <u>critical components</u>.**

Venus Exploration

GaN Electronics for Venus Exploration via the NASA Hot Operating Temperature Technology "HOTTech" Program

(Debbie G. Senesky, Mina Rais-Zadeh, Tomas Palacios, Yuji Zhao)

Image Credit: NASA/JPL/Magellan

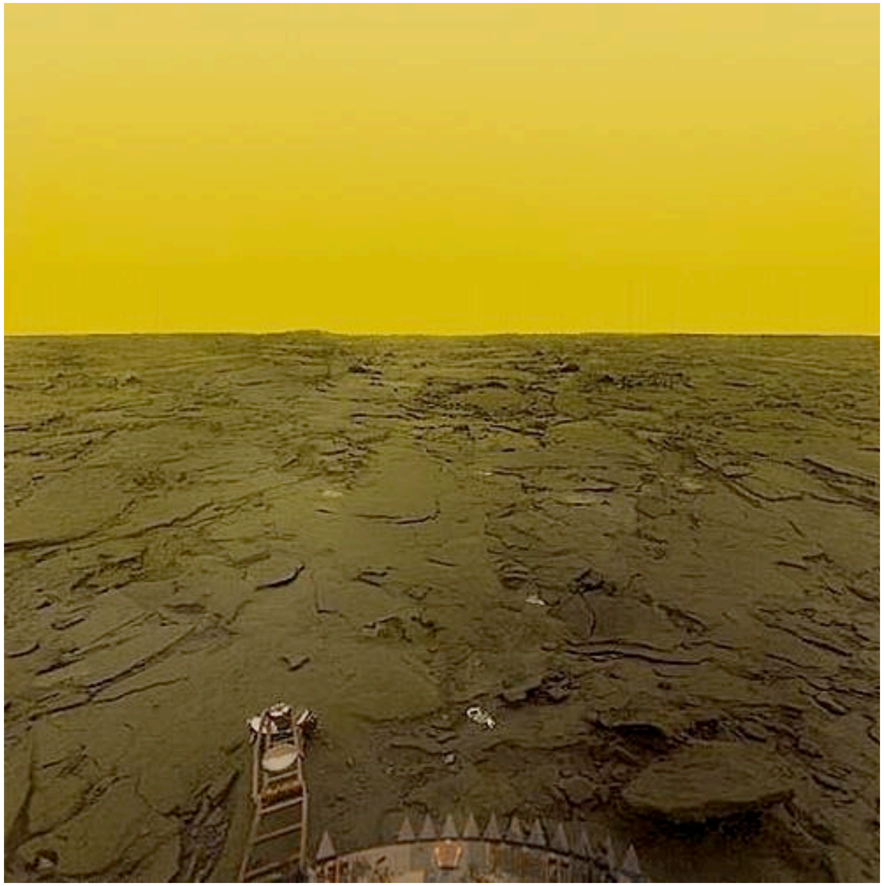


Image Credit: Soviet/Venera 13 (1982)

Material Properties (Gallium Nitride)

Property	GaN	6H-SiC	AlN	Diamond	Silicon
Melting Point (°C)	2500	2830 sublimes	2470	4000 phase change	1420
Energy Gap (eV)	3.4	3.0	6.2	5.6	1.12
Critical Field ($\times 10^6$ V/cm)	5.0	2.5	10	5.0	0.25
Thermal Conductivity (W/cm-K)	1.3	5.0	1.6	20	1.5
Young's Modulus (GPa)	390	450	340	1035	190
Acoustic Velocity (x10^3 m/s)	8.0	11.9	11.4	17.2	9.1
Yield Strength (GPa)	-	21	-	53	7
Coeff. of Thermal Expansion (°C $\times 10^{-6}$)	3.7	4.5	4.0	0.8	2.6
Chemical Stability	Good	Excellent	Good	Fair	Fair

Material properties of GaN, SiC, AlN, diamond and Si.

→ GaN is a thermally stable, mechanically robust, ultraviolet sensitive and high breakdown semiconductor.

AlGaN/GaN 2DEG Formation

Spontaneous polarization

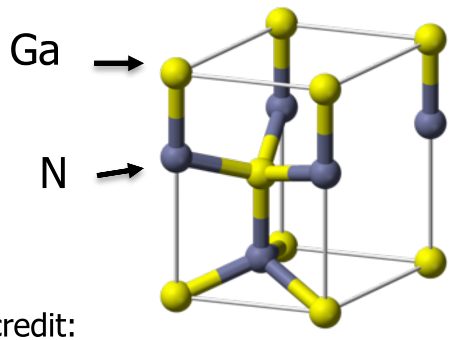
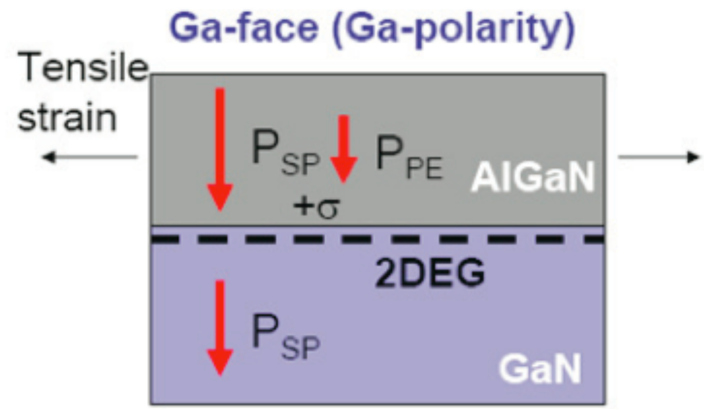


Image credit:
http://en.wikipedia.org/wiki/Wurtzite_crystal_structure



Piezoelectric polarization

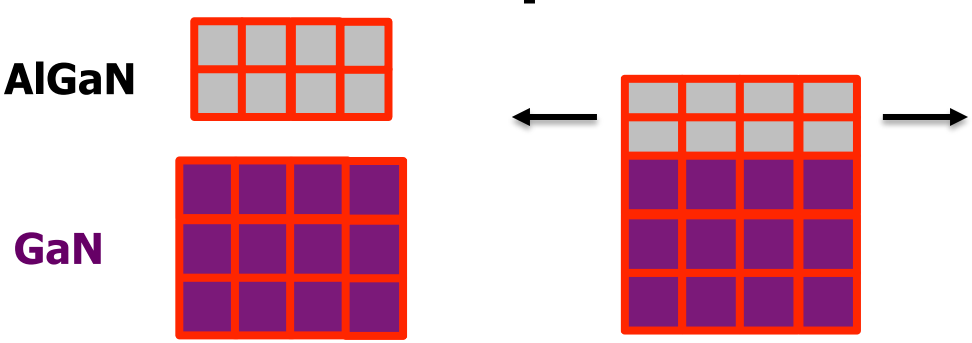


Image credit: C. Chapin, Stanford University, 2015.

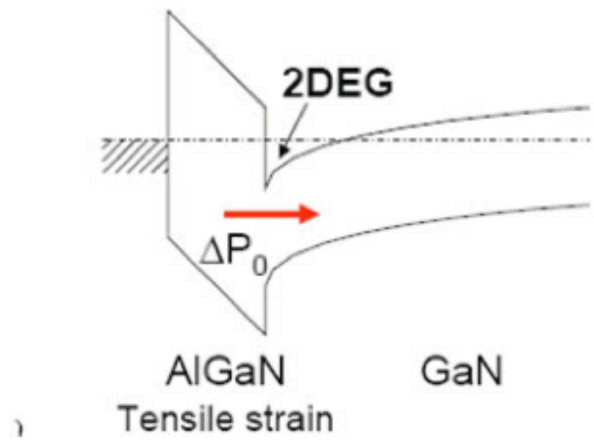


Image credit: M. Lindeborg et al., UCSB, 2011.

GaN High Electron Mobility Transistor (HEMT)

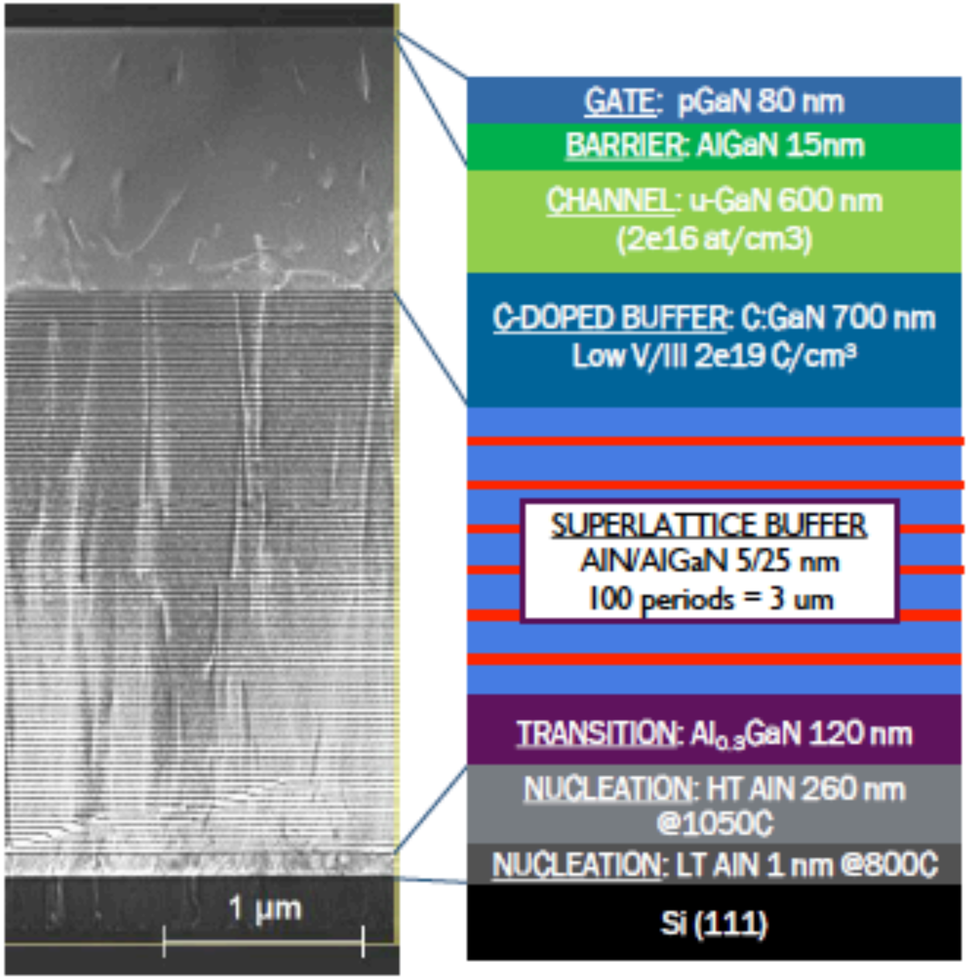
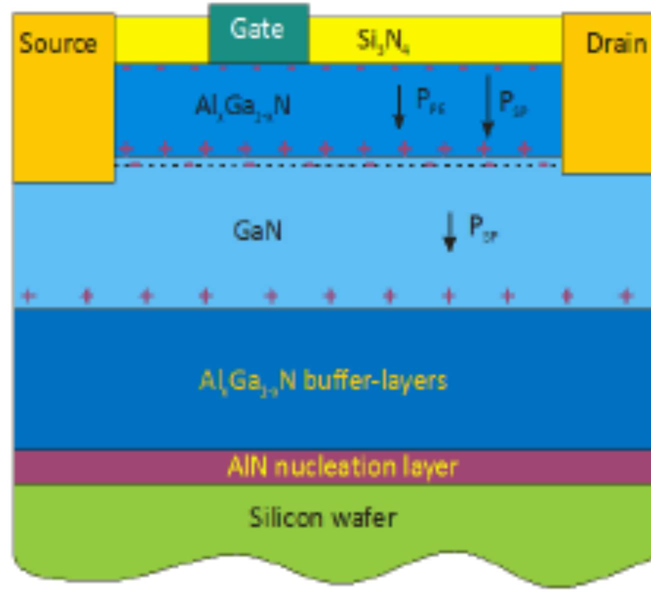


Image credit: Dr. Hans Stork, ON Semiconductor, 2018



Low Ron

high **2DEG** $n_s \sim 1 \times 10^{13}$ cm^{-2}

high 2DEG **mobility** ~$2000 cm^2/Vs$

High Breakdown

wide bandgap (3.4 eV)

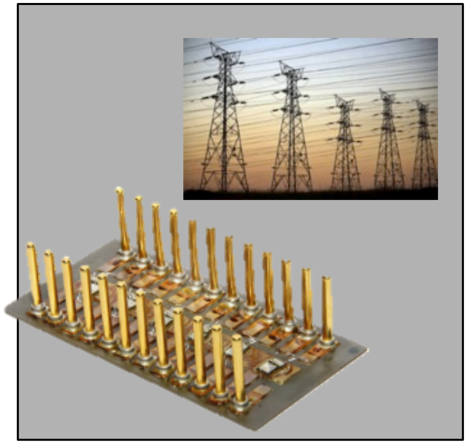
Low Capacitance

no junctions (undoped)

ON Semiconductor®

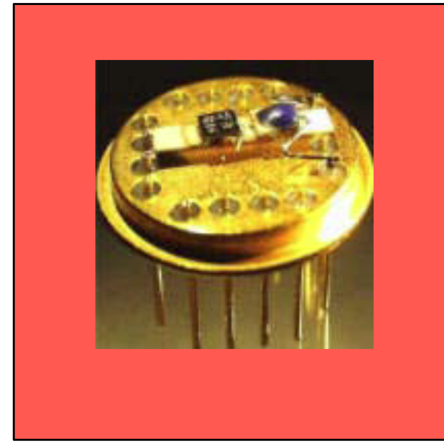
GaN Everywhere...

Power & RF

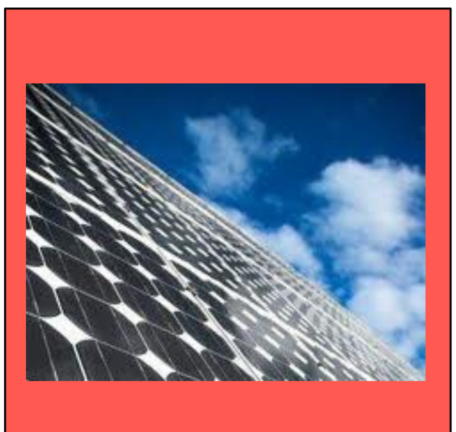


LEDs

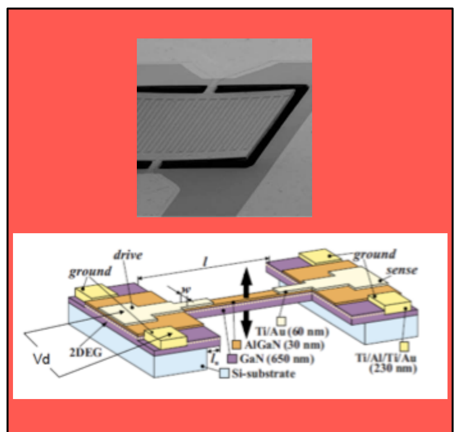
Sensing/IoT



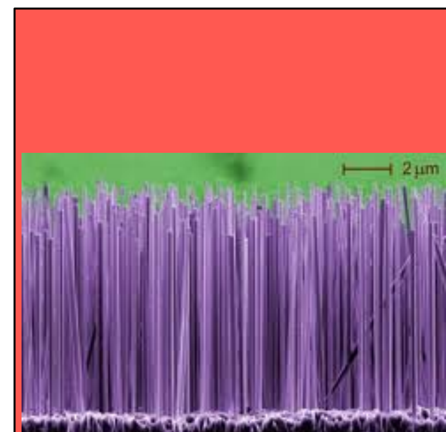
Solar Cells



RF Resonators

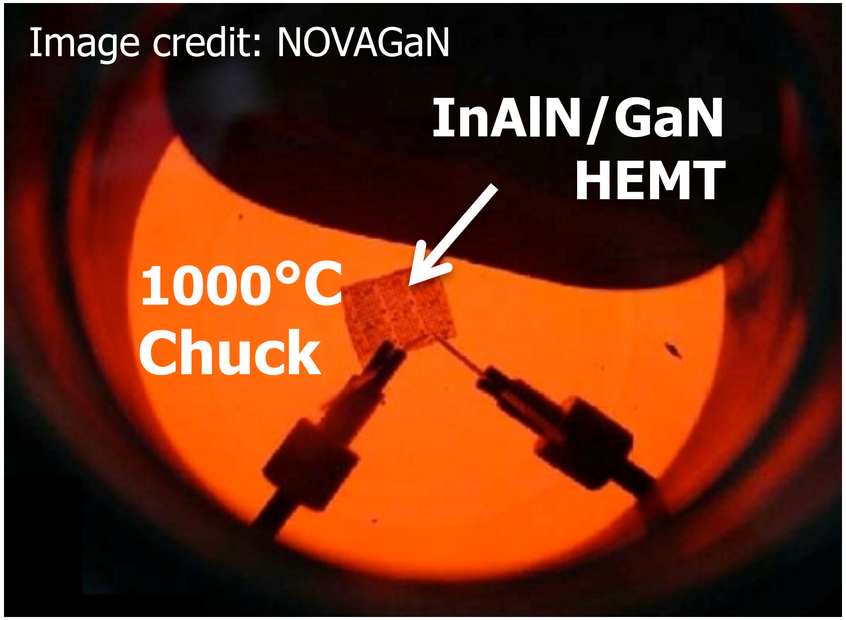


Nanostructures



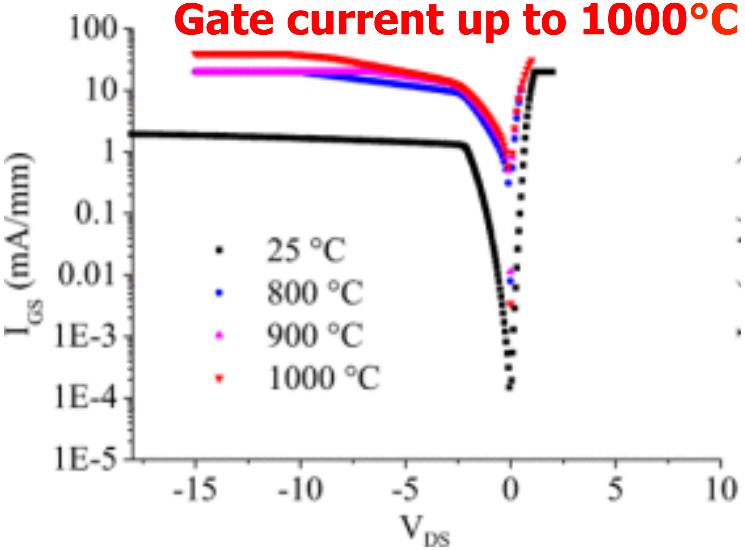
...to realize the "more than Moore" diversification!

Extreme-Temp. (1000°C!) Operation of GaN



- GaN heterostructures have demonstrated remarkable thermal stability
- Lattice-matched InAlN/GaN HEMTs have been shown to operate up to 1000°C in vacuum for 25+ hrs (Kohn et al., 2012)

Gate current up to 1000°C



Evolution of gate current at 1000°C

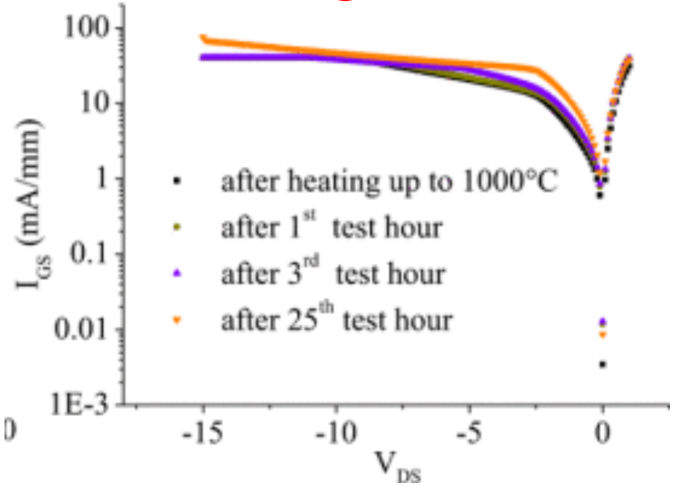
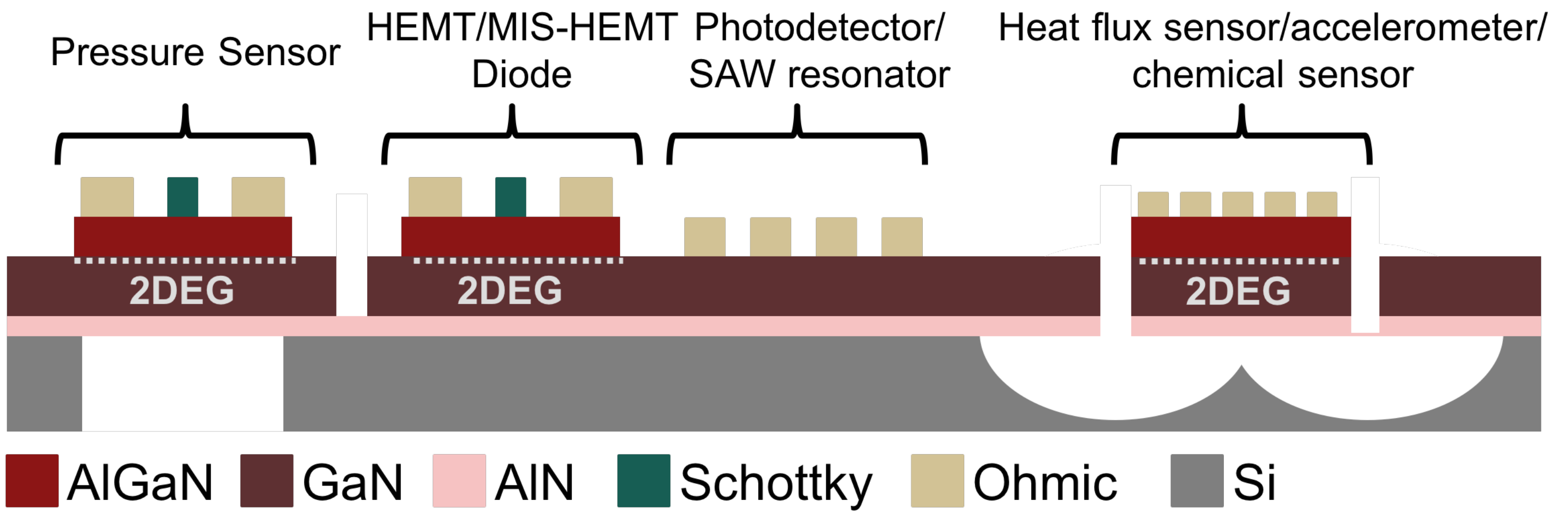
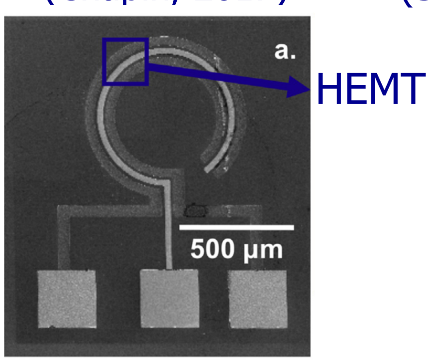


Image credit: Kohn et al., (2012)

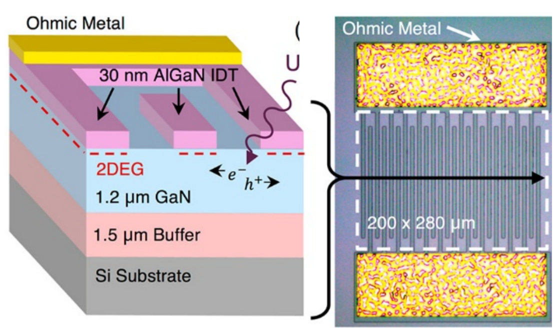
GaN-on-Si "IoT" Sensing Platform



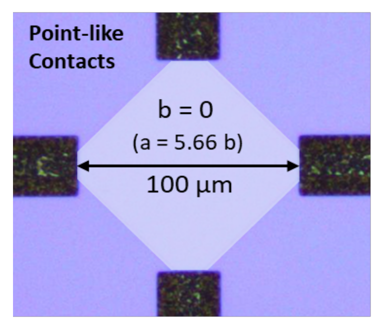
Pressure Sensor [1]
(Chapin, 2017)



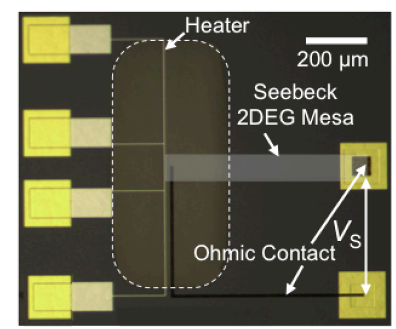
UV Photodetector [2]
(Satterthwaite & Yalamarthy, 2018)



Hall-effect Sensor [3]
(Dowling & Alpert, 2018)

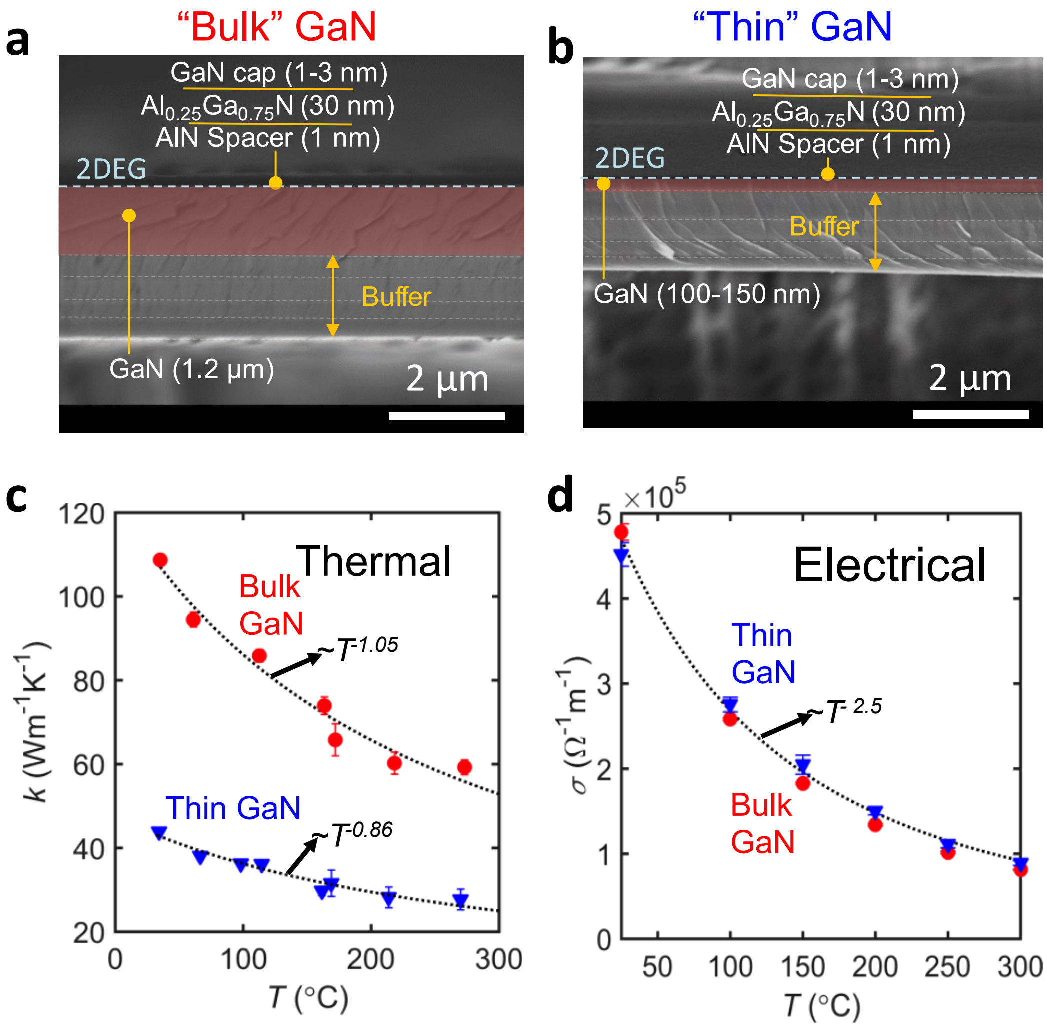


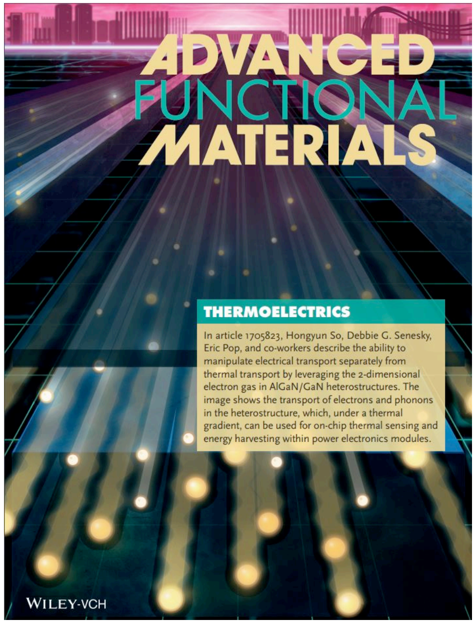
Thermoelectrics [4]
(Yalamarthy, 2018)



[1] C. Chapin,…D.G. Senesky, et al., Sensors and Actuators A: Physical (2017)
[2] P. Satterthwaite, A. Yalamarthy,…D.G. Senesky, et al., ACS Photonics (2018)
[3] H. Alpert, K. Dowling,…D.G. Senesky, et al., under review (2018)
[4] A. Yalamarthy,…E. Pop, D.G. Senesky, et al., Advanced Functional Materials (2018)

“Tunable” Transport in AlGaN/GaN 2DEGs

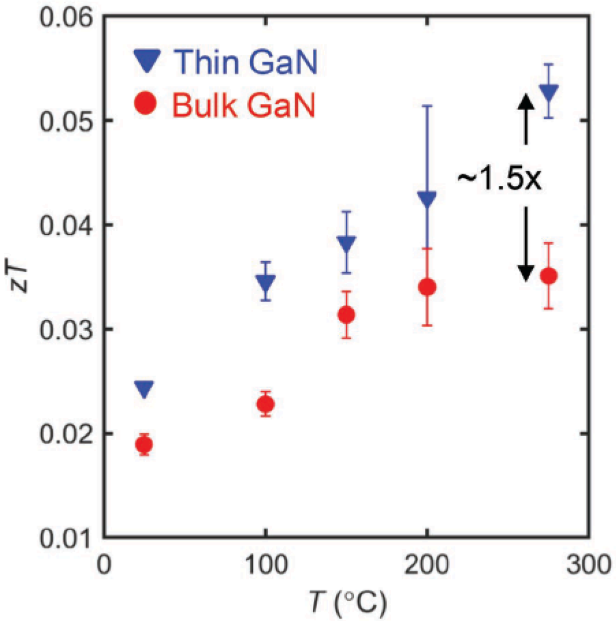


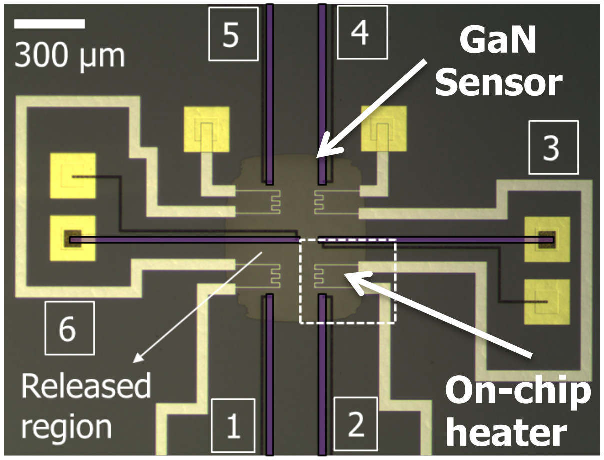


- Large, ~2.3X (room temperature) reduction in thermal conductivity for “thin” GaN in comparison to “bulk”
- Approximately identical electrical conductivities
- Ability for “tuning” **thermal** and **electrical** transport with film structure.

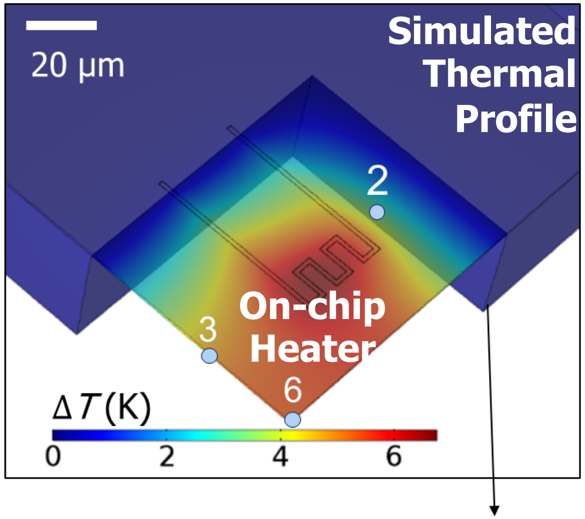
A. Yalamarthy,…E. Pop, D.G. Senesky, et al., Advanced Functional Materials (2018)

On-chip GaN Thermoelectric "Hot Spot" Sensors





Suspended AlGaN/GaN film with four on-chip heaters (hot spots) and six thermoelectric sensors



Base held at 150°C

Figure-of-merit, $zT = \frac{S^2}{\rho\kappa}T$

S : Seebeck coefficient (ΔV/ ΔT)
ρ : electrical resistivity
κ : thermal conductivity
T : absolute temperature

Image credit: http://hjwu.mse.nsysu.edu.tw

Location	Simulated ΔT	Measured ΔT
2	~2.98 K	~3.2 K
3	~4.63 K	~4.71 K
6	~5.43 K	~5.63 K

Errors ~ 5-10%

A. Yalamarthy, E. Pop, D.G. Senesky, et al., Advanced Functional Materials (2018)

Stanford XLab Sensor Summary

Device/ Measurand	Materials Platform	Sensitivity/ Range	Max. Temp*	TRL
Pressure	InAlN/GaN-on-Si	0.64%/psig/ 0 to 28 psig	300°C	2
Heat flux (dT)	AlGaN/GaN-on-Si	4 to 7×10^{-3} W/mK^2	300°C	2
Point Temperature	4H-SiC pn diode	3.5 mV/°C	600°C	3
Magnetic Field/ Current	AlGaN/GaN-on-Si	~76 mV/V/T -5 to 5 mT	200°C	3
UV Photodetector	Graphene/GaN-on-Sapphire	2000 A/W	200°C	2
UV Photodetector	AlGaN/GaN-on-Si	578 A/W NPDR = 7×10^{10}	300°C	3
Micro-hotplate (Chem/Bio)	AlGaN/GaN-on-Si	75 mW (heat from 25°C to 270°C)	600°C	2

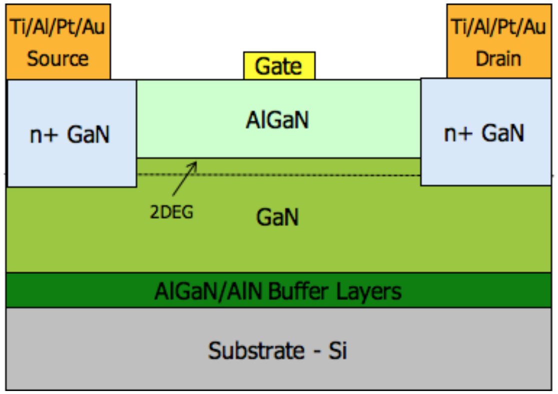
*Demonstrated in the XLab

Principal Investigator: Prof. Debbie G. Senesky (dsenesky@stanford.edu)

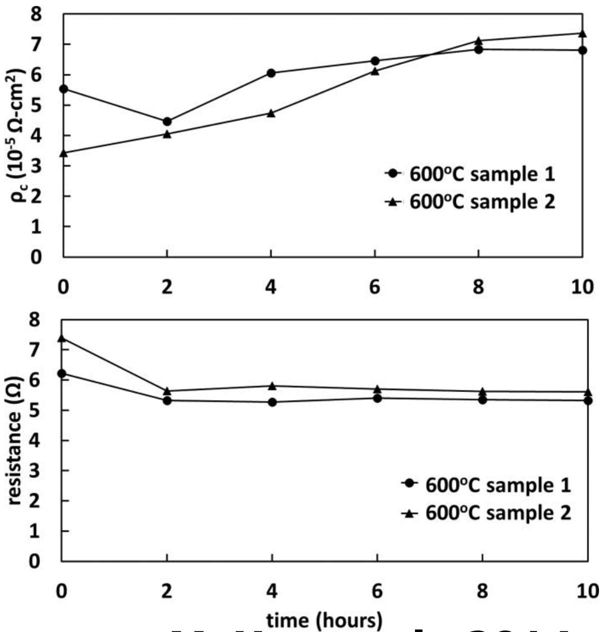
High-temperature Contacts to GaN

Author, Year		Ohmic Metallization	ρ (Ω-cm²)
Zhou, Chen, 2001		Ti/Al/Pt/Au	8.4×10^{-5}
Hu, Ding, 2006		Ti/Al/Pt/Au	1×10^{-5}
Hou, Senesky, 2014	*600C operation	Ti/Al/Pt/Au	1×10^{-5}
Lee, Kou, 2000		Ti/Al/Pt/Au	7×10^{-6}
Selvanathan, Mohammed, 2004		Ti/Al/Mo/Au	3×10^{-7}
Yue, Xing, 2012	Regrown n+ regions	Ti/Au	9.7×10^{-7}
Kumar, Selvanthan, Kuliev, 2002		Ti/Al/Mo/Au	4.7×10^{-7}
Ganguly, Jena et al., 2014	Regrown n+ regions	Ti/Au	2.5×10^{-7}

- Several contact metallization stacks to GaN, InAlN/GaN, and AlGaN/GaN have shown promise
- Formation of nitride alloys such as TiN formed at the interface are thought to cause Ohmic contact behavior
- XLab has shown contact resistance of Ti/Al/Pt/Au-GaN contacts were stable for 10 hrs at 600°C in air (Hou, 2014)
- Lowest reported Ohmic contact resistivities have been achieved through etch-back and regrowth of heavily doped n+ source and drain regions (Ganguly, 2014)



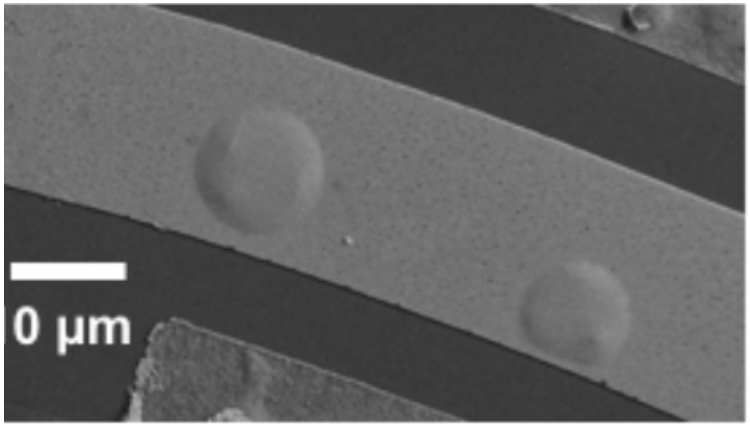
Ganguly et al., 2014



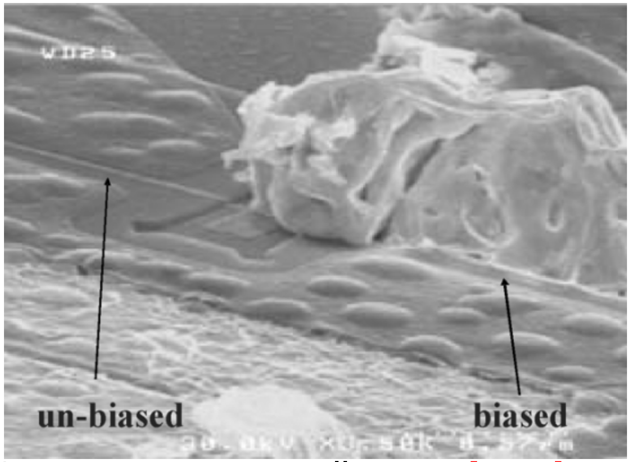
M. Hou et al., 2014

High-temperature Contacts to GaN

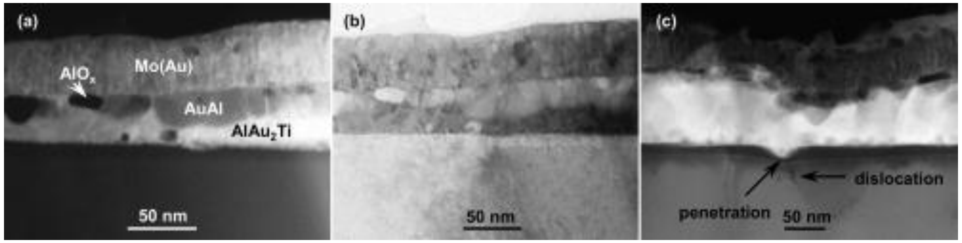
- Currently, reliability of GaN devices at high-temp is limited by contact integrity
- Common failure mechanisms include
  - Au interdiffusion and Ga outdiffusion in Ohmic contacts
  - Gate sinking above 400°C in Schottky contacts
- R_c dependence on metallization ratios and thicknesses + anneal time not well understood
- Further research is needed to lower contact resistivities and improve high-temp reliability



Ni/Au Schottky contacts to AlGaN/GaN exposed to 600°C in XLab, formation of **bubbles** is thought to be from Ni/Au interdiffusion (A. Suria et al., 2017)



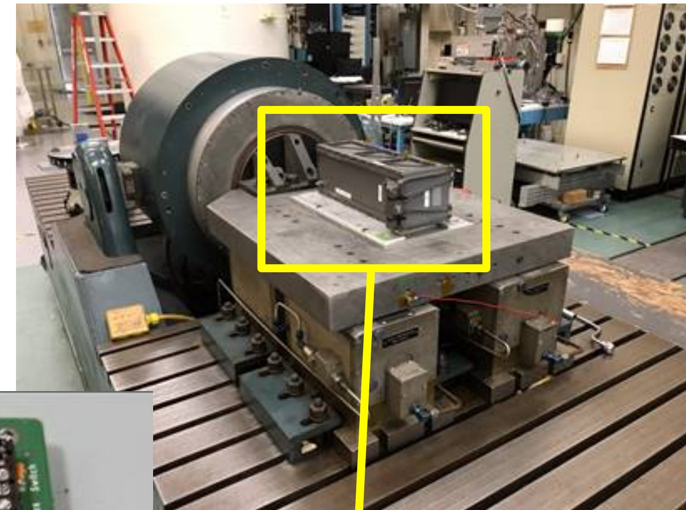
Source contact metallization **breakup** induced failure in InAlN/GaN HEMT after 23 hrs at 700°C (Kohn et al, 2012)



Cross section of a Ti/Al/Mo/Au Ohmic contact stack on AlGaN showing the undesirable **interdiffusion** of Au and the formation of intermetallics after a 600°C anneal (Wang et al., 2007)

Ready, Set, Launch! (Docked w/ISS!)

GaN Sensor Payloads on the KickSat II Mission

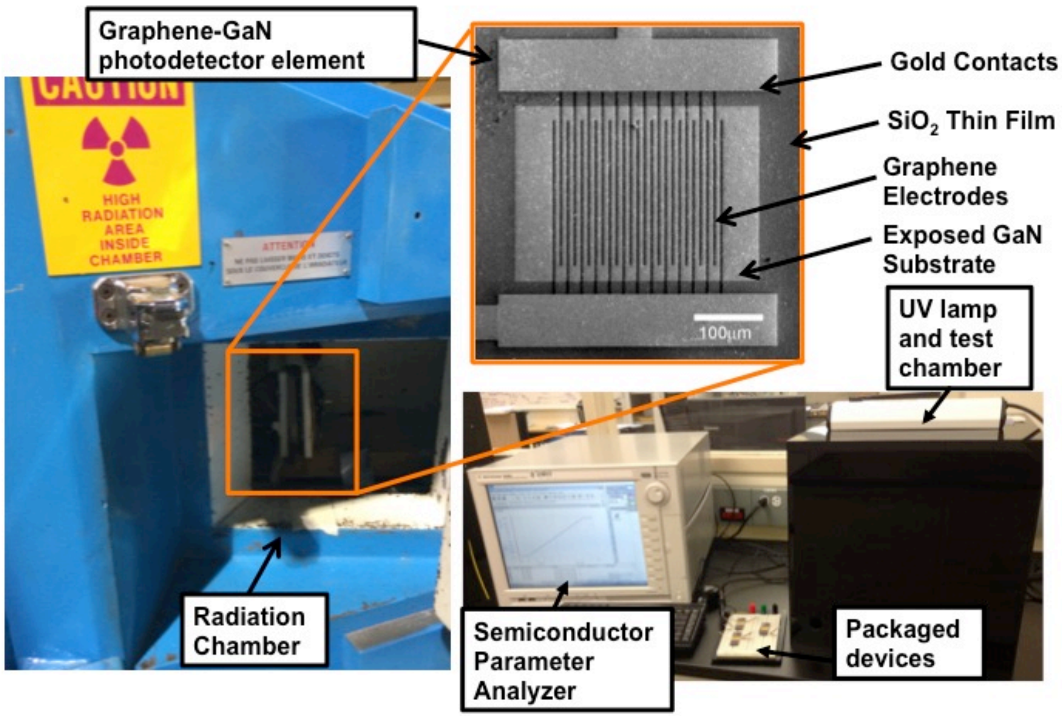


KickSat II cubesat passed shock and vibe!

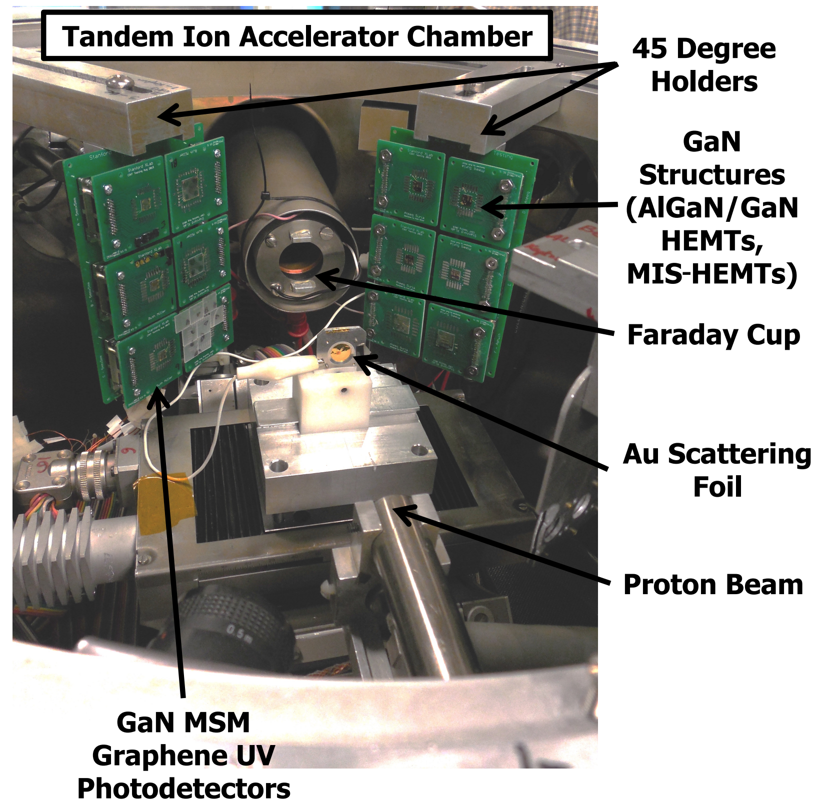
Payload w/ GaN Sensor
(Stanford XLab)

Irradiation (Gamma & Proton) Exposure

Gamma Irradiation at JL Shephard in Pasadena, CA

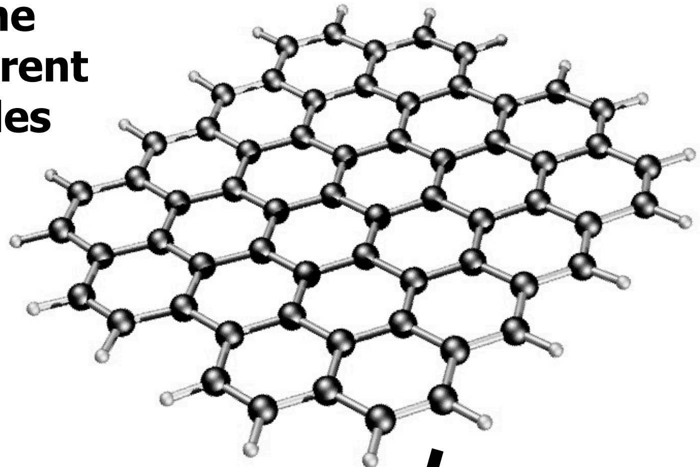


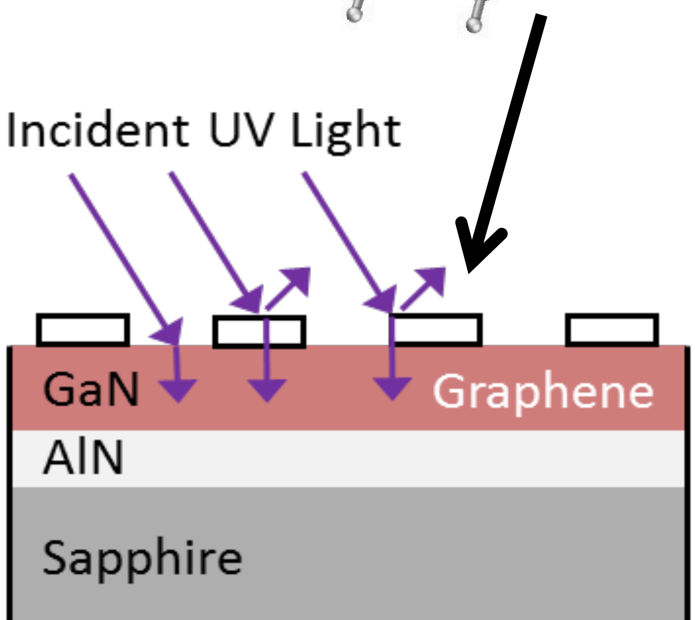
Proton Irradiation at Los Alamos National Laboratory



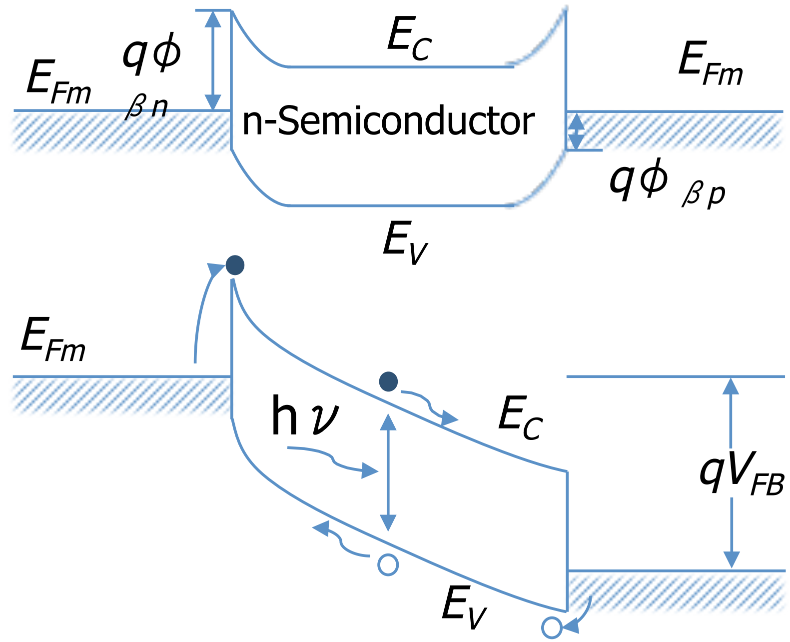
Graphene/GaN UV Photodetectors

Graphene Transparent Electrodes





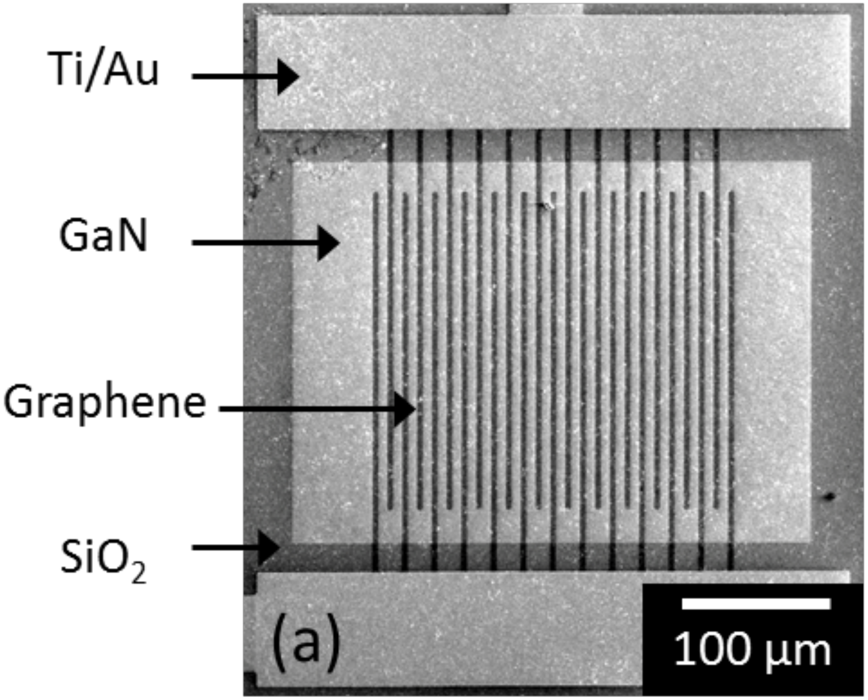
In the metal-semiconductor-metal (MSM) architecture, electrodes and semiconductors are typically considered back-to-back Schottky barriers



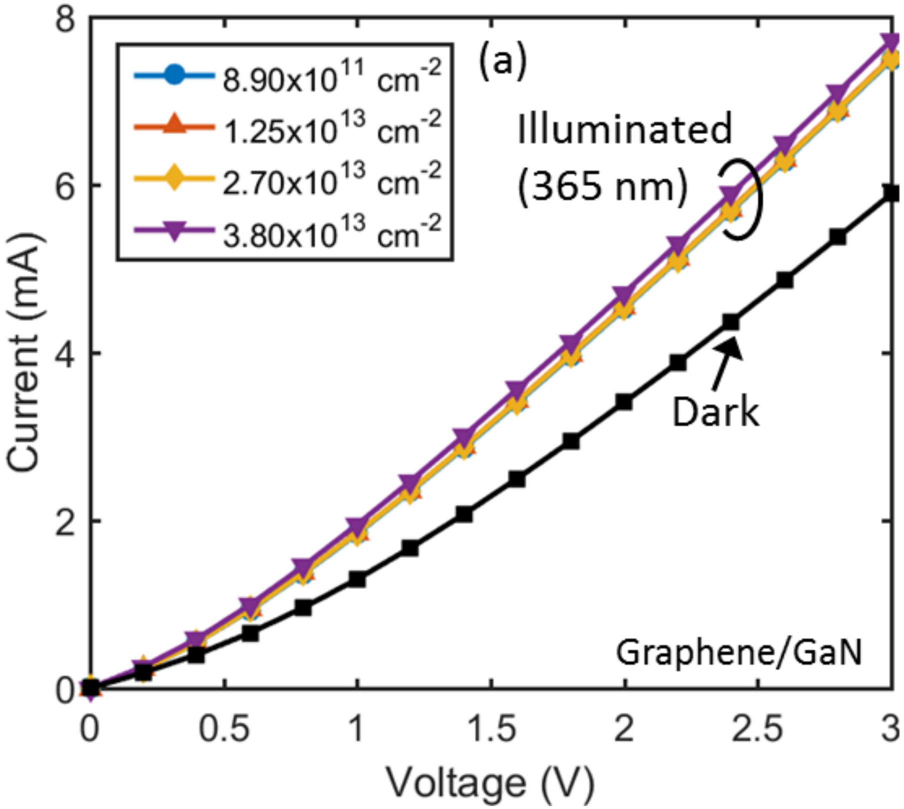
Light passes through exposed active area

Photogenerated current under applied bias

Graphene/GaN Under Proton Irradiation

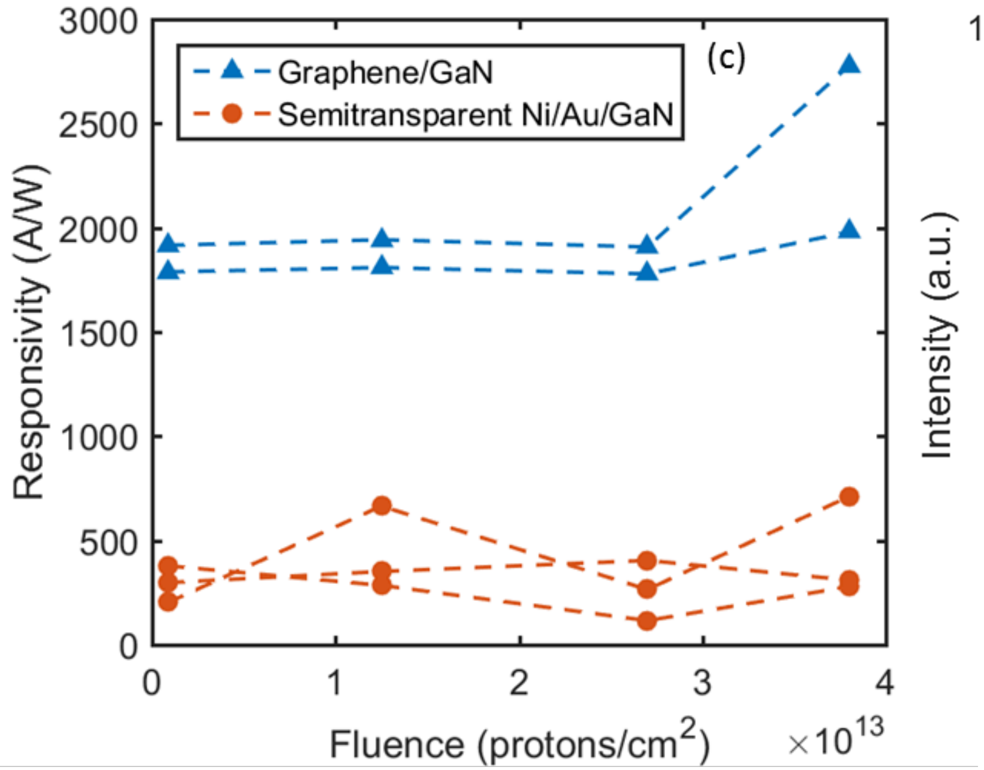


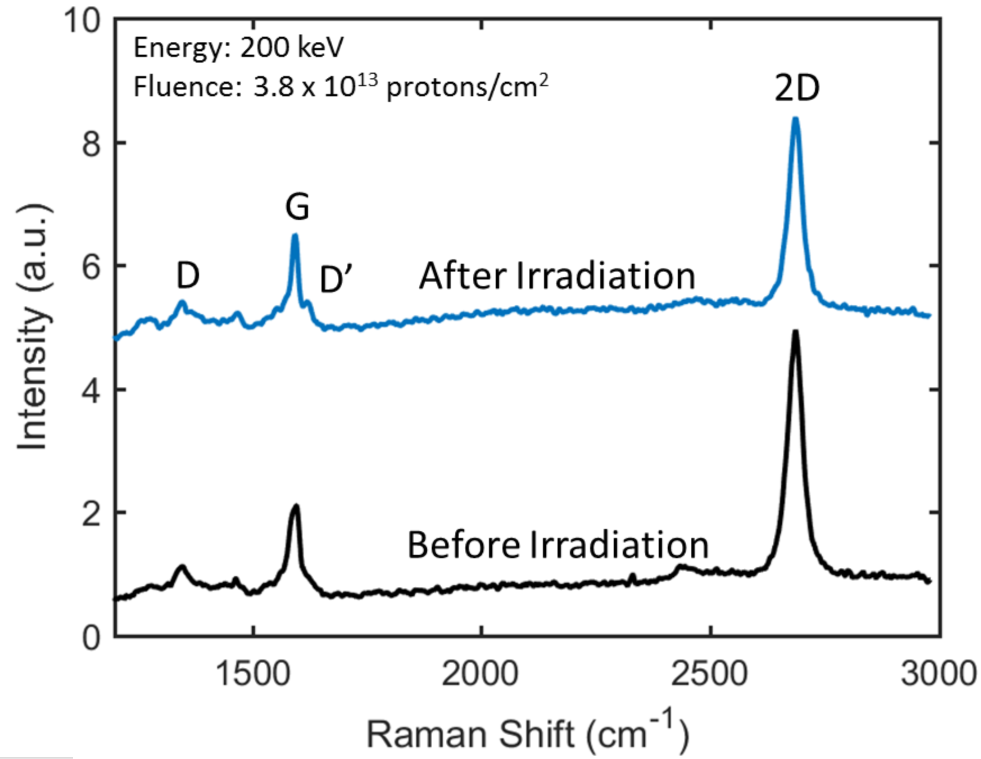
SEM image of microfabricated graphene photodetector element on GaN thin film on sapphire.



1.) H. C. Chiamori et al., SPIE DSS, 2015.
2.) R. Miller et al., Applied Physics Letters, 2017.

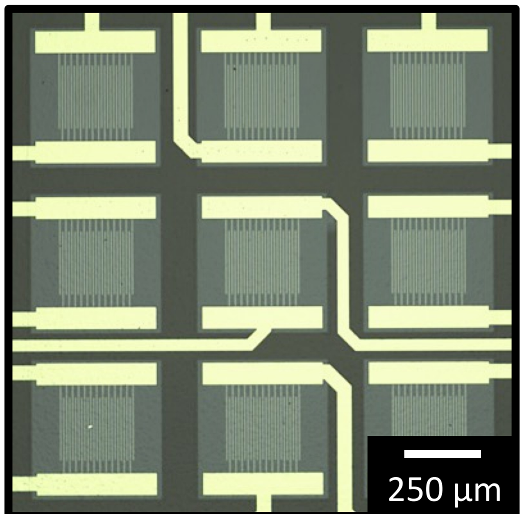
Graphene/GaN Under Proton Irradiation



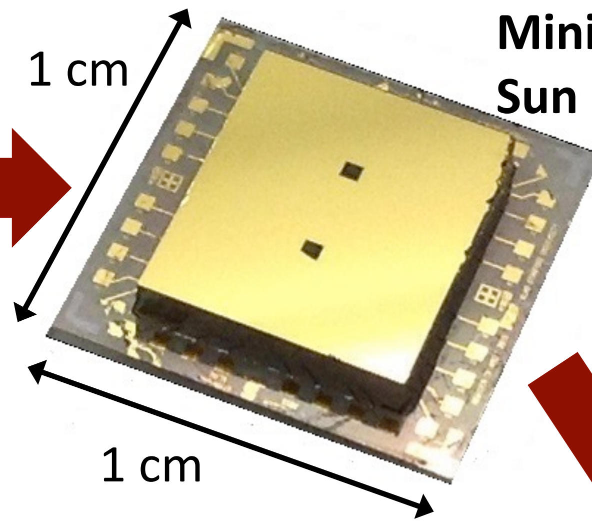


R. Miller et al., Applied Physics Letters (2017)

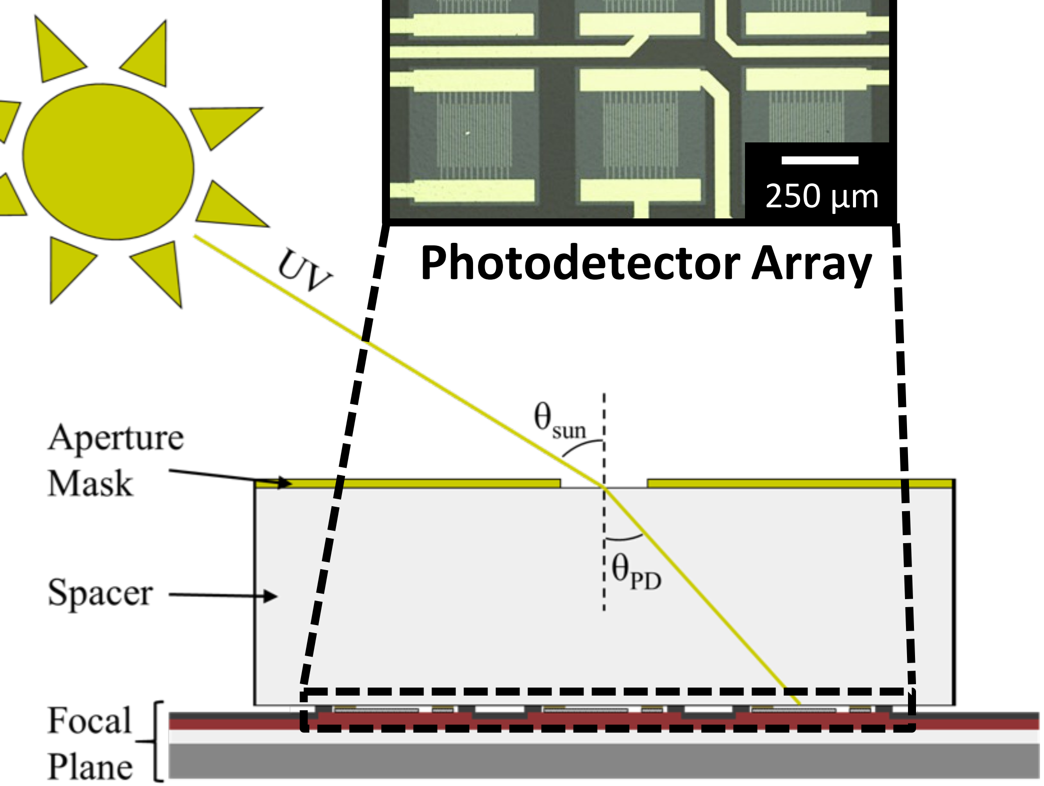
GaN UV sensors for CubeSats



Photodetector Array



Miniature Sun Sensor



CubeSat Orientation

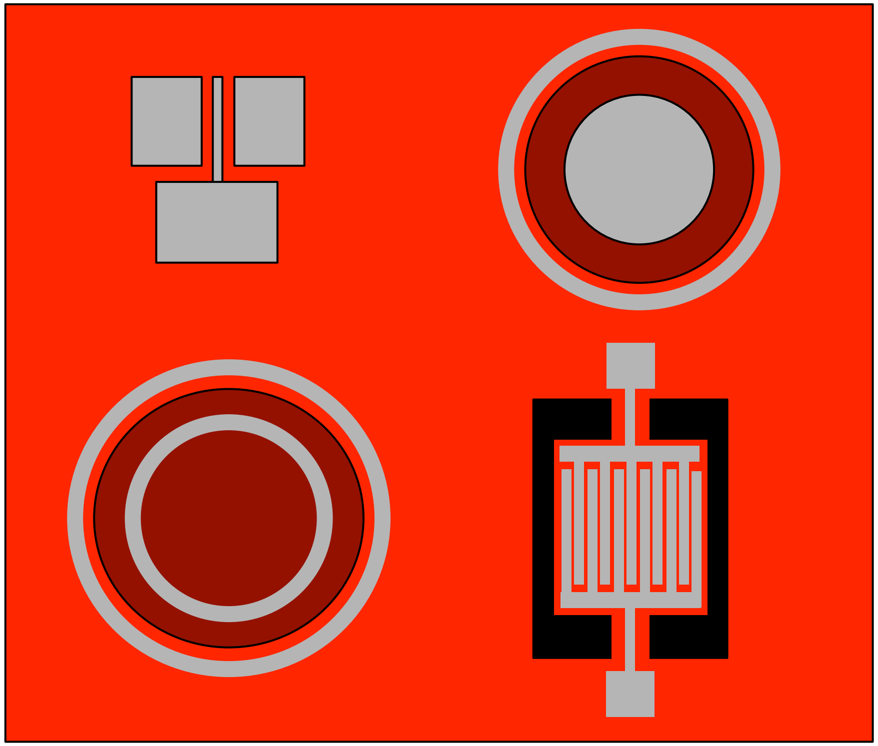
R. Miller *et al.*, Rev. Sci. Instrum. (2016)

Multifunctional Device Integration

- **Development of multiple devices (HEMT circuits, energy harvesters, sensors and RF resonators) on a single chip using the multi-functional properties of the AlGaN/GaN heterostructure.**

GaN High Electron Mobility Transistor (HEMT) Circuit

GaN Sensor (e.g. acceleration, pressure)

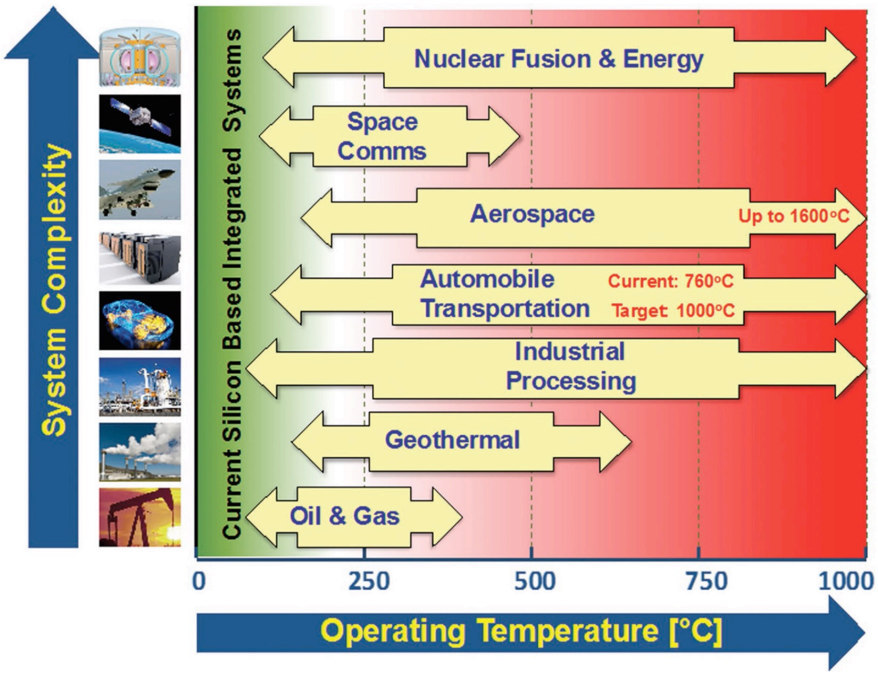


GaN Piezoelectric Energy Harvester

GaN Piezoelectric RF Resonator

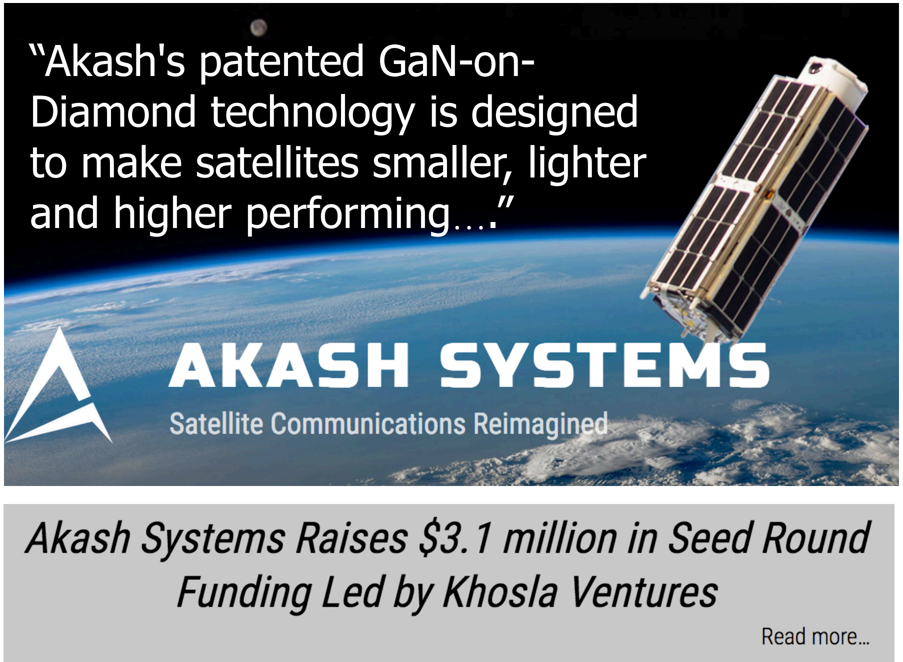
Extreme-environment GaN Electronics

High-temperature Operation



Tsao, J. Y. et al., *Advanced Electronic Materials* (2017)

Radiation-rich Environments



Thank You!

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