Enabling Circuits and Technologies for Addressing Some of the 21st Century's Hard Energy Challenges with Wide Bandgap Semiconductors and Devices

Dong Ji, Burcu Ecran, Mohammad Malakoutin, Siwei Li, Chenhao Ren, Maliha Noshin, Rafael P. Martinez, Jaeyi Chun, Rohith Soman, Yingying Li, Shreyas Muralidharan
& Srabanti Chowdhury

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Alumni : Shirong Zhao, Saptarshi Mandal, Maitreya Dutta, Wenwen Li,, Jiyani Gao, Zheng Xu, Saba Rajabi, Matthew Laurent, Joseph Brown, Dong Ji , Mahadeva Bhat

***Intel, Alpha-Omega, Apple, Skyworks, Global Communication SC, GigaDevice, Northorp Grumman**

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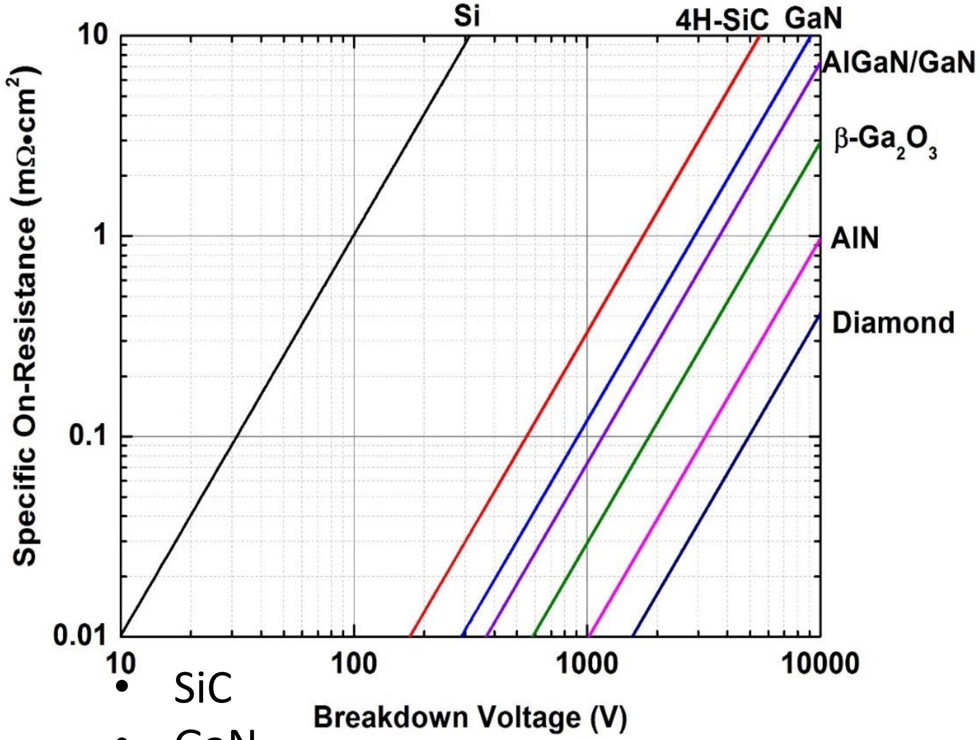
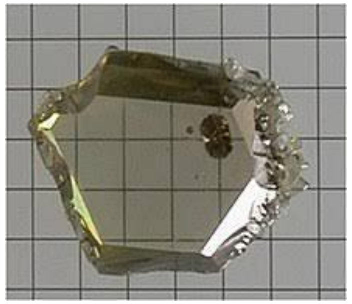
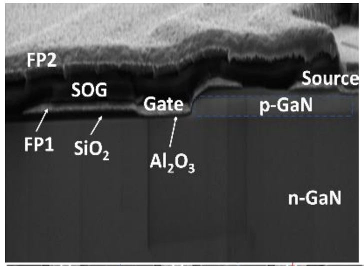
A vertically integrated approach to understand the potential of WBG materials

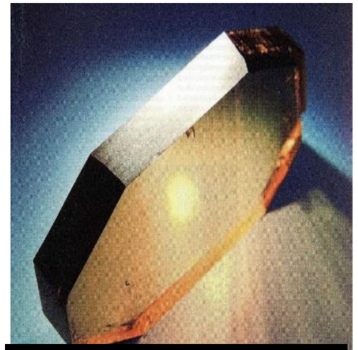
Figure of Merit

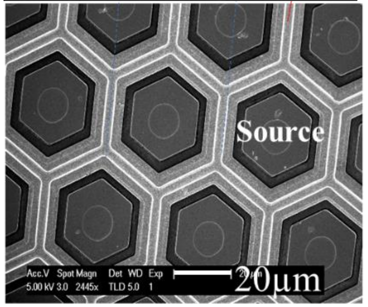


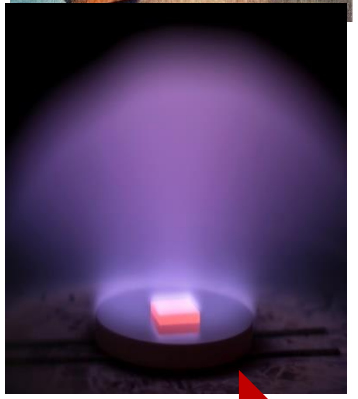
- SiC
- GaN
- AlN
- Ga_2O_3
- Diamond

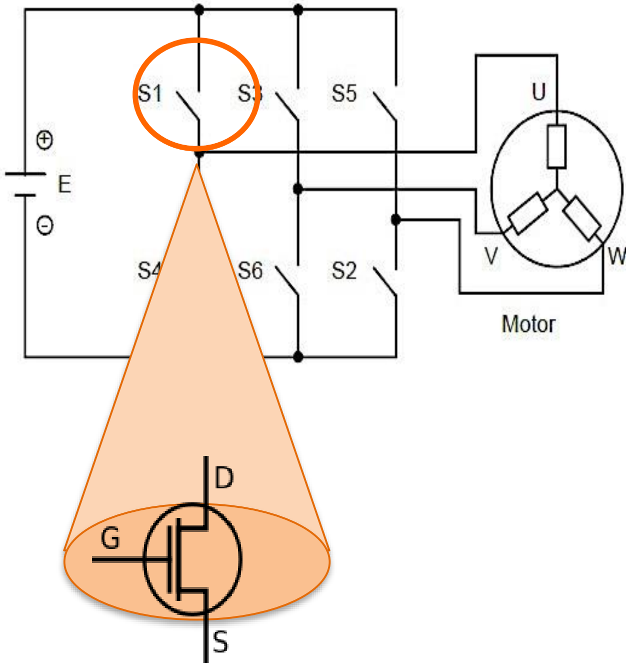






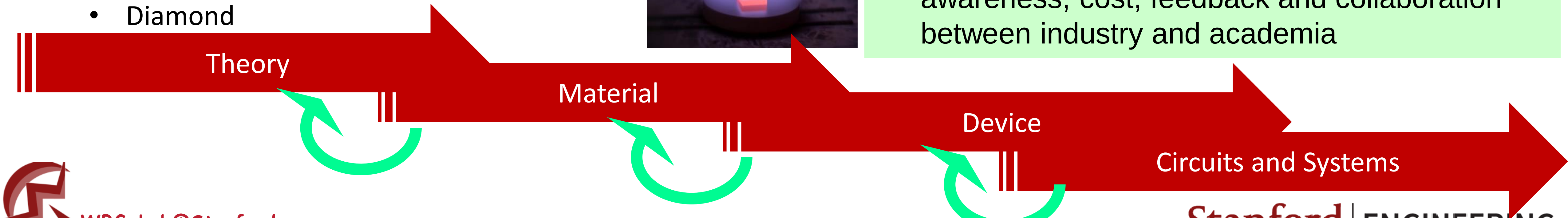






Enables

- ✓ COMPATIBILITY with an existing architecture
- ✓ Performance from device to Circuit to system
- ✓ Define new architectures
- ✓ A sustainable eco-system that develops with awareness, cost, feedback and collaboration between industry and academia



WBG-Lab@Stanford

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Power conversion is ubiquitous

21st century electronics: Enable Electrification

More Electricity is Supplied by Electronic Sources

Most of Electricity is Consumed by Electronic Loads

- Efficiency
- Weight & Size
- Reliability & Lifetime
- Thermal Management
- Power Management
- Subsystem Interactions
- Power Quality
- EMI
- Cost
- Maximize Power Density

Adapted from Prof. Dushan Boroyevich's talk (Virginia Tech.)

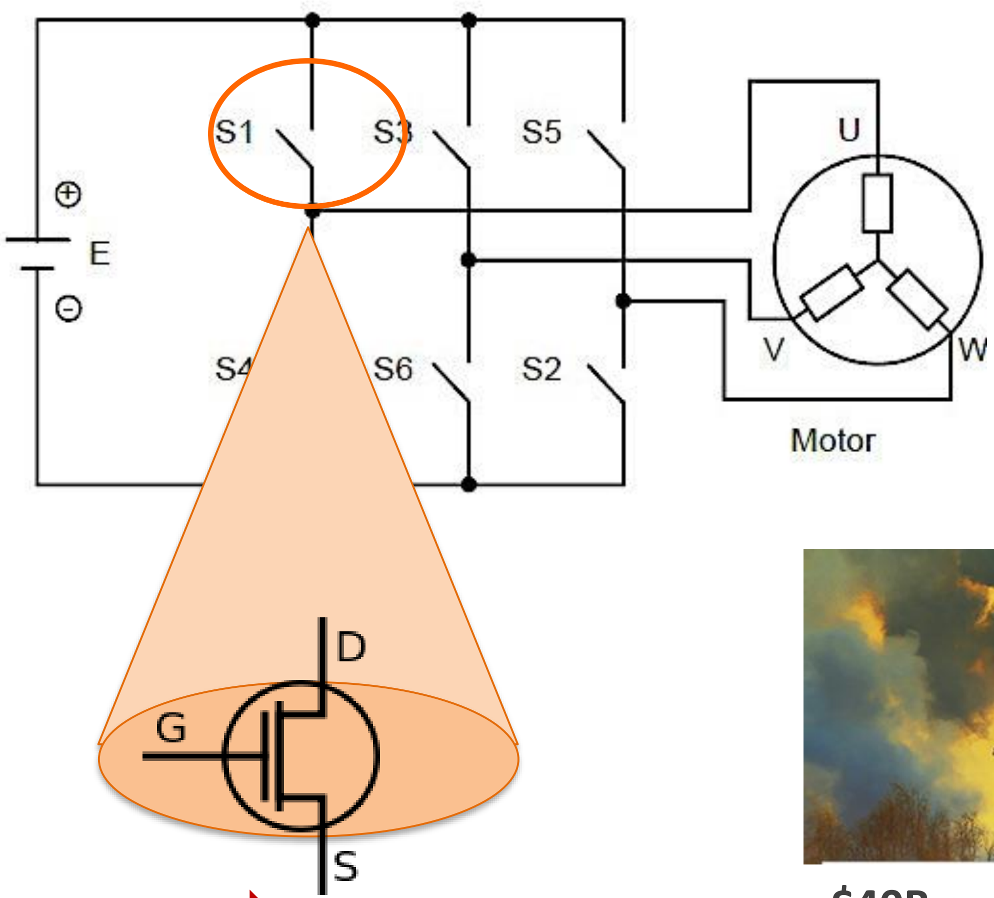
The role of a semiconductor device

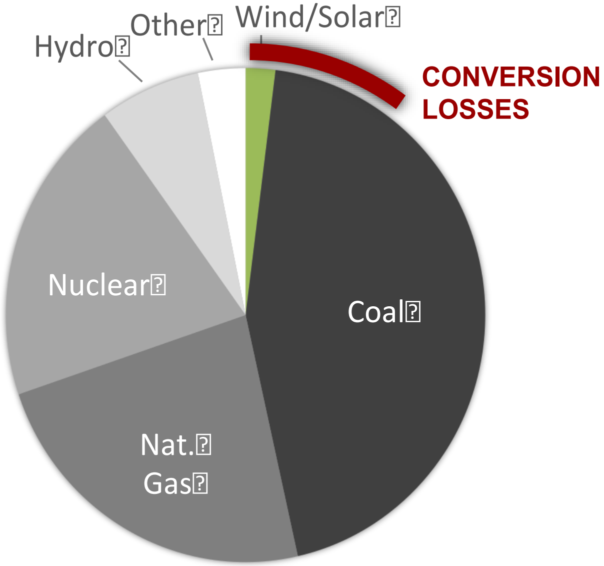
The integral part of a power converter is a "Switch"

Residential/Commercial

Industrial

Transportation





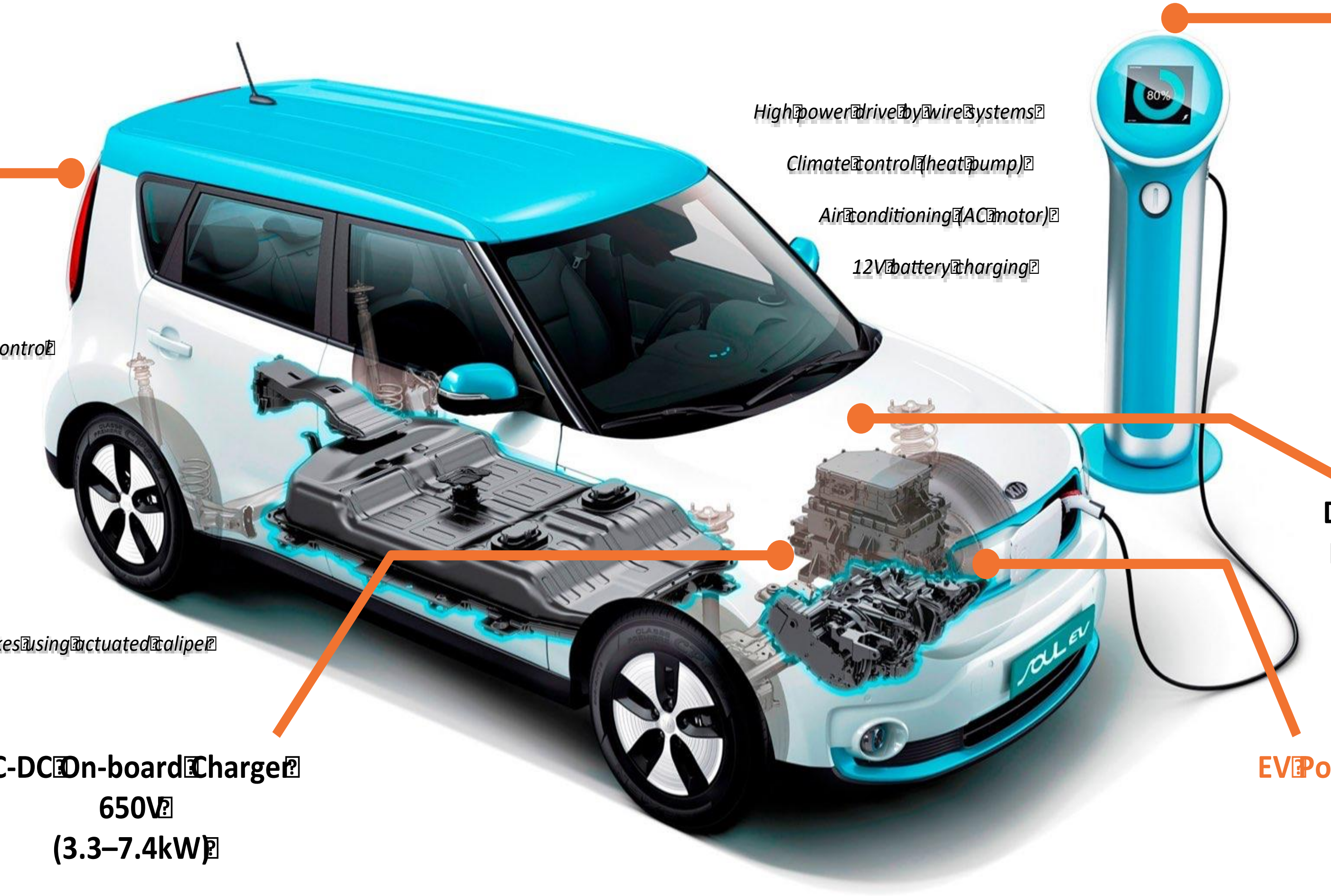
U.S. Electricity Generation
(EIA 2009)

$40B economic cost
318 coal power plant-equivalent
>300TWh annual consumption of entire West coast

Device platforms to support 100's W to 100's MW efficiently

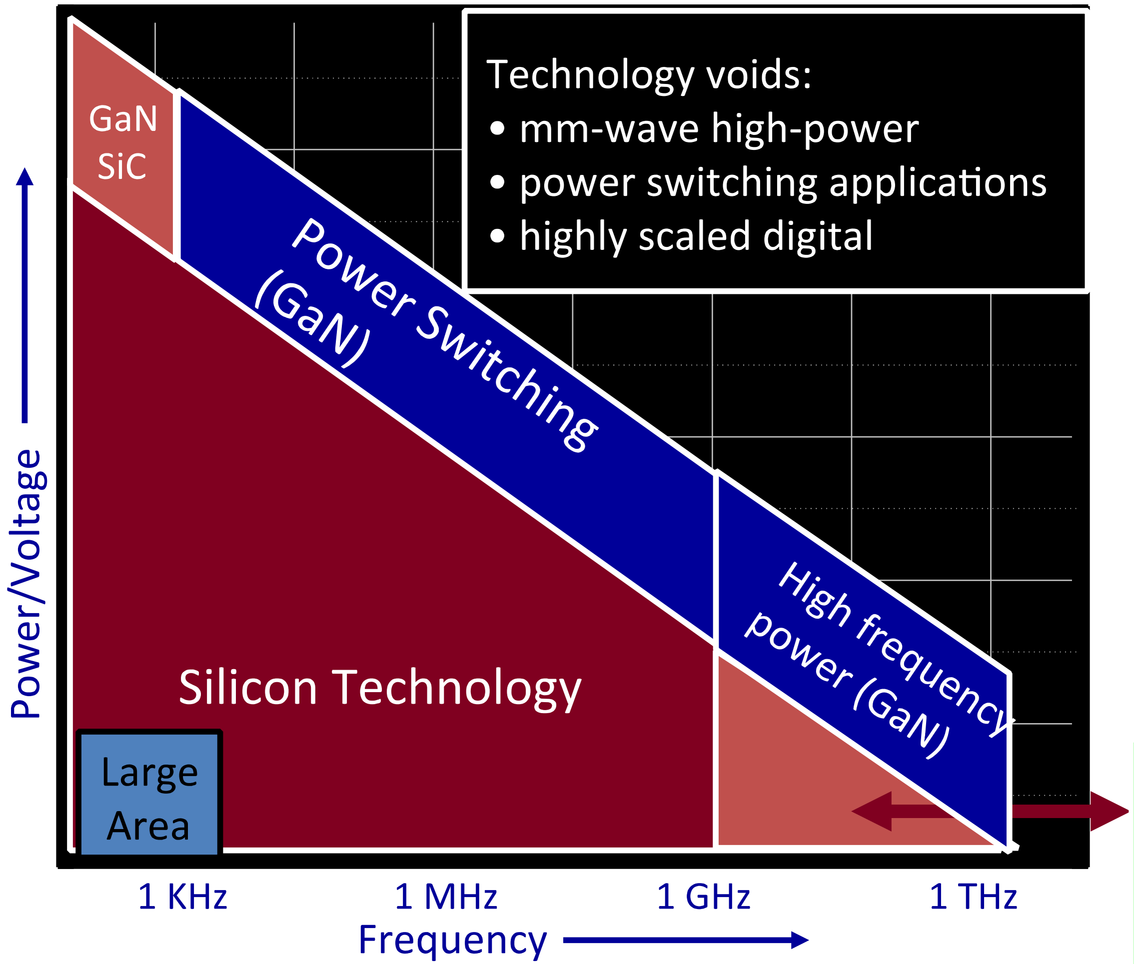
Zooming into one of the current application : EV

Efficiency, Weight & Size, Reliability & Lifetime, Thermal Management, Power Management, Cost



Device platforms to support 100W to 100KW efficiently with high reliability

Identifying technology voids : High frequency power switching

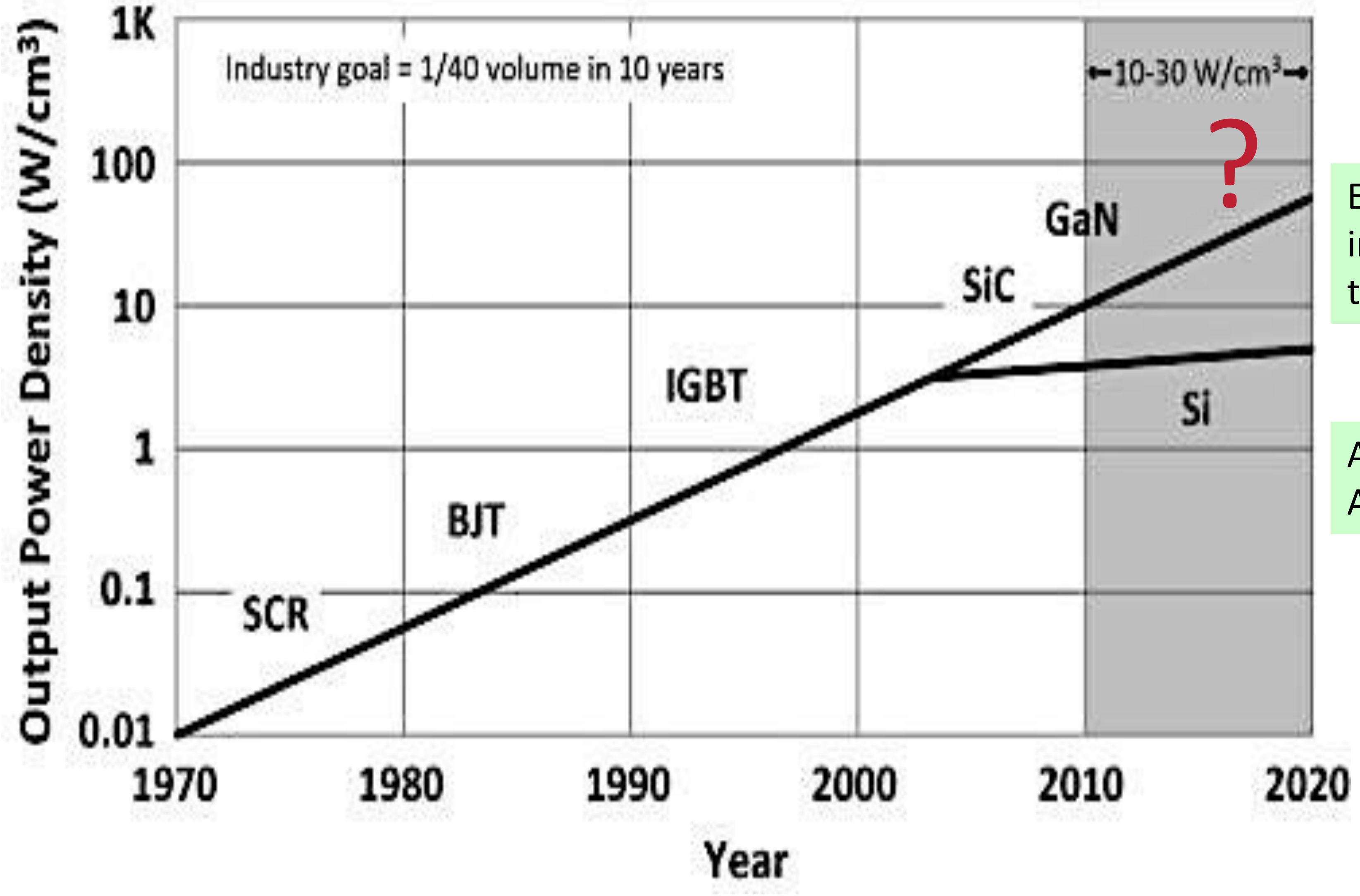


- GaN
- SiGe
- InP
- GaAs
- Nanotubes

How can power density increase?

"Moore's Law" of Power Electronics

Ga_2O_3, Diamond, AlN, BN?

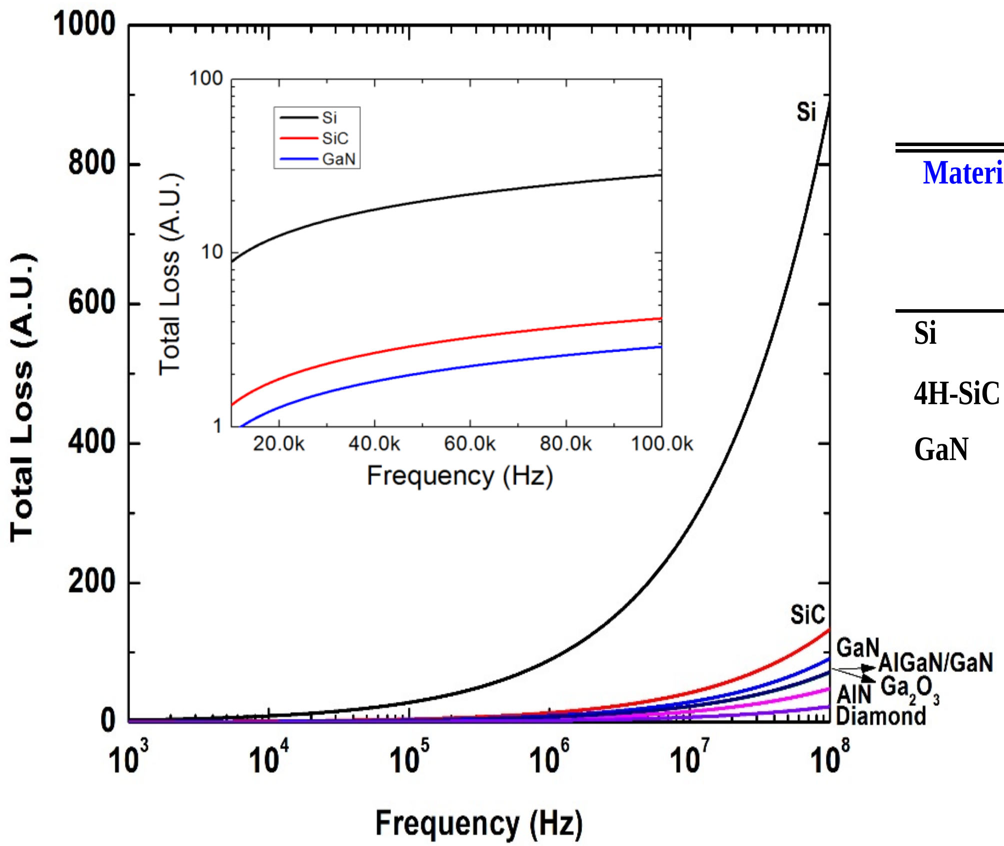


Exhausting all circuit-based innovations –with topologies and tactics

Adding new material
Adding new device platform

Power Devices: Dynamic Loss Argument

$$P_{\text{loss,min}} = \frac{\left\{4I_{\text{rms}}(V_B V_D)^{\frac{3}{4}}\sqrt{\frac{kI_D f}{i_{g,\text{av}}}}\right\}}{(E_c\sqrt{\mu})} \Rightarrow HMFOM = E_C\sqrt{\mu}$$



Material	Mobility (cm^2/Vs)	Dielectric constant (ε)	Bandgap (eV)	Critical Electric field (E_C, MV/cm)	HMFOM
Si	1400	11.7	1.12	0.3	1
4H-SiC	700	9.7	3.26	3.1	7.5
GaN	900	9	3.4	3	8

High mobility channel also minimizes the switching losses and therefore the total loss at higher frequencies

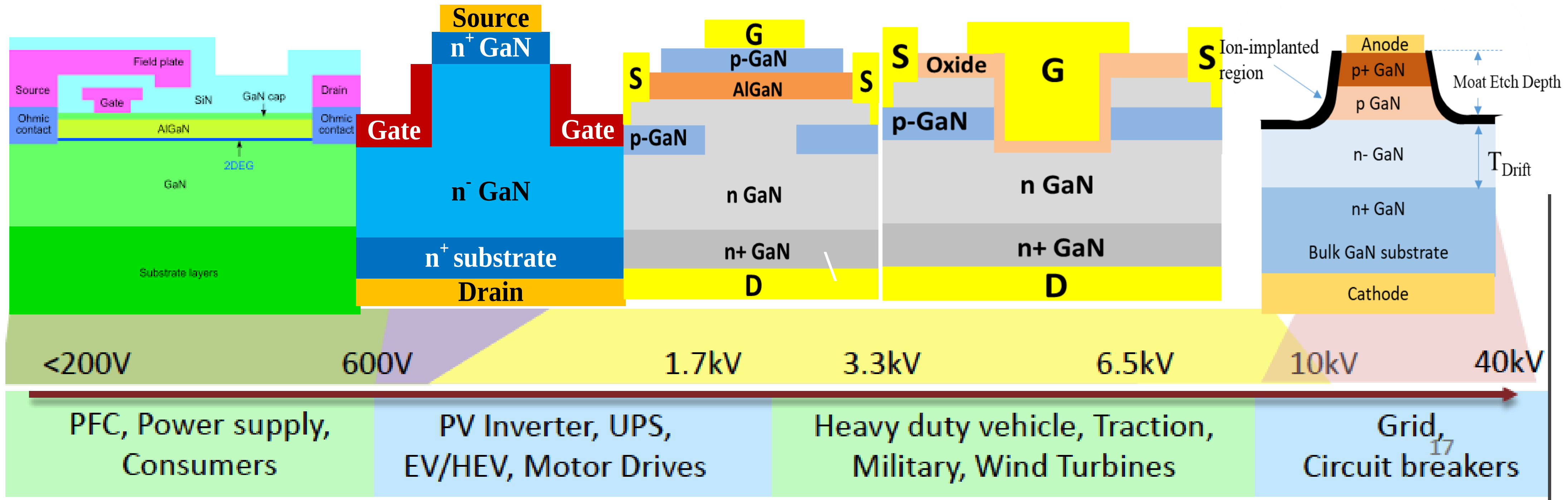
Today, repeatable bulk mobility over 1200cm^2/V.s is achieved in Univ. research lab and industry

D. Ji and S. Chowdhury, "Design of 1.2 kV Power Switches With Low RON Using GaN-Based Vertical JFET," IEEE Trans. Electron Devices , vol. 62, no. 8, pp. 2571–2578, 2015

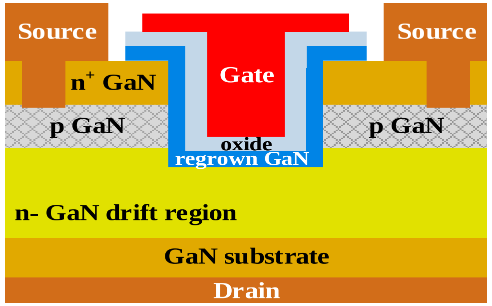
WBG lab activities : Creating a GaN platform

Lateral | Vertical

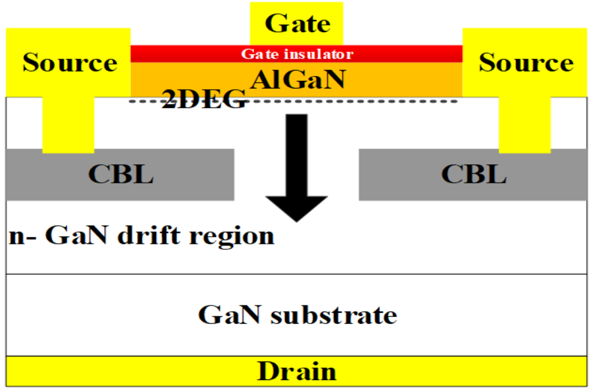
HEMTs **SITs** **CAVET** **MOSFET** **DIODES**



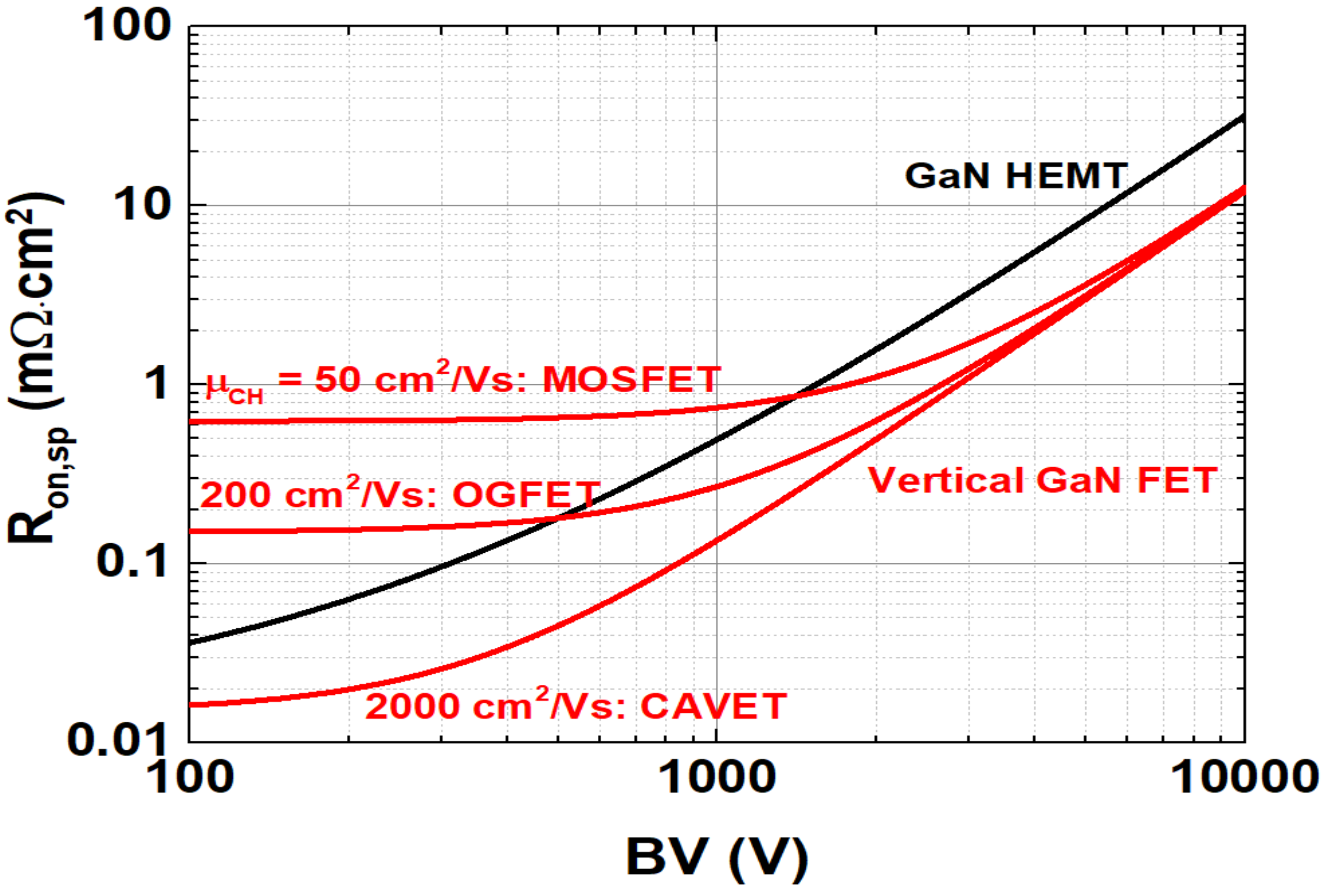
Vertical GaN FETs for >10KW /1kV applications



Oxide GaN interlayer based MOSFET (OGFET)



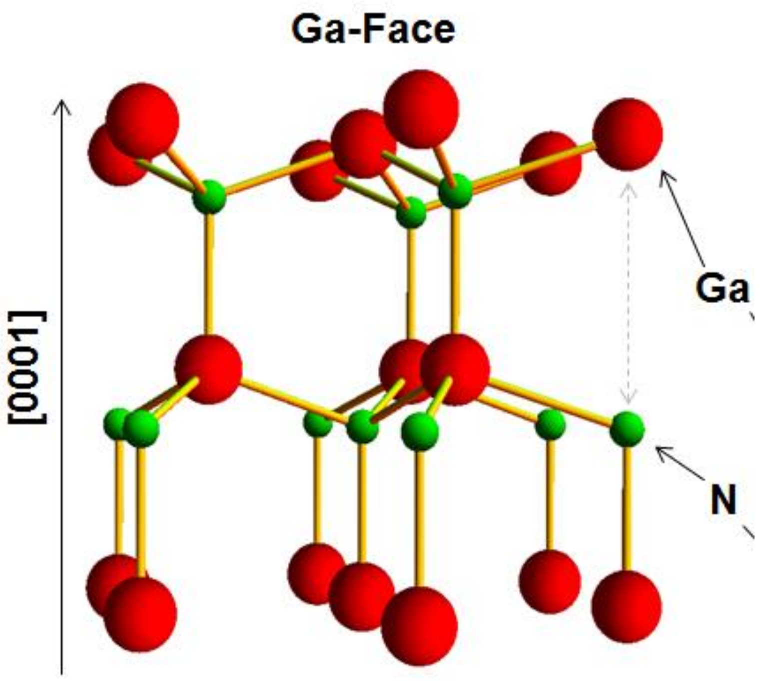
GaN CAVET

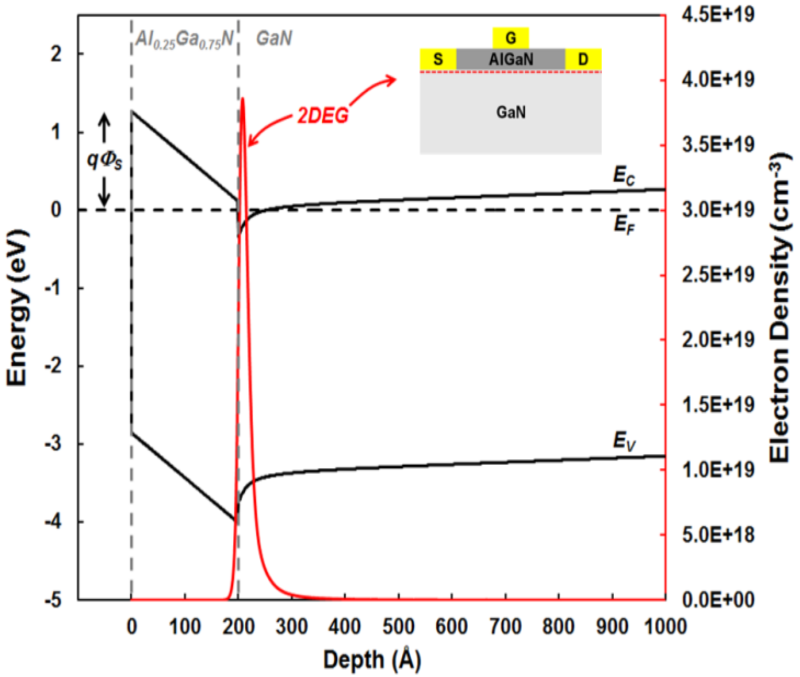


Higher drift layer mobility (>1200cm²/Vs) + Higher Channel mobility (>185cm²/Vs) distinguishes GaN from SiC

Avalanche based devices

Polarization doped high mobility channel in HEMT





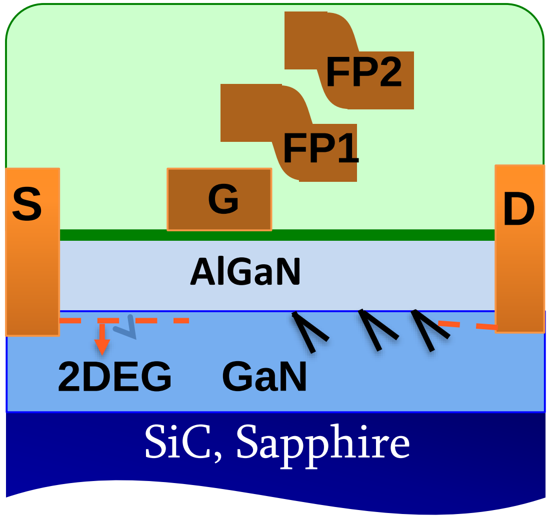
2-Dimensional Electron Gas 2DEG

Net Polarization

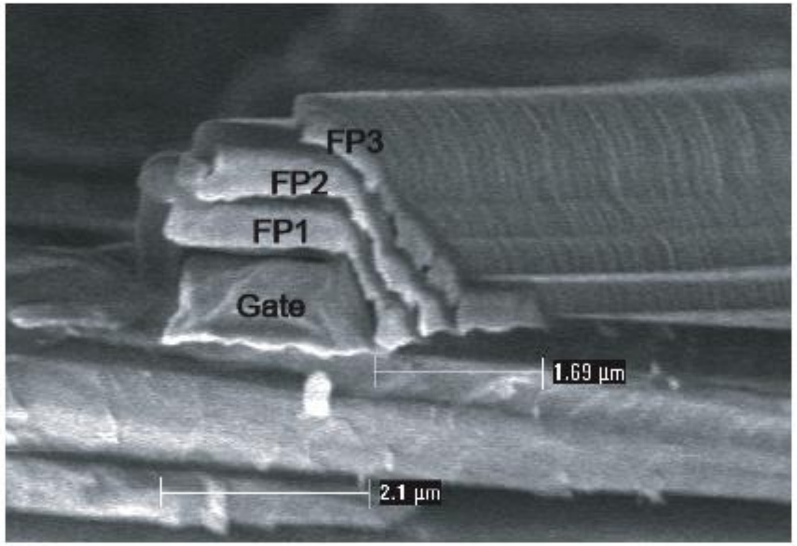
$\Delta P_{SP} + P_{PE}$

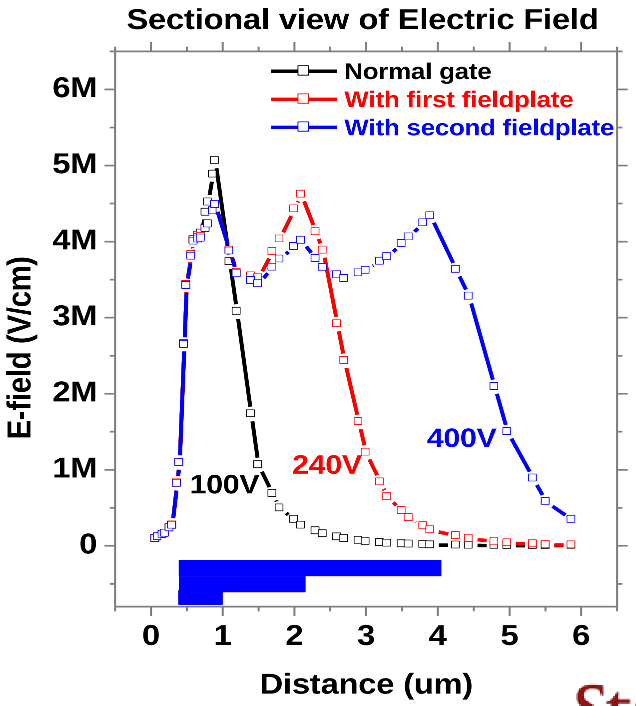
- Unlike inversion channel in MOSFET, HEMTs rely on the polarization difference at the AlGaN-GaN interface to induce 2DEG
- No scattering from the positive charge due to the periodic nature
- Electron mobility of 2200cm^2/Vs in channel

Power HEMTs: Field plates increase breakdown voltage



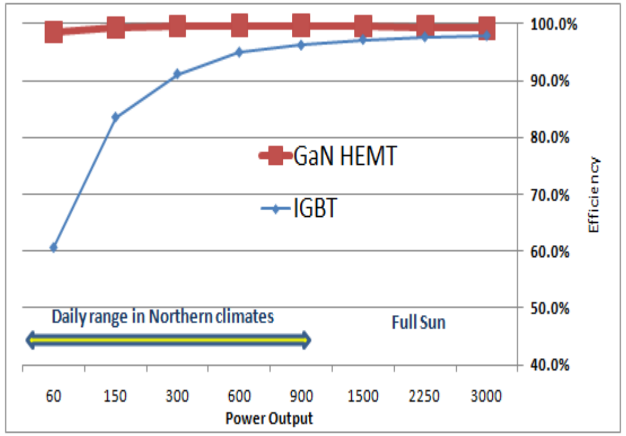
	GaN	InN	AlN
Bandgap (eV)	3.4 eV	0.6 eV	6.4 eV
Mobility ($cm^2V^{-1}s^{-1}$)	2200	>3000	300
Breakdown Field (MV/cm)	3	Low	11
Effective Mass	0.21 m_e	0.09 m_e	0.4 m_e
Velocity (cm/s)	2 x 10^7	2 x 10^8	-
Polarization	High charge, carrier confinement		





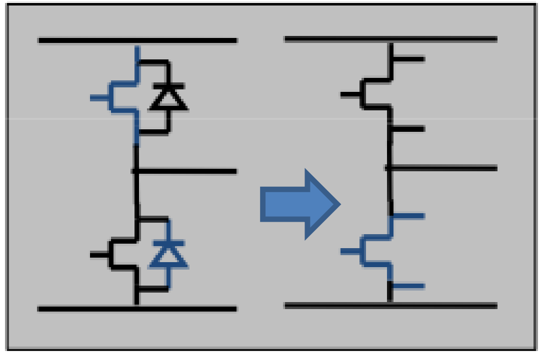
Three big innovations made possible by GaN transistors

Low switching loss allows constant efficiency over all loads (hard-switched topologies)



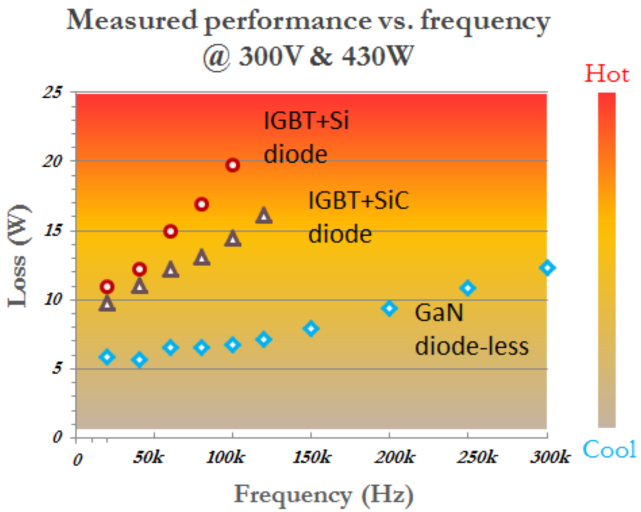
Highest delivered efficiency: 99.2% record demonstrated

Bidirectional nature allows diode free bridges



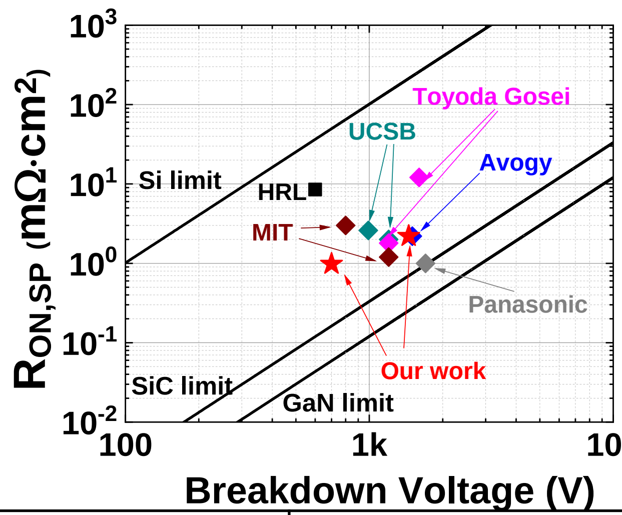
Diode-free operation

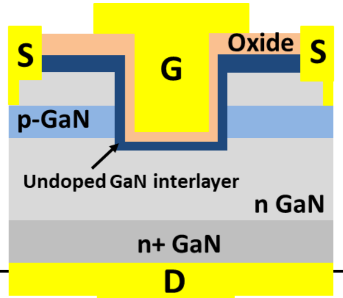
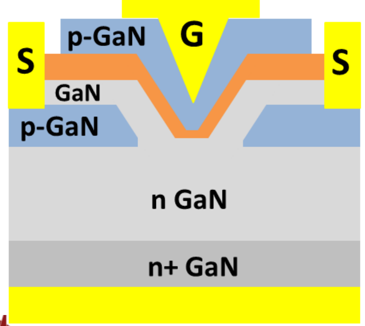
High frequency devices enables compact magnetics

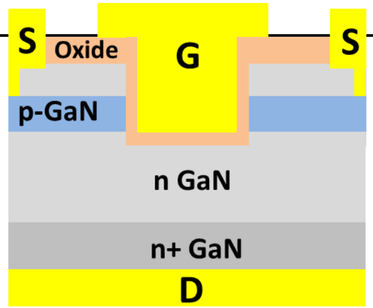
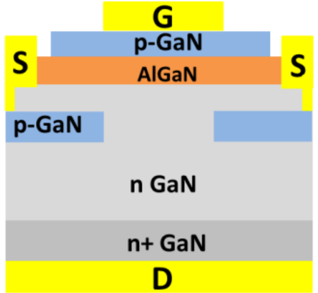
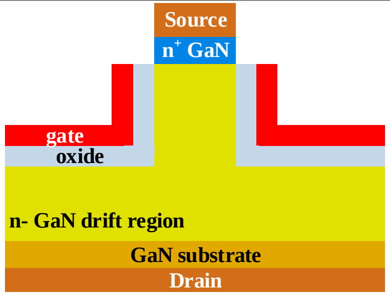
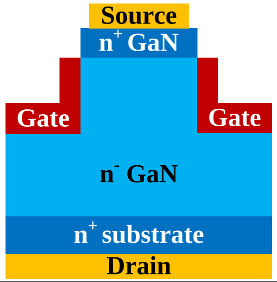


High efficiency compact power conversion units

Vertical GaN FETs: Selected few (key) device results

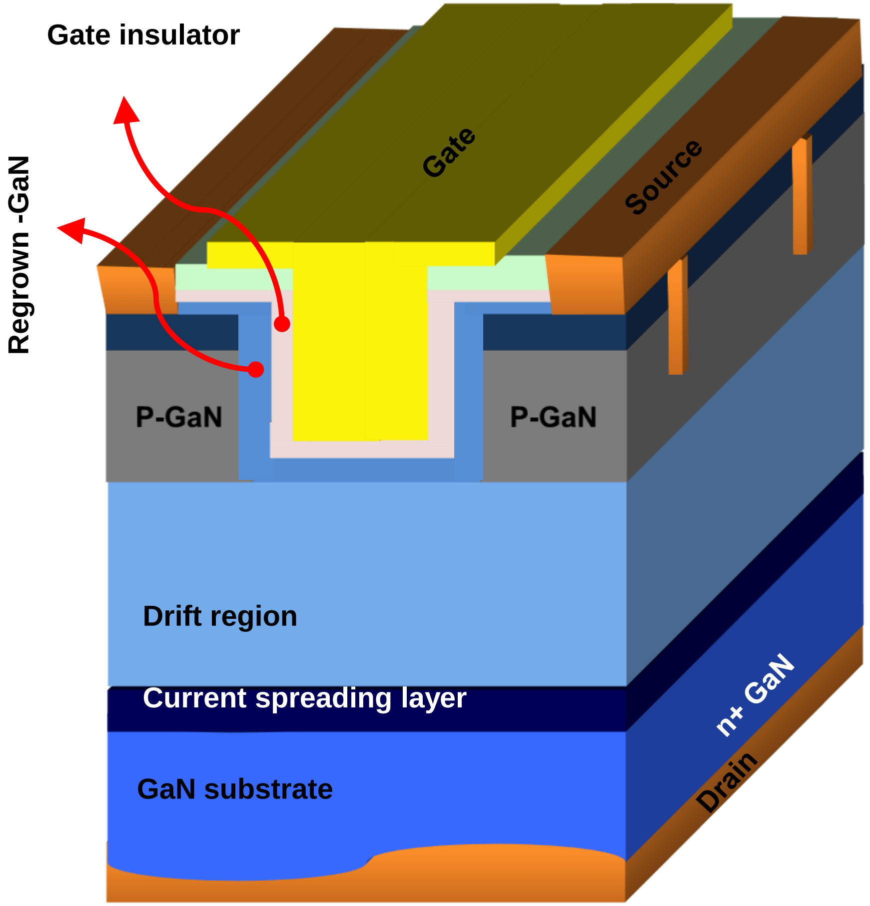


Device structure	Key results	Reference
	(1) 1.4KV/ 2.2mΩcm² (2) 1.2 KV/2mΩcm2	1. D Ji et al, IEDM, 2017. 2. C. Gupta et al., EDL, 2017.
	(1) 1.7KV/ 1 mΩcm² (2) 880V/2.7mΩcm²	1. D. Shibata et al., IEDM, 2016. 2. D. Ji et al., EDL, 2018.

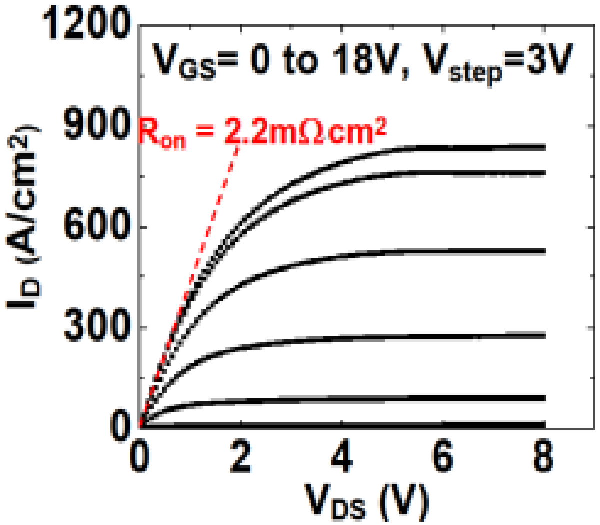
Device structure	Key results	Reference
	(1) 1.2KV/ 1.8mΩcm² (2) 1.6kV/12.1mΩcm²	1. T. Oka et al., APEX, 2015. 2. T. Oka et al., APEX, 2014.
	1.5KV/ 2.2 mΩcm²	H. Nie, et al., EDL, 2014.
	1.2 KV/ 1 mΩcm²	Y. Zhang et al., IEDM, 2017
	150V/1.48mΩcm²	J. Chun et al., Adv. Elec. Matt., 2019.

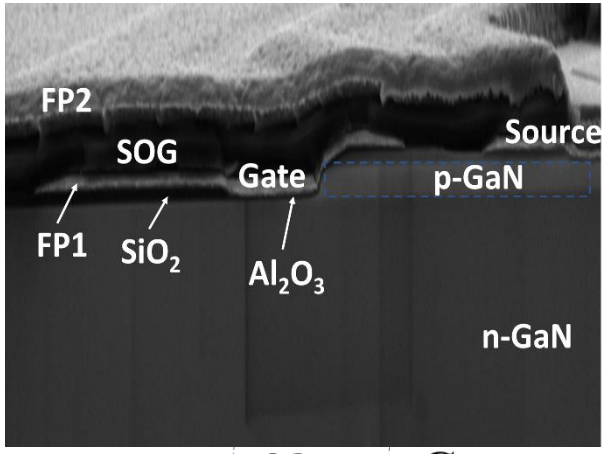
Trench MOSFETs: 1.4kV/2.2mΩ.cm^2

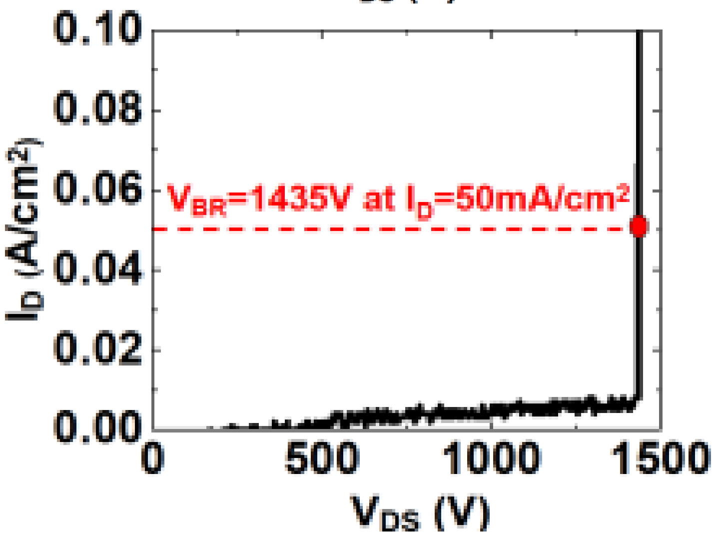
- Drift layer doping <1E15/cm^3
- Channel mobility : highest reported to date 185cm^2/Vs

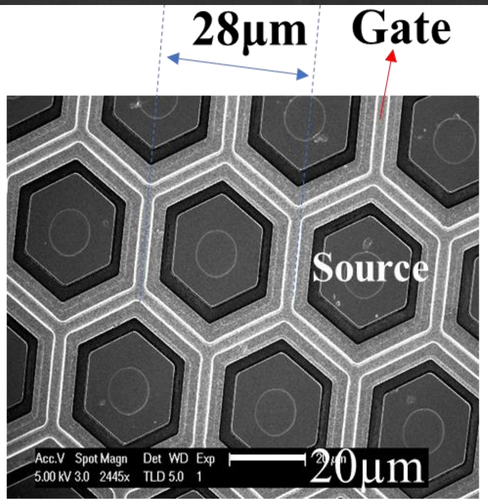


>1.4kV normally-off switches with R_{on} <2.2mΩcm^2





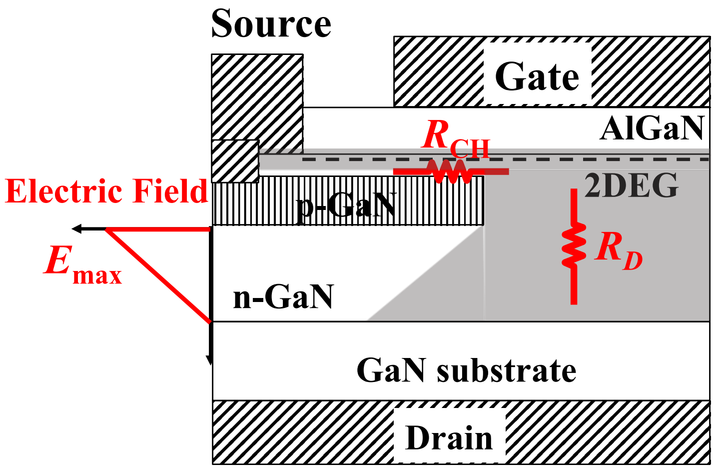




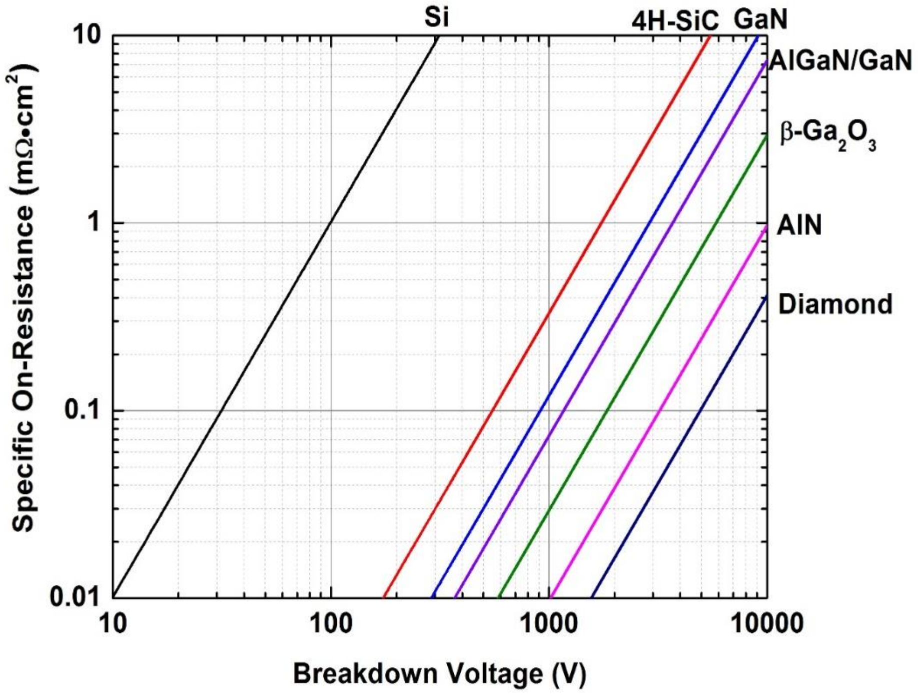
D.Ji… S.Chowdhury , IEDM 2017

Why go for vertical when we have HEMTs

: resistivity argument



$$R_{ON,SP} = \frac{4BV^2}{\epsilon_S \mu_n E_C^2}$$



INFLUENCES OF MOBILITY ON V_{BR} AND R_{on}

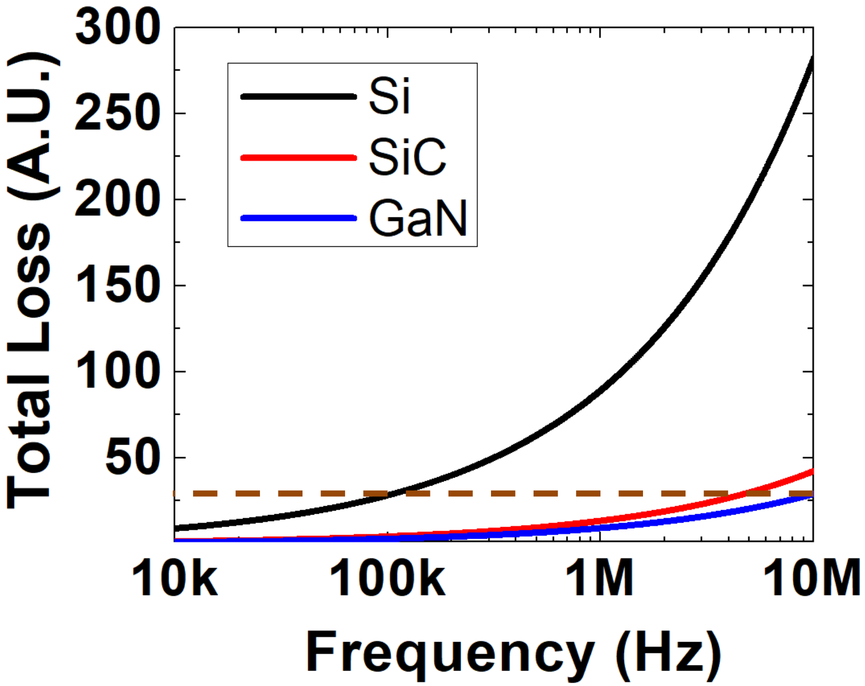
Mobility (cm²/vs)	V_{BR} of VC-VJFET (V)	R_{on} of VC-VJFET (mΩ•cm²)	V_{BR} of LC-VJFET (V)	R_{on} of LC-VJFET (mΩ•cm²)
1100	1240	4.1	1200	1.4
900	1260	5.2	1310	1.7
700	1280	7.0	1400	2.2
500	1300	10.3	1400	3.1

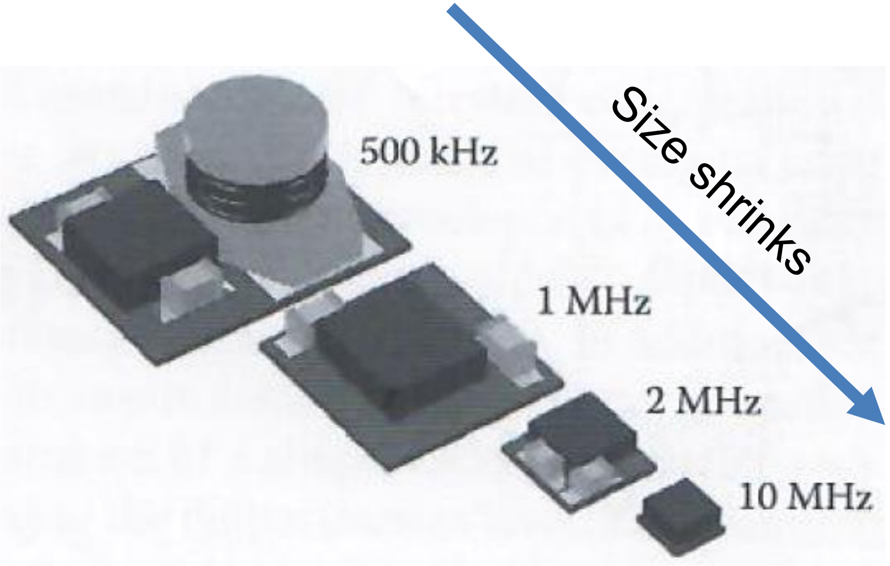
With R_{on} ~ 1mΩ.cm² air cooling can be used if GaN replaces today's Si device in Toyota Prius

D. Ji and S. Chowdhury, "Design of 1.2 kV Power Switches With Low RON Using GaN-Based Vertical JFET," IEEE Trans. Electron Devices , vol. 62, no. 8, pp. 2571–2578, 2015

Why go for vertical when we have lateral (HEMTs)

$$P_{\mathrm{loss,min}} = \frac{\left\{4 I_{\mathrm{rms}} (V_B V_D)^{\frac{3}{4}} \sqrt{\frac{k I_D f}{i_{g,\mathrm{av}}}}\right\}}{(E_c \sqrt{\mu})}$$



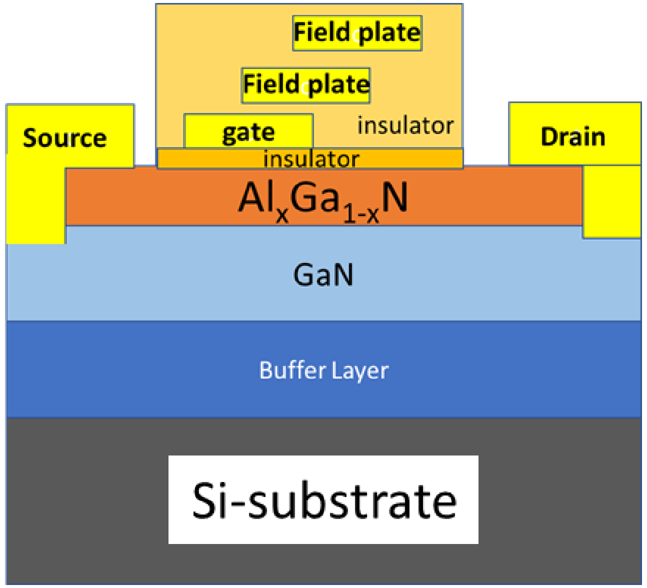


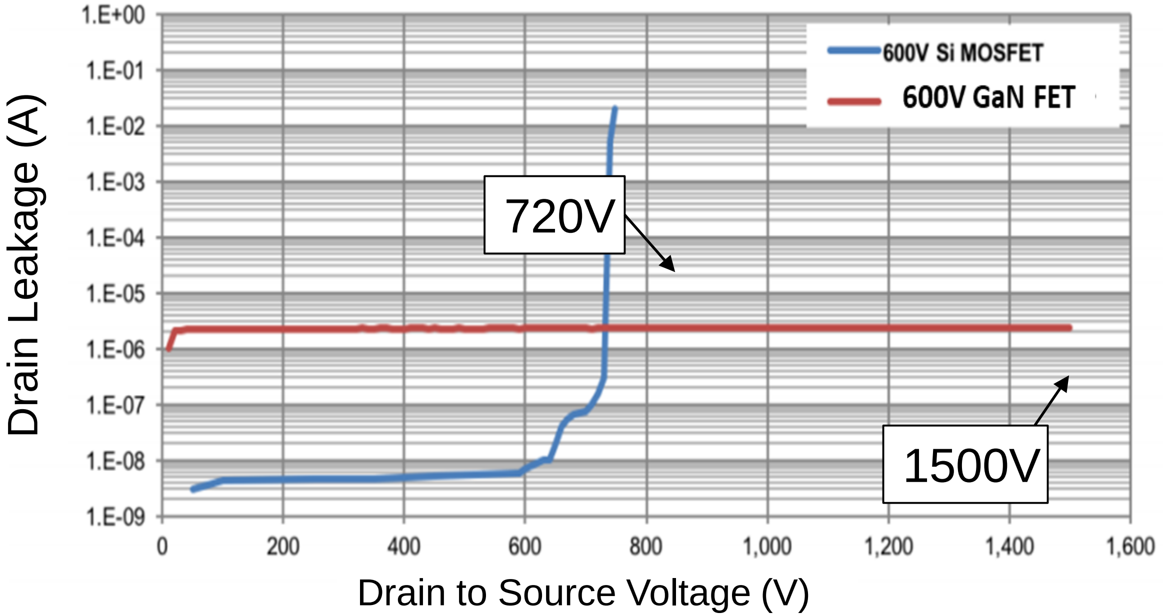
Picture from “Fu et al., CRC press”

GaN provides lowest total loss at all frequencies compared to Si and SiC.
GaN enables higher frequency operation to reduce size, weight and overall cost.

Is there an avalanche capability in today's GaN HEMTs?

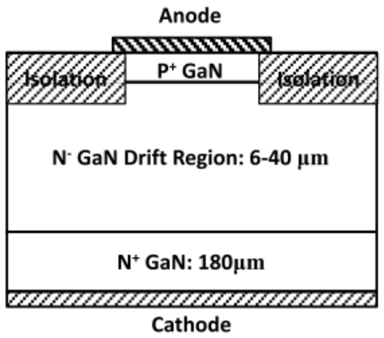
Lateral GaN devices based on Si substrates → No Avalanche





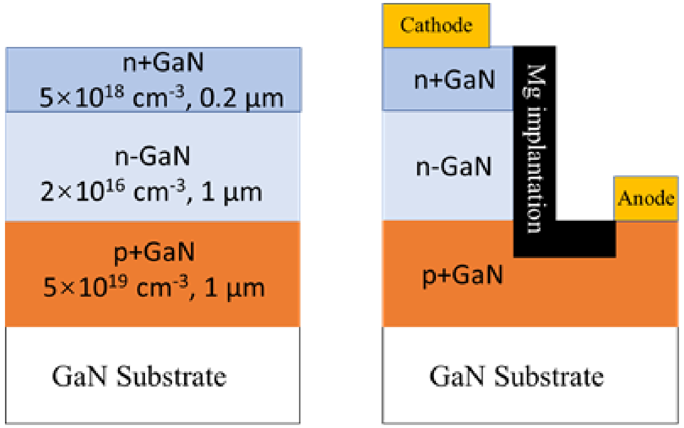
devices

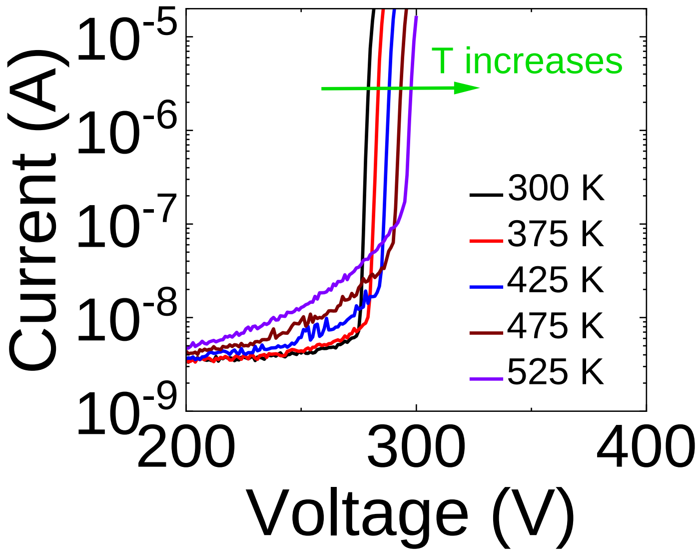
Vertical GaN devices based on GaN substrates can offer avalanche

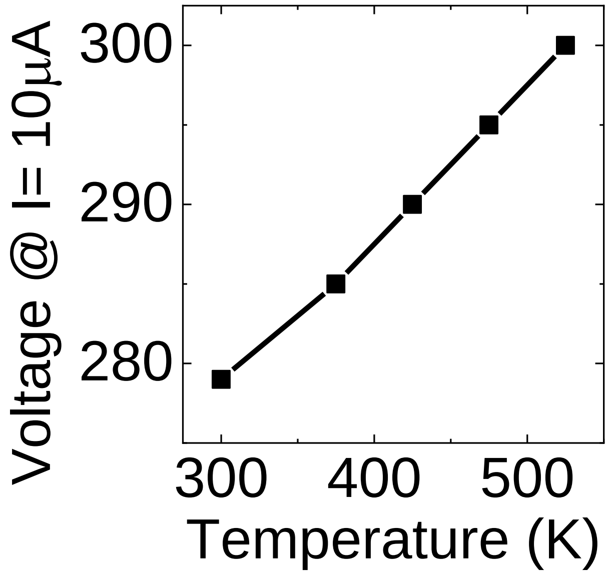


First demonstration of avalanche breakdown voltage in GaN

Demonstration of Avalanche Capability in GaN: Temp. dependent BV







$$BV(T) = BV_{300K}\,(1+\alpha(T-300))$$

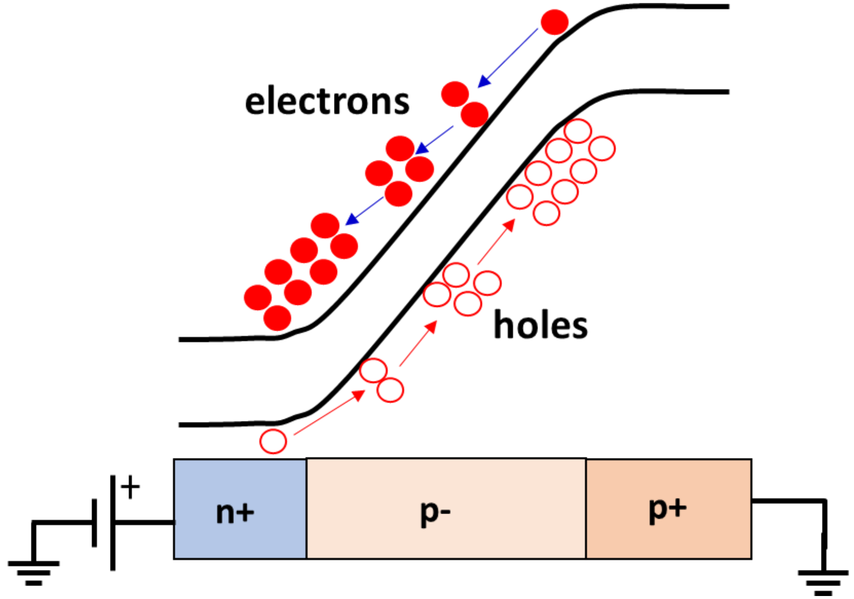
↓ *Temperature coefficient of breakdown voltage*

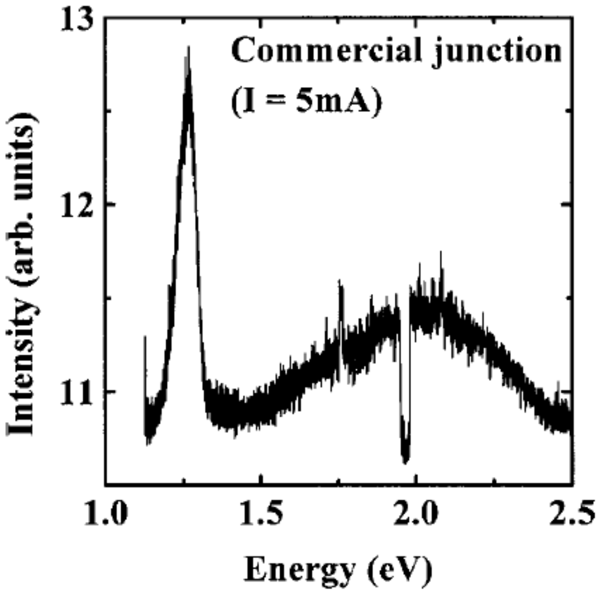
The temperature coefficient of GaN is close to reported values for other materials
→ The temperature-dependent BV is caused by avalanche breakdown.

Semiconductors	Temperature coefficient of breakdown voltage (K^{-1})
Silicon	1.9×10^{-4} to 6.8×10^{-4}
GaAs	1.4×10^{-4} to 10×10^{-4}
InP	3.85×10^{-4}
InAlAs	2.7×10^{-4}
SiC	1.5×10^{-4}
GaN	**3.85×10^{-4}**

Demonstration of Avalanche Capability in GaN (2): Electroluminescence

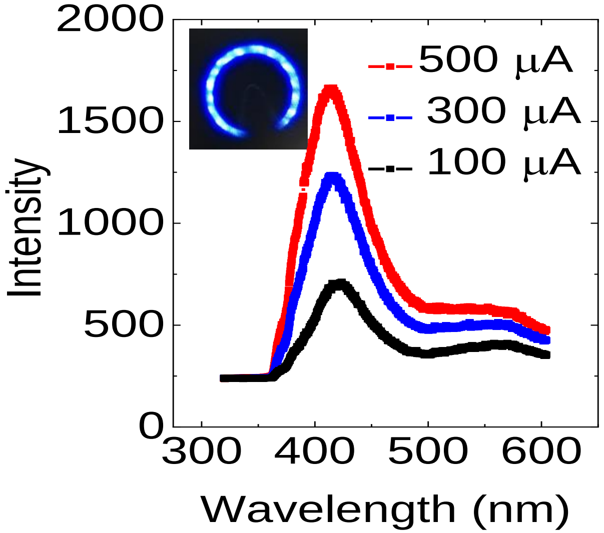
Avalanche Electroluminescence in GaAs





Measured electroluminescence in GaAs, Lahbabi et al., JAP, 2004.

Avalanche Electroluminescence in GaN

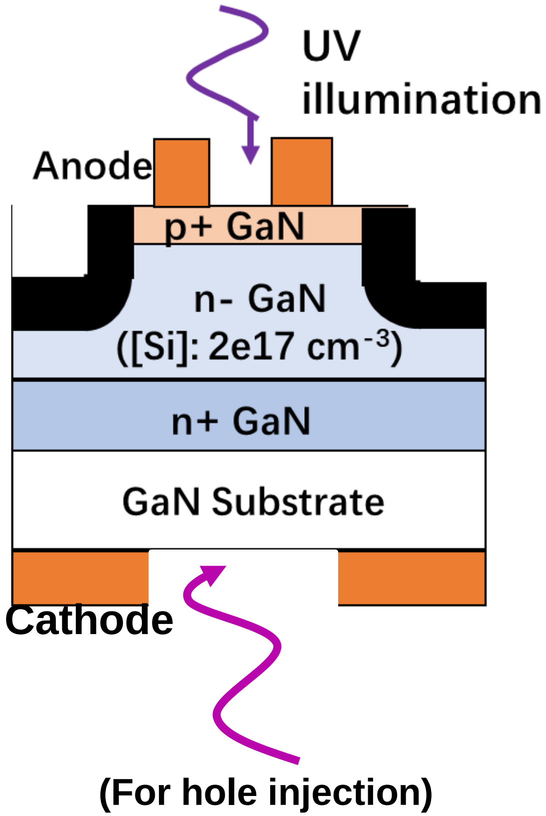


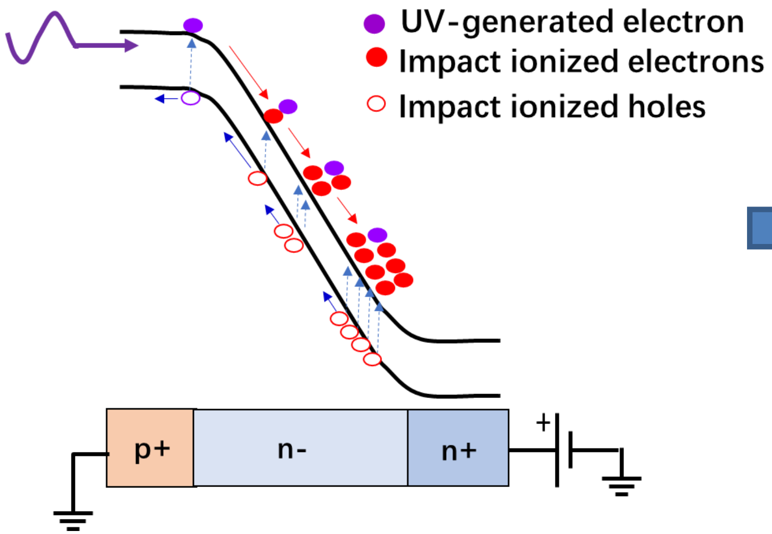
Demonstrated our lab for the first time (S.Mandal, D.Ji et al.)

The avalanche multiplication of electrons and holes → recombination of extra carriers
→ Light emission in direct bandgap materials, like GaAs and GaN.
No reports on avalanche electroluminescence other than Stanford WBG Lab.

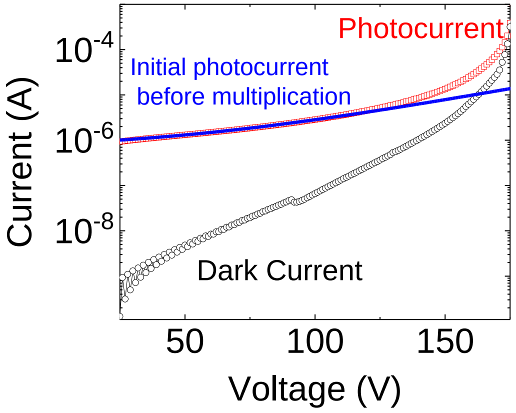
S. Mandal, M. Kanathila, C. Pynn, W. Li, J. Gao, T. Margalith, M. Laurent, S. Chowdhury, "Observation and discussion of avalanche electroluminescence in GaN p-n diodes offering a breakdown electric field of 3 MV cm-1," Semicond. Sci. Technol., vol. 33, no. 6, p. 065013, 2018.

Measurement of impact ionization coefficients in GaN

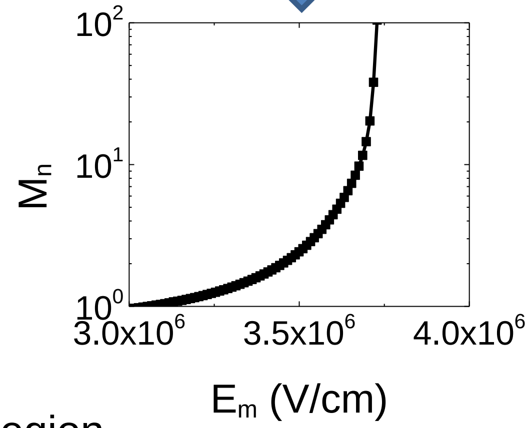




Band diagram of the reverse biased pn junction.



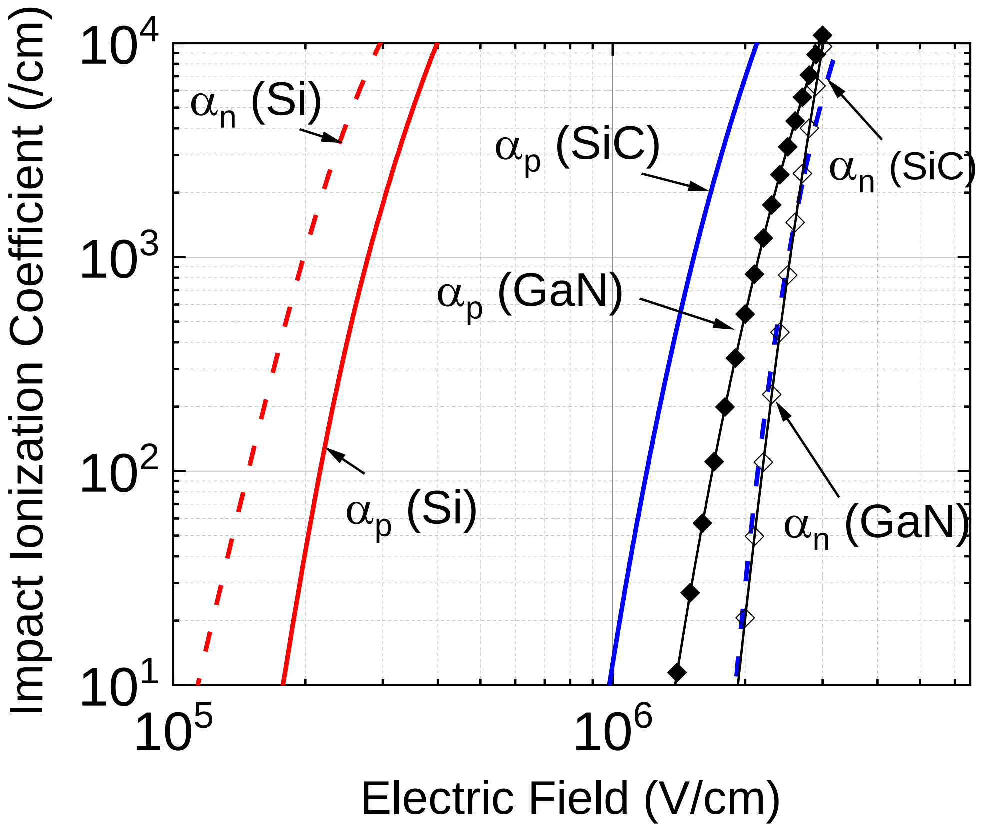
$$M_n = \frac{Photocurrent - Dark\ current}{Inital\ current\ before\ multiplication}$$

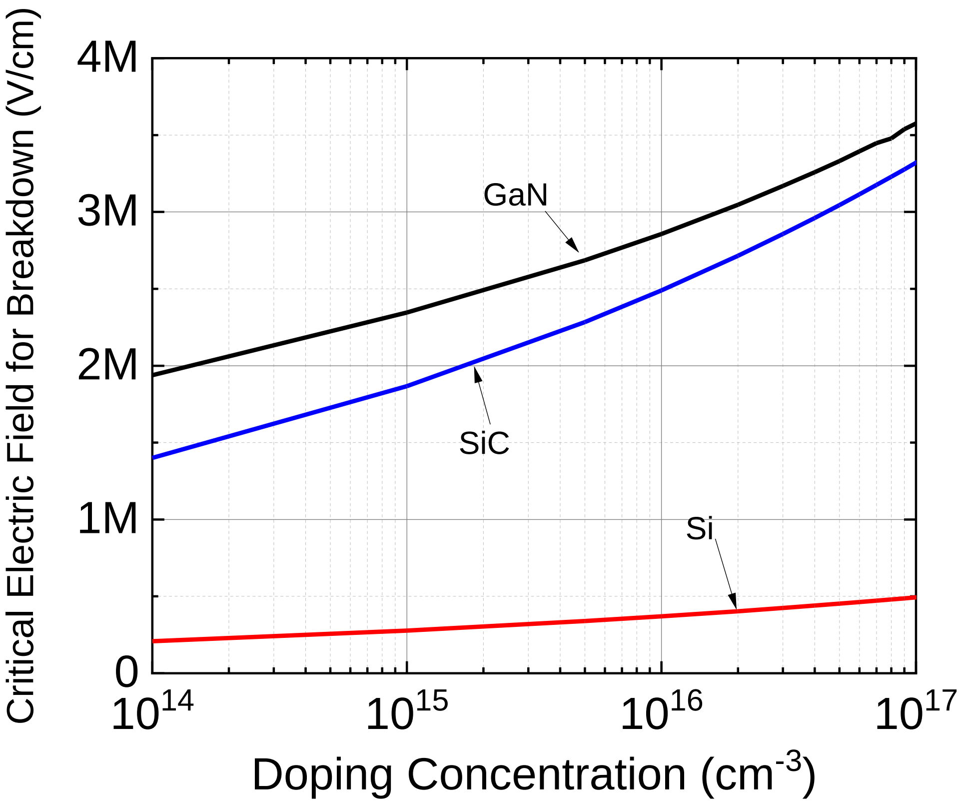


Step 1: By illuminating the anode region, UV-generated electrons are drifted into the high field region.
Step 2: Measuring the multiplication factor of the photocurrent induced by electrons.
Step 3: Repeat steps 1&2 for hole injection by illuminating the cathode region.
Step 4: Combine both Mn and Mp to extract the impact ionization coefficients.

D. Ji, B. Ercan, and S. Chowdhury, Appl. Phys. Lett., 115, 2019.

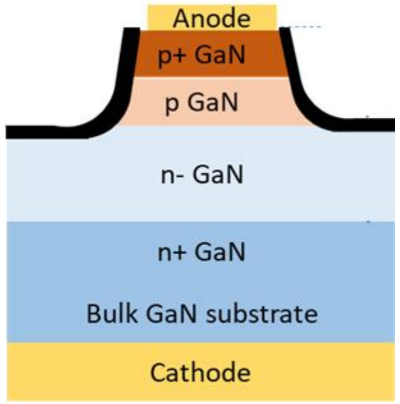
Impact ionization coefficients and critical electric fields for breakdown



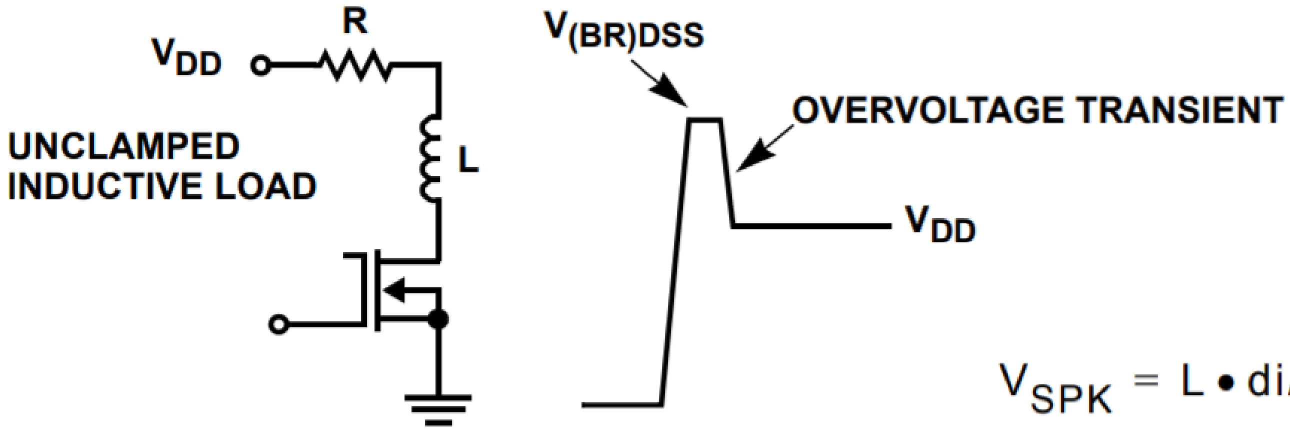


- GaN has the lowest impact ionization coefficients among SiC, Si, and GaN
- GaN has the highest critical electric field for breakdown.

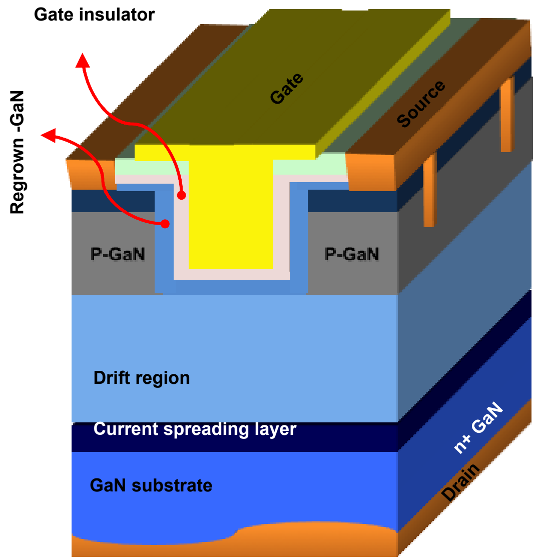
Applications of Avalanche: Power Switches



Power Diode



$$V_{SPK} = L \bullet di/dt + V_{DD}$$



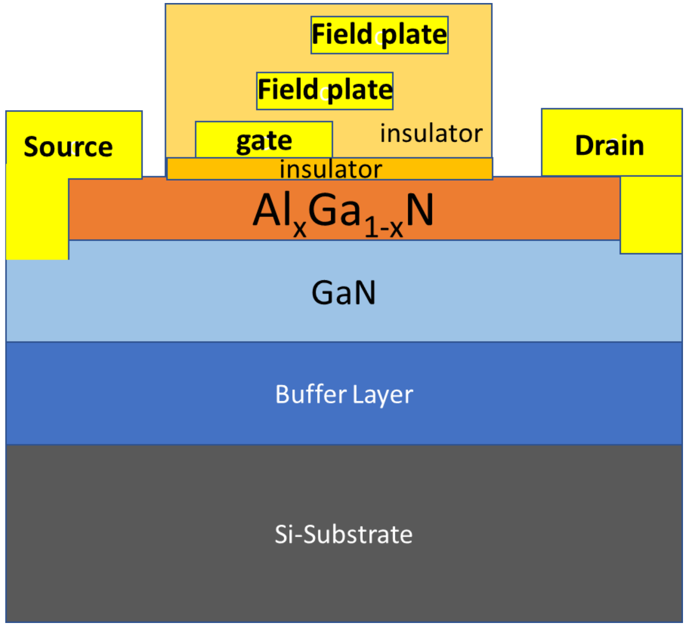
Power Transistor

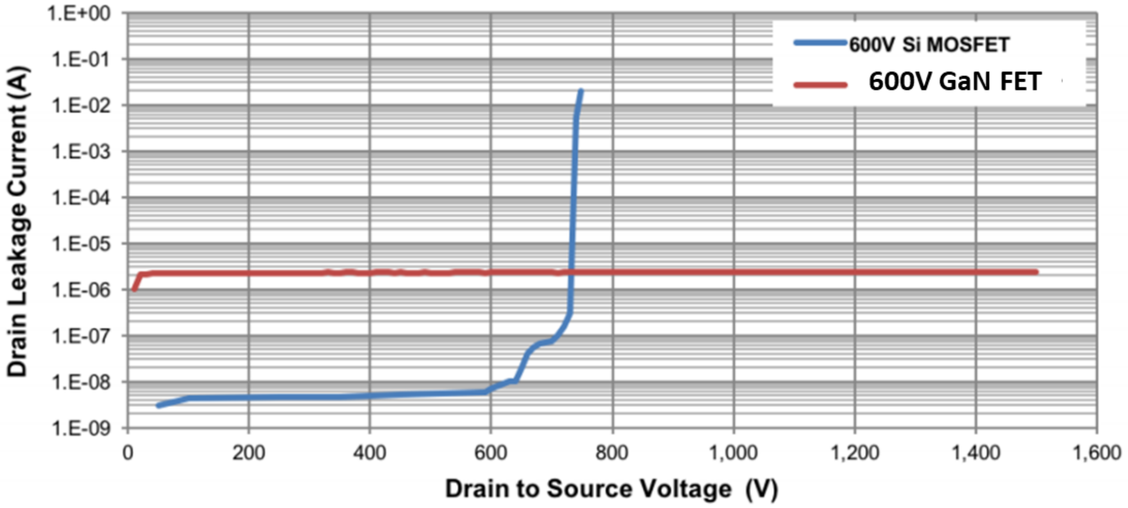
If (1) ***L*** is high; or (2) **di/dt** is high
→ Overvoltage transient
→ Avalanche occurs to absorb the energy stored in the parasitic inductances.

Avalanche Ruggedness is an important parameter for power semiconductor devices.

Applications of Avalanche : Power Switches

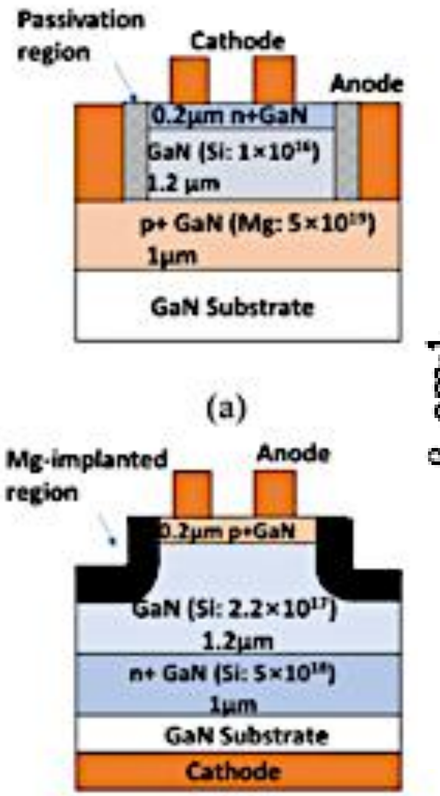
In current GaN-on-Silicon technology, the avalanche capability has not been demonstrated yet, therefore, device has to be overdesigned to survive in unexpected conditions.

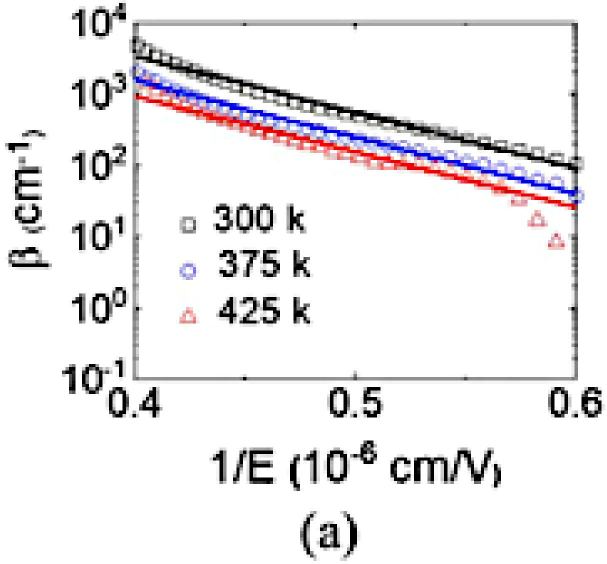


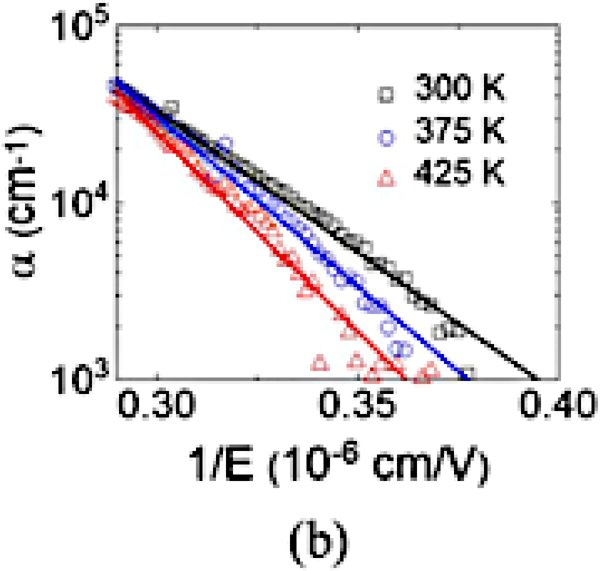


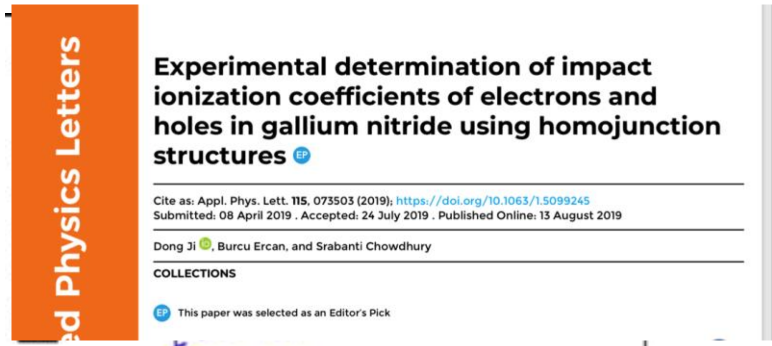
If there's robust avalanche capability, the R_{ds}(on) of GaN-based devices can be further reduced by 50%.
Full potential of GaN on power electronics can be reached by avalanche.

Experimental determination of Impact ionization coefficients in GaN









Applied Physics Letters

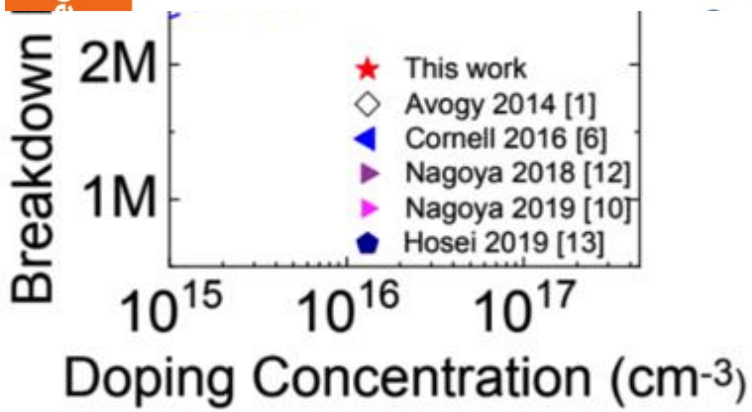
Experimental determination of impact ionization coefficients of electrons and holes in gallium nitride using homojunction structures

Cite as: Appl. Phys. Lett. 115, 073503 (2019); https://doi.org/10.1063/1.5099245
Submitted: 08 April 2019 . Accepted: 24 July 2019 . Published Online: 13 August 2019

Dong Ji, Burcu Ercan, and Srabanti Chowdhury

COLLECTIONS

This paper was selected as an Editor's Pick

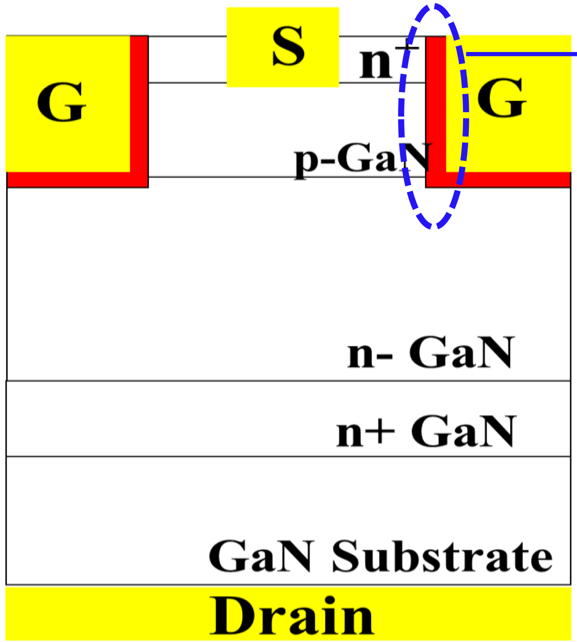


(d) Experimentally determined impact ionization coefficients in GaN: (1) hole impact ionization coefficient in GaN; (b) electron impact ionization coefficient;

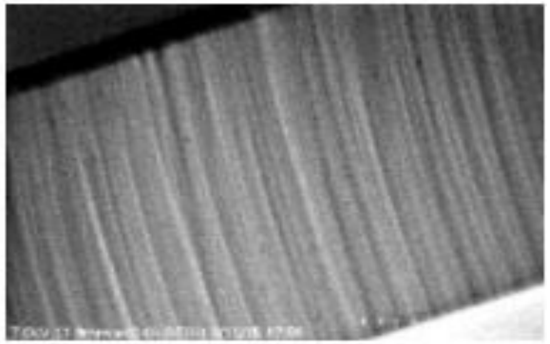
Highly impactful for predictive modeling
Basis of Avalanche-based devices : High power IMPATT didoes, Avalanche Photodiodes

Improved dynamic R_{on} on OGFETs using dry/wet hybrid etch

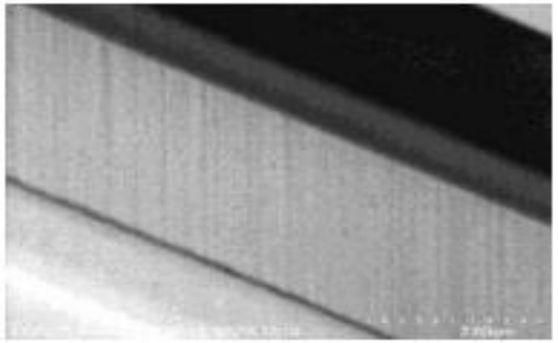
Commercial GaN HEMT dynamic Ron data are from: B. Lu et al., IEEE CSICS, pp. 1-4, 2011.

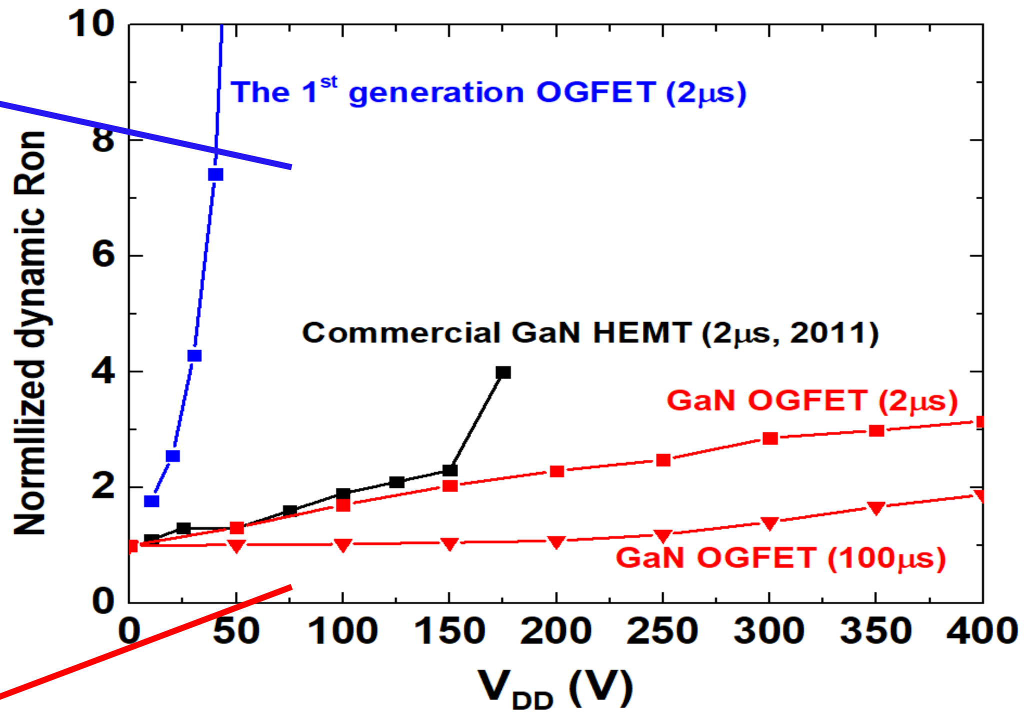


After RIE dry etch



With TMAH wet etch

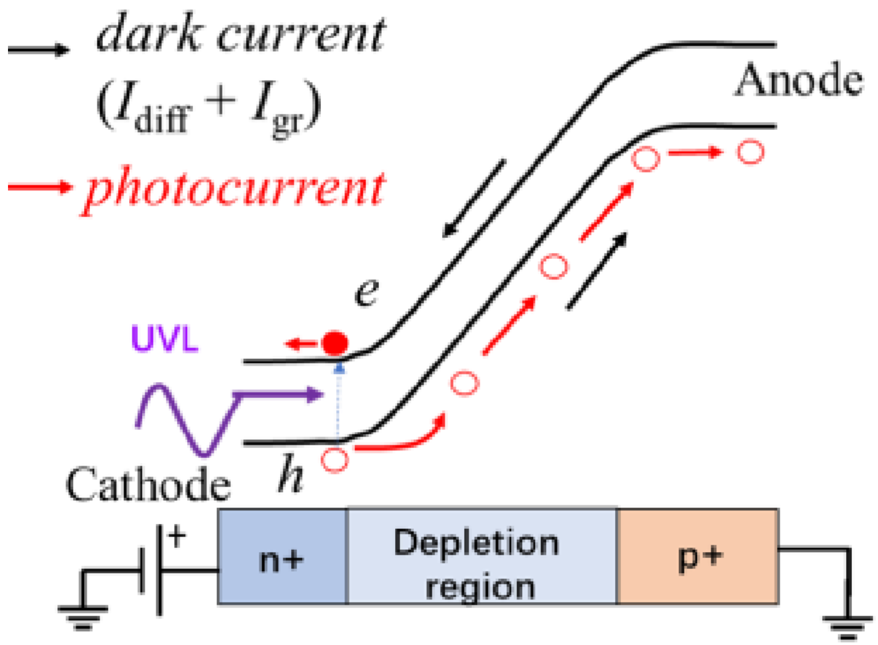


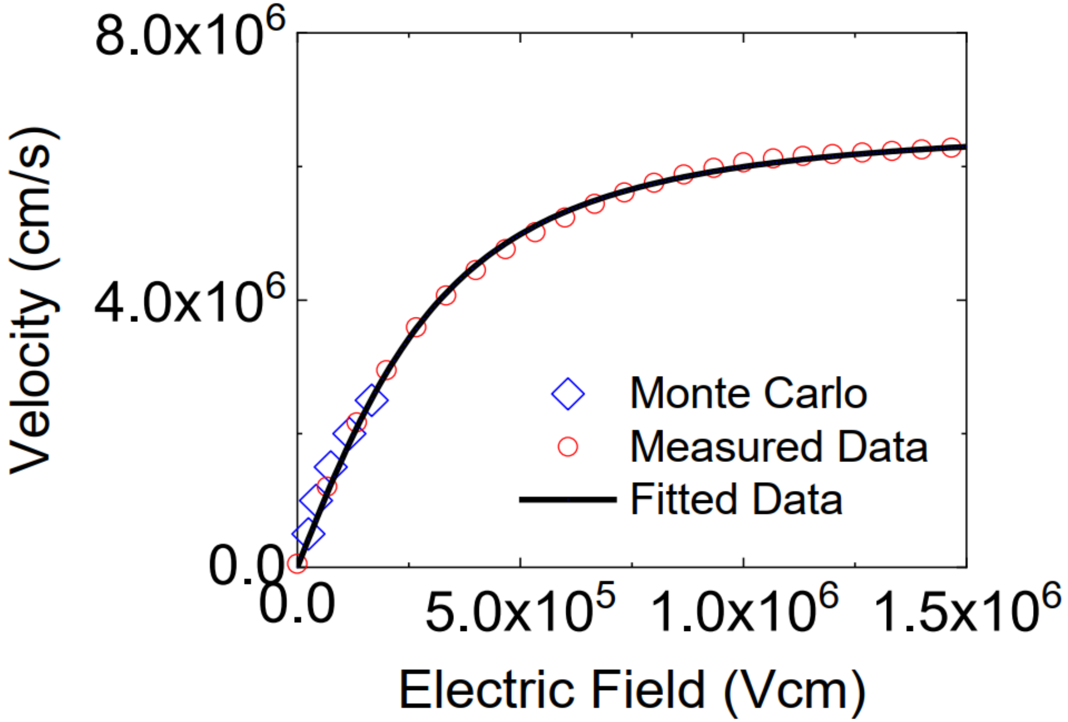


Dong Ji,......., and Srabanti Chowdhury, "Improved Dynamic Ron of GaN vertical trench MOSFETs Using TMAH Wet Etch," *IEEE Electron Device Letters*, vol. 39, no. 7, July 2018

*Dynamic Ron of OGFET was measured at Transphorm, Inc.

First Report on GaN Hole Velocity Measurement





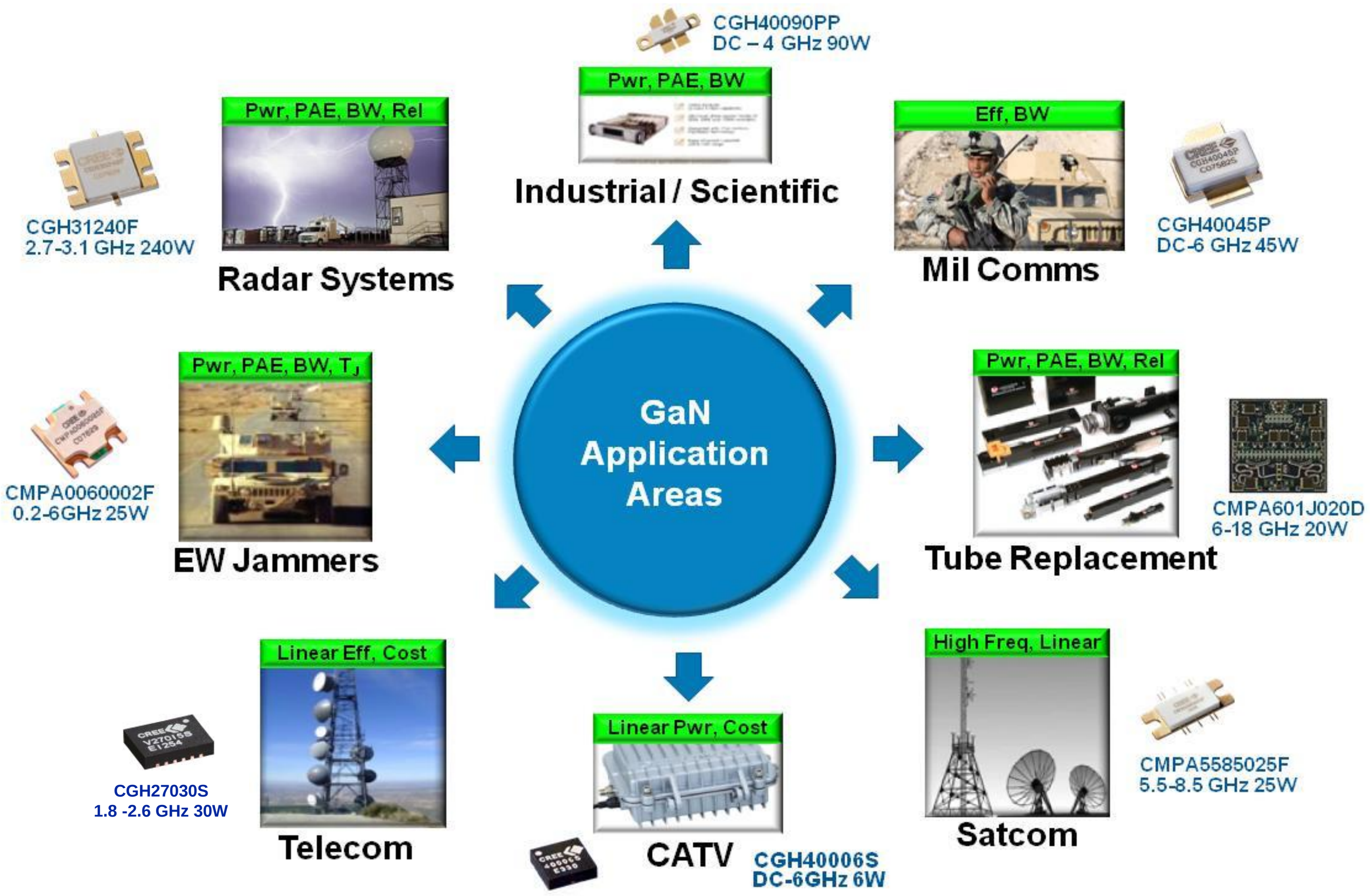
Standards | Device Letters > Early Access

Experimental Determination of Velocity-Field Characteristic of Holes in GaN

Publisher: IEEE

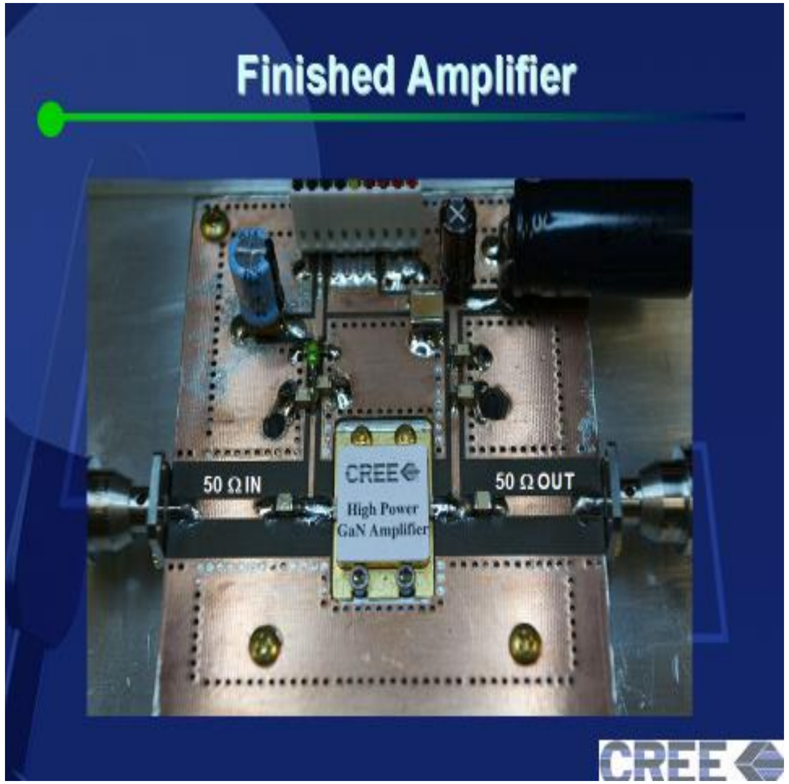
3 Author(s) Dong Ji ; Burcu Ercan ; Srabanti Chowdhury **View All Authors**

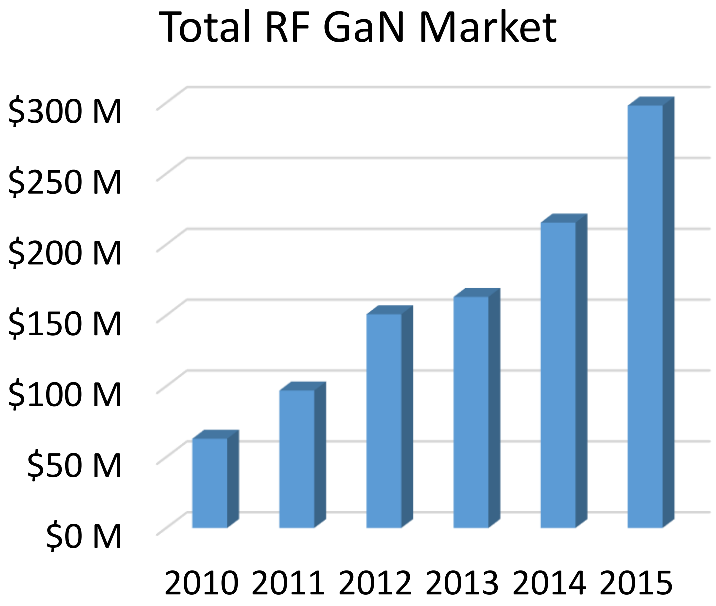
RF market with GaN

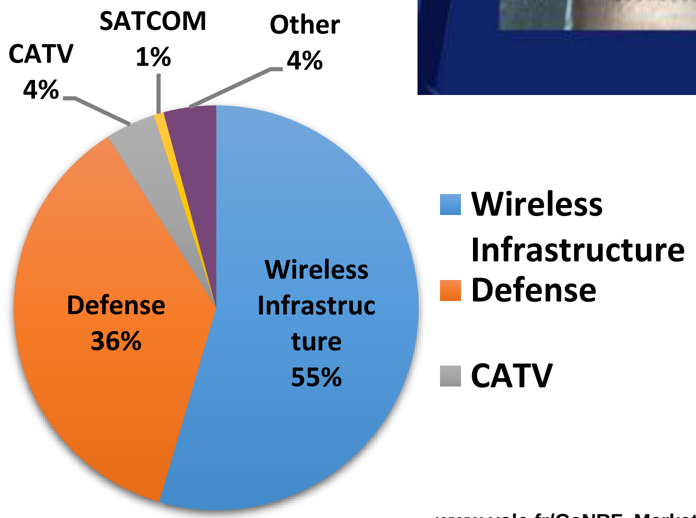


RF GaN market: past, present, and future

- $65M in 2010 ➔ $300M in 2015
- Commercial > Defense





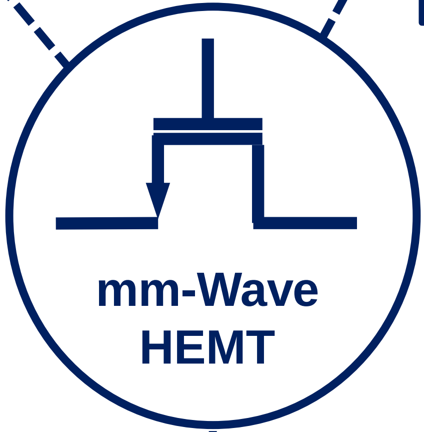


www.yole.fr/GaNRF_Market.aspx

RF amplifier key performance metrics

Large Signal Gain
- High Mobility & Velocity
- Electrostatic Control
- Physical Scaling
- Reduced Parasitics

Output Power
- Large Current Swing
- Large Voltage Swing
- Low Dispersion
- High Gain

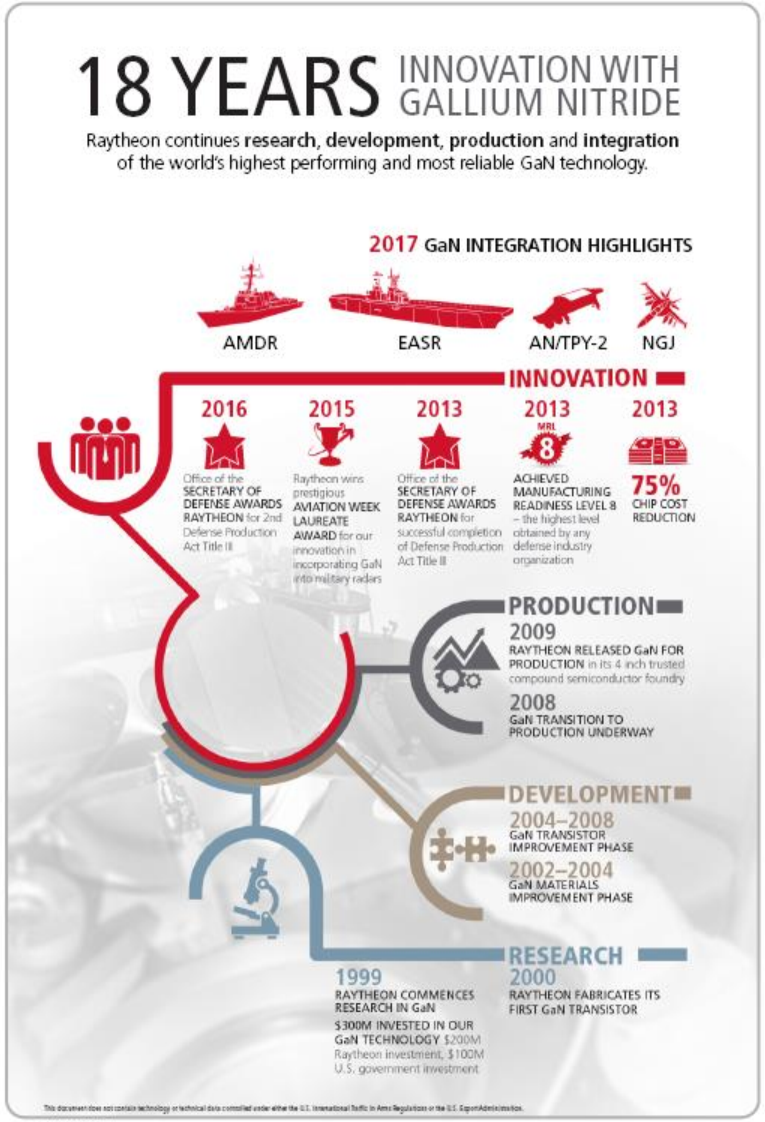


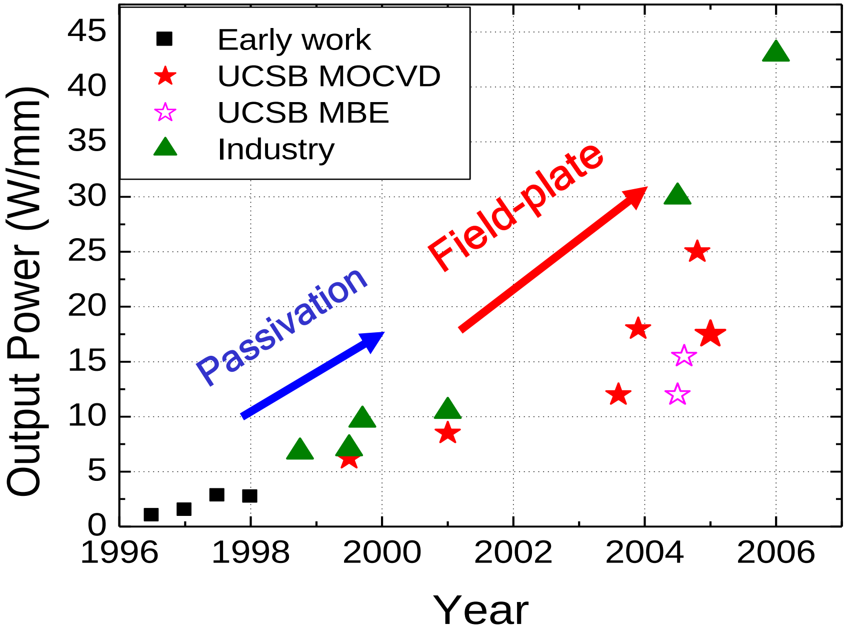
Efficiency
- High Gain
- High Power
- Low leakage

$$PAE = \frac{P_{RF,out}}{P_{DC}}\left(1-\frac{1}{G}\right)$$

PAE= Power Added Efficiency
G=Gain

X-band radar: One of many DoD applications enabled by Gallium Nitride



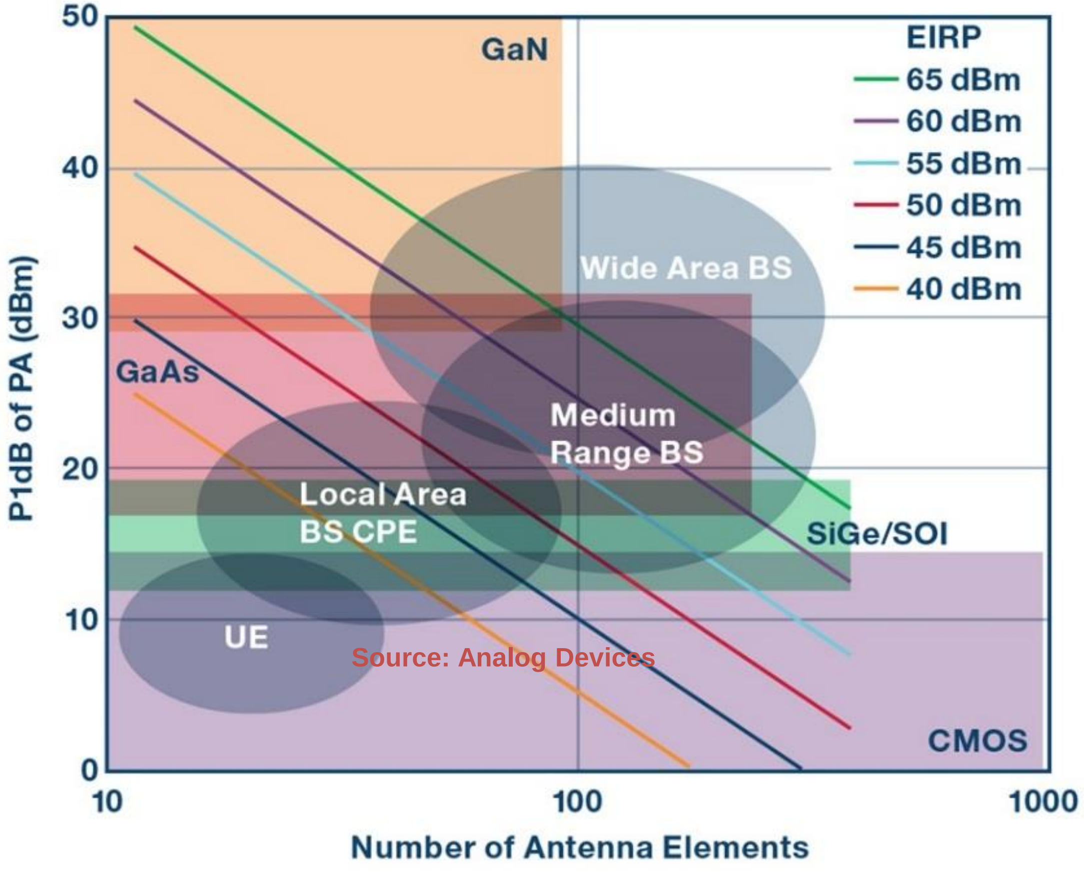


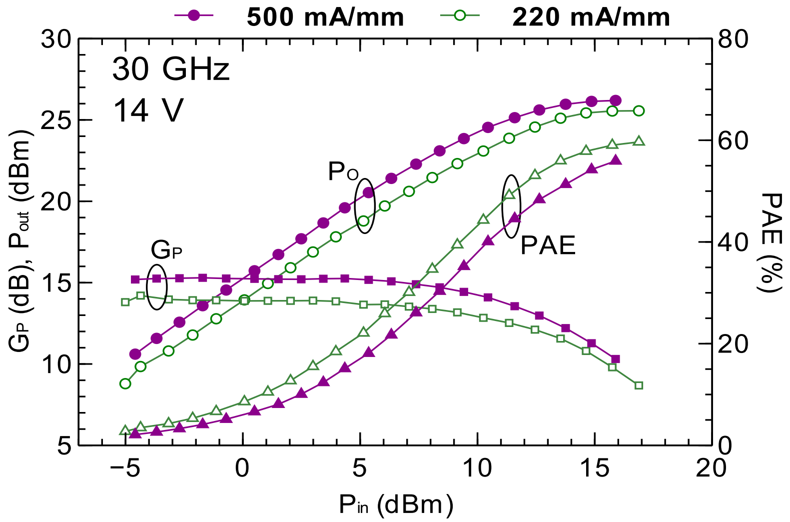
10GHz or less

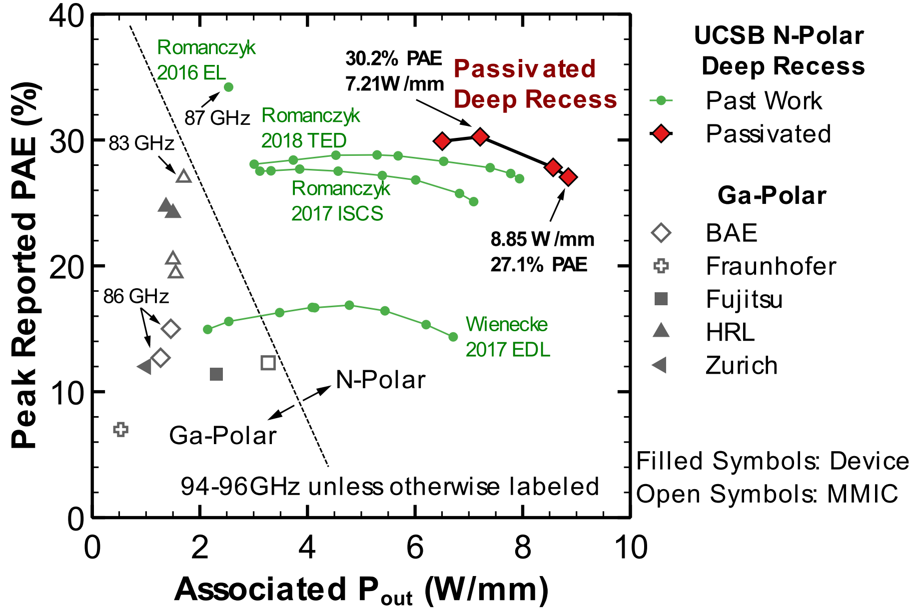
Raytheon

Slide credit: Dr. Matthew Guidry (UCSB), Prof. Umesh Mishra (UCSB)

5G MIMO architectures: Enhanced range & data rate enabled by GaN power amplifiers

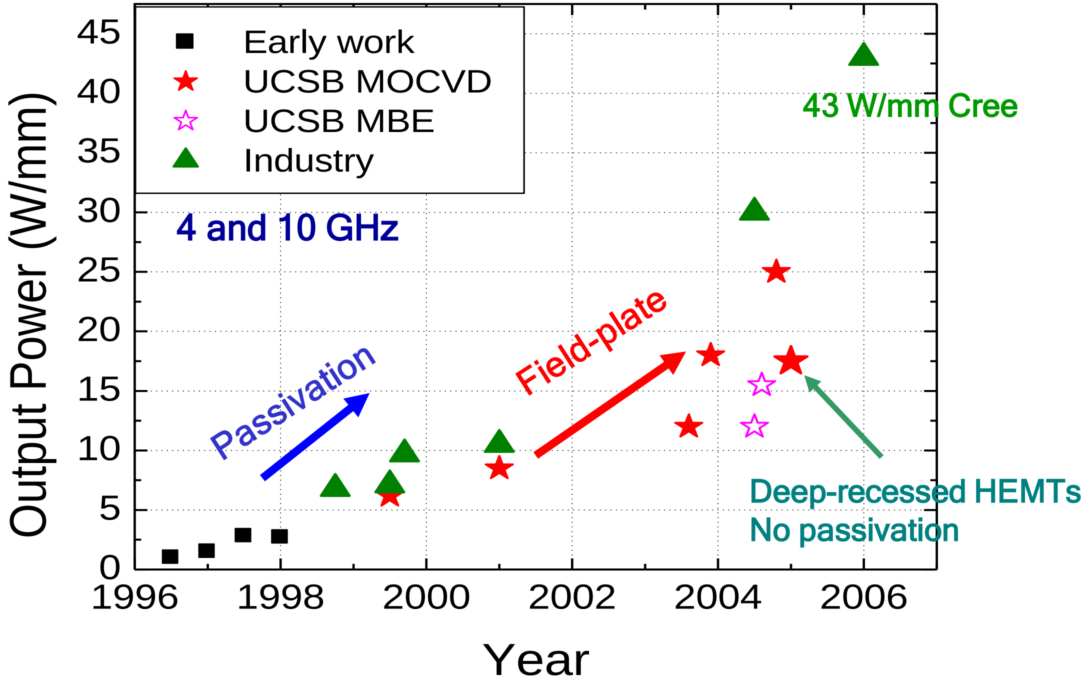


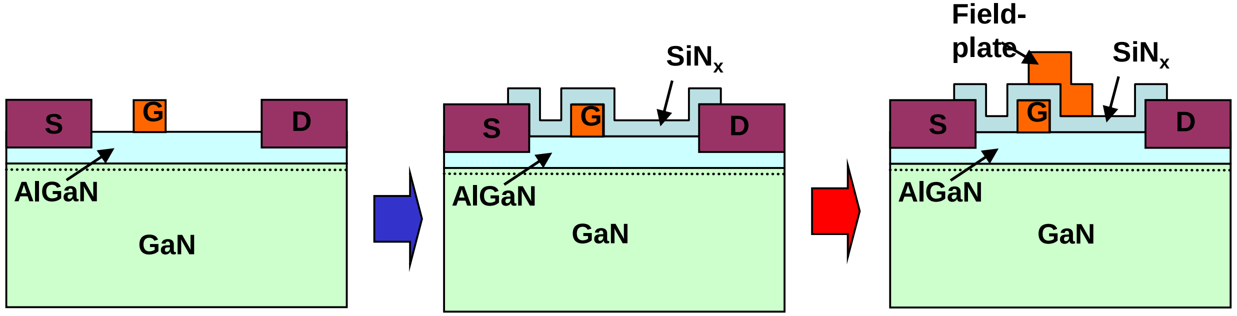




Slide credit: Dr. Matthew Guidry (UCSB), Prof. Umesh Mishra (UCSB)

Dispersion was managed with field plates and passivation





Field plate technology has limits and compromises maximum possible voltage per micron

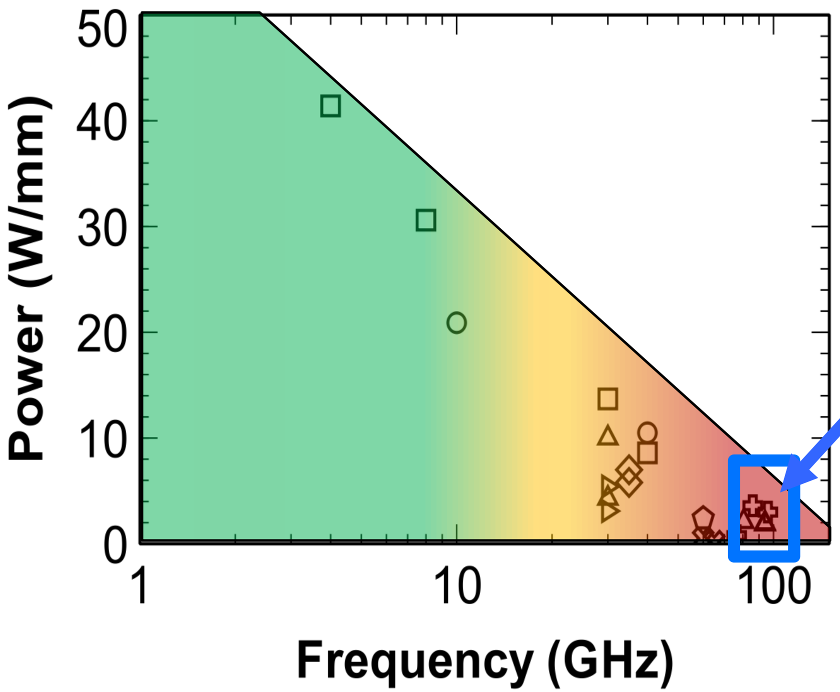
Low power density above 90 GHz (W-band)

Gain

Efficiency

Power

Hard to get at high frequency

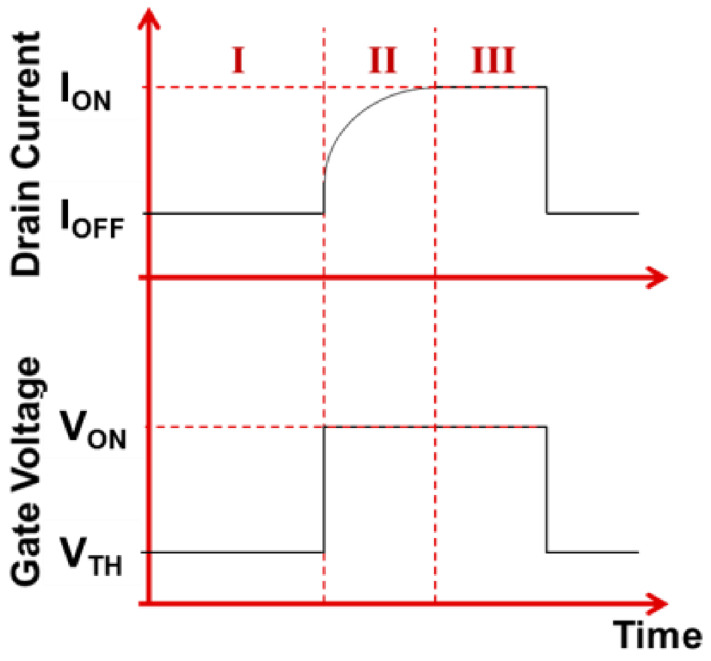


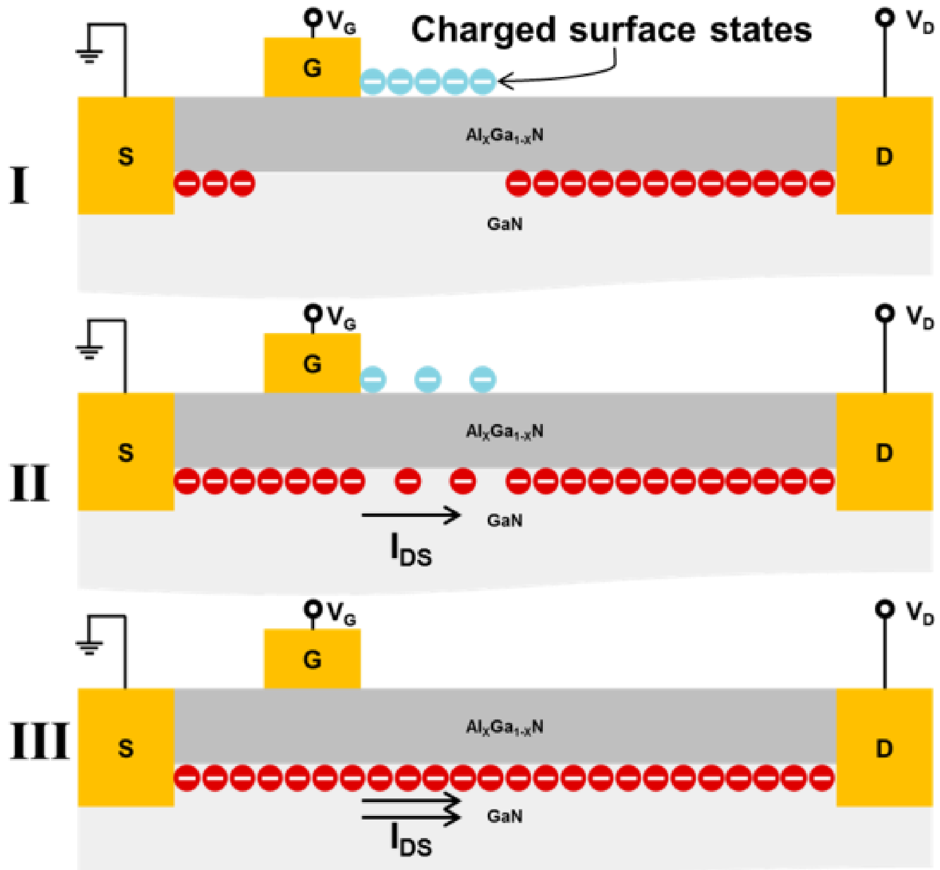
Low P_{out} above 90 GHz

Dispersion limits Power density drastically at high frequencies

Dispersion or current collapse limits efficiency

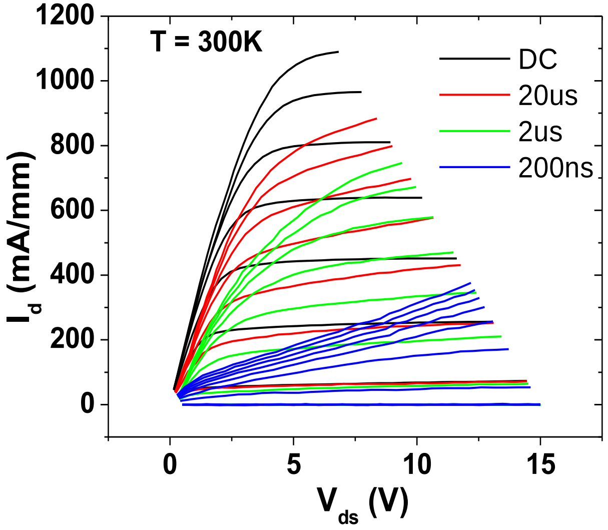
$$PAE = \frac{P_{RF,out}}{P_{DC}}\left(1-\frac{1}{G}\right)$$

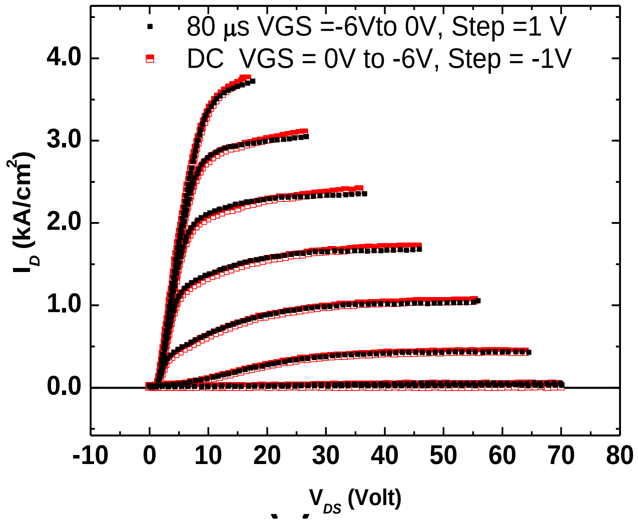


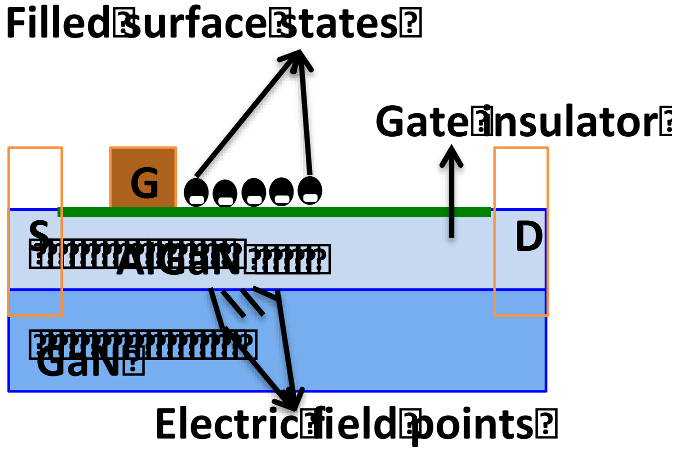


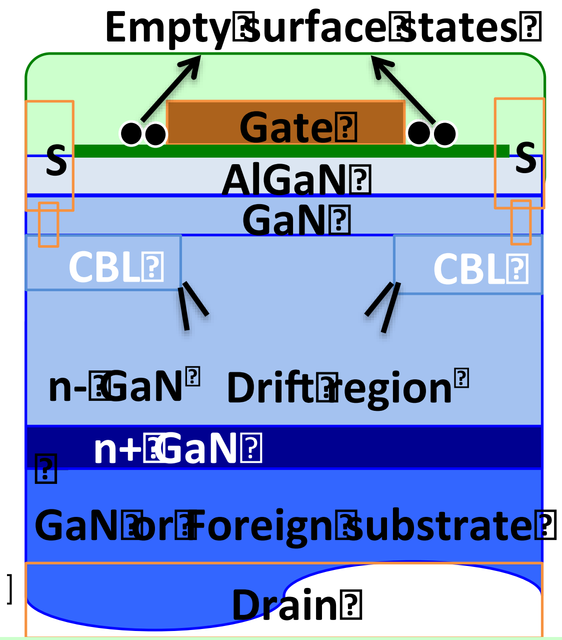
Dispersion affects both drain efficiency represented by P_{RF}/P_{DC} and also gain(G). This can ruin PAE – A fundamental problem of lateral HEMTs

Vertical device topology alleviates dispersion, naturally









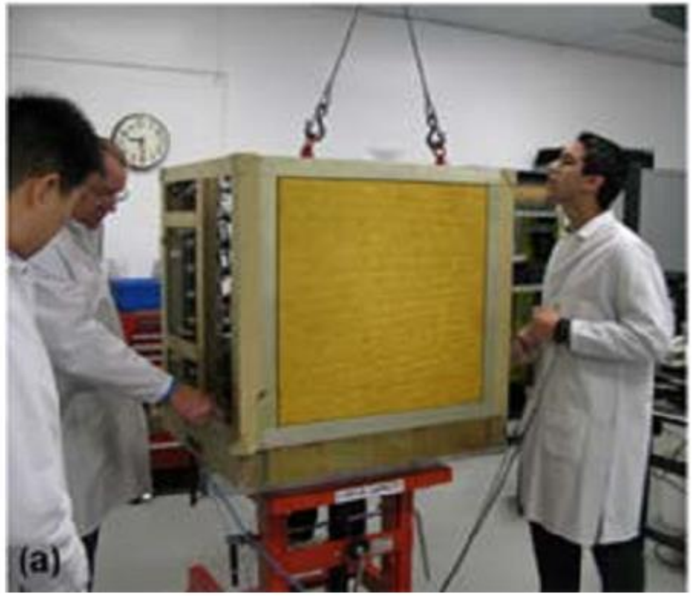
Buried peak electric field is a big positive in vertical device – Dispersion free characteristics

Consequences of low device level power density

May 2016: 7,000 Watt Amplifier Demonstrated by Raytheon at 95 GHz Band

> 8,100 ICs Power Combined

Size = 25.6” x 25.6”

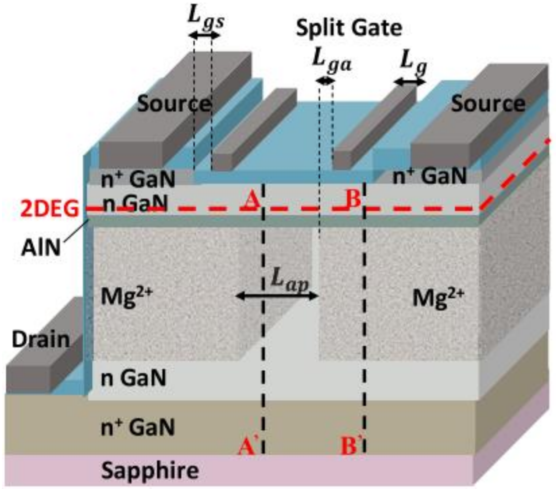


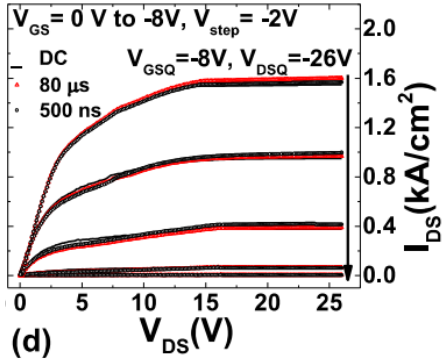
Brown, K. et al. *IEEE IMS* (2016)

Maximize the RF power density with GaN vertical devices

N-Polar CAVET

- High electric field regions buried in the bulk of the material : Dispersion less I-V
- Channel within 2-5 nm from gate → high aspect ratio

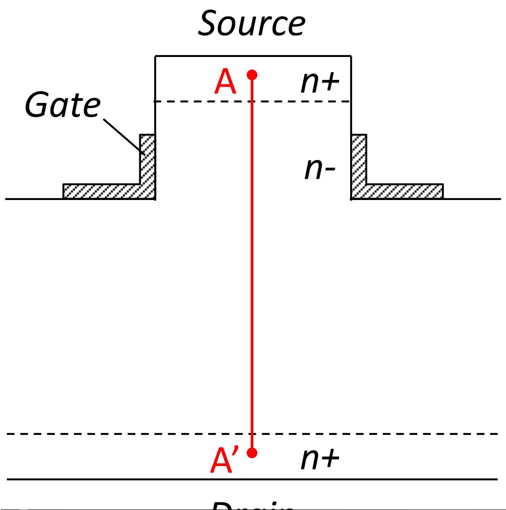


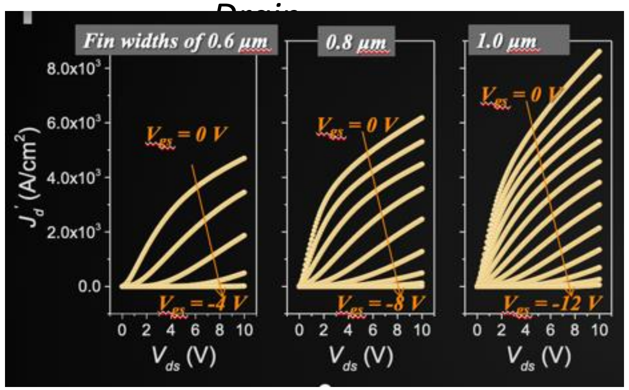


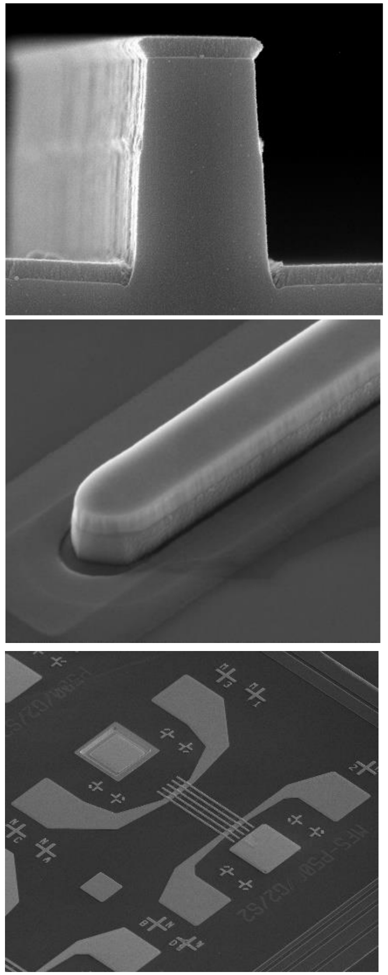
S. Rajabi, S. Mandal, M.A Laurent, H.Li, S.Keller and S. Chowdhury et al., "A Demonstration of Nitrogen Polar Gallium Nitride Current Aperture Vertical Electron Transistor," IEEE Electron Device Letters, vol. 40, no. 6, pp. 885–888, 2019

Static Induction Transistor

- Vertical current controlled by the electrostatics in channel
- No requirement of p-type GaN and dielectric layer

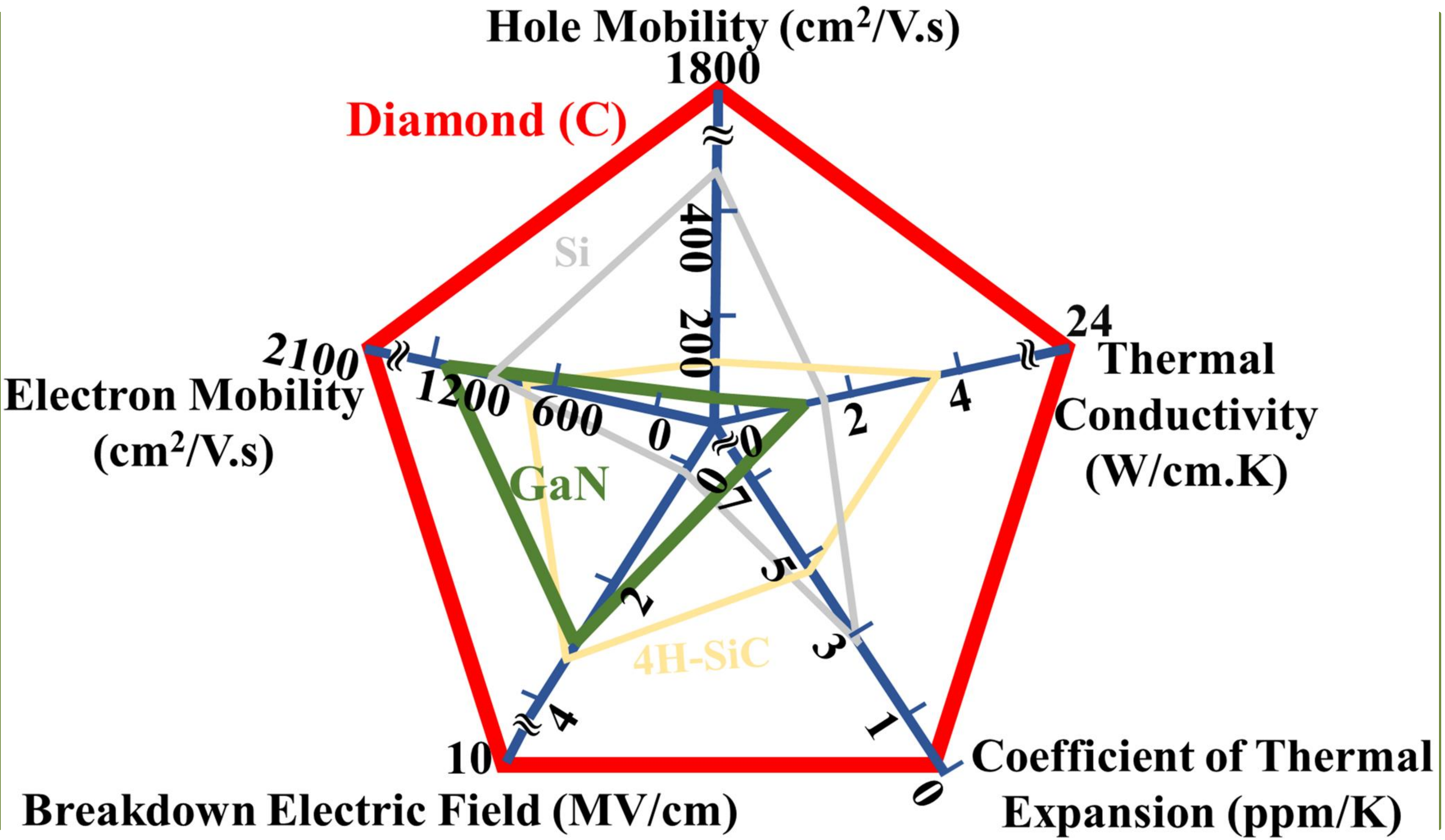






J. Chun, W. Li, A. Agarwal, and S. Chowdhury, "Schottky Junction Vertical Channel GaN Static Induction Transistor with a Sub-Micrometer Fin Width," Advanced Electronic Materials, vol. 5, no. 1, p. 1800689, 2019

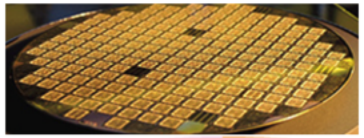
Ultra wide-bandgap semiconductors: Diamond



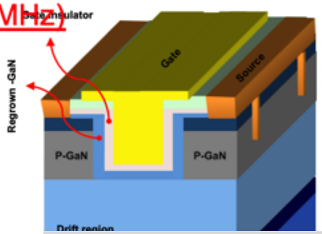
Exploring WBG and UWBG for current and future power requirements

Our efforts on GaN

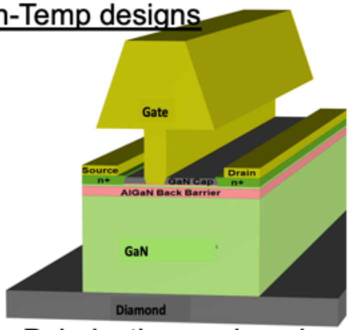
Device integration for power on a chip and co-located sensor electronics

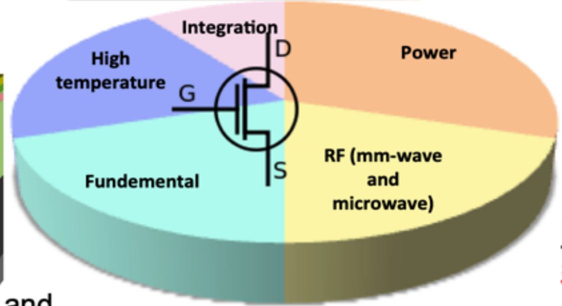


Vertical device for high power density (300KHz-10 MHz)



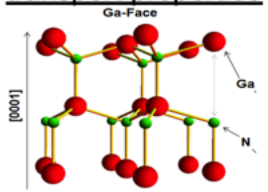
Thermal management (GaN and diamond) and High-Temp designs





Highly s
500GHz

Polarization engineering and transport properties



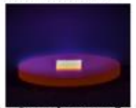
Chowdhury, S. "GaN-on-GaN Power Device Design and Fabrication." *Wide Bandgap Semiconductor Power Devices: Materials, Physics, Design and Applications*, by B. Jayant Baliga, Woodhead Publishing, 2018, pp. 209–248

Chowdhury, S. "Vertical Gallium Nitride Technology ", Power GaN Devices: materials applications and reliability, by M. Meneghini, G. Meneghesso, E. Zanoni , Springer Publishing, 2016, pp. 101-121

Our efforts on Diamond

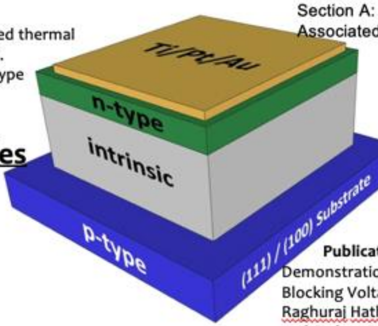
Materials: Plasma Enhanced CVD Growth

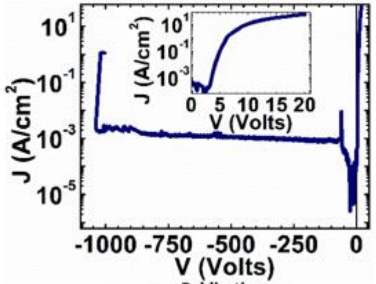
Develop novel approaches for intrinsic and doped diamond homoepitaxy



Patents
Pat. Pend. 62/334,281 -Sample stage/holder for improved thermal and gas flow control at elevated growth temperatures.
Pat. Pend. 15/151,295 -Phosphorus incorporation for n-type doping of diamond with (100) and related surface orientation.

High Power Schottky/ PIN Diodes



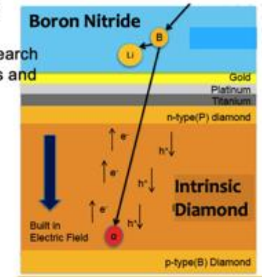


Publication
High Voltage Diodes in Diamond Using (100)-and (111)- Substrates," M. Dutta, F.A.M. Koeck, W. Li, R.J. Nemanich, S. Chowdhury, IEEE Electron Device Letters 38, 600-603 (2017). DOI: 10.1109/LED.2017.2681058

Radiation Detectors

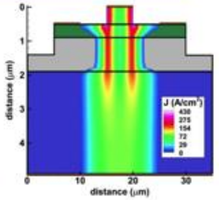
Develop novel approaches for particle detection.
PIN diamond diode (reverse bias) with high purity i-layer

Publication
"A 4.5-μm PIN Diamond Diode for Detecting Slow Neutrons," Jason Holmes, Maitreya Dutta, et. al, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 903, 297-301 (2018)



Transport properties

Publication
Demonstration of Diamond-Based Schottkyp-i-n Diode With Blocking Voltage > 500 V," Maitreya Dutta, Franz A. M. Koeck, Raghuraj Hathwar, Stephen M. Goodnick, Robert J. Nemanich, and Srabanti Chowdhury, IEEE Electron Device Letters 37, 1170-1173 (2016)
Determination of Minority Carrier Lifetime of Holes in Diamond p-i-n Diodes Using Reverse Recovery Method," Maitreya Dutta , Saptarshi Mandal , Raghuraj Hathwar, Alec M. Fischer, Franz A. M. Koeck, Robert J. Nemanich, Stephen M. Goodnick, and Srabanti Chowdhury, IEEE Electron Device Letters, 39, 552-555 (2018)



Integration for thermal management

Adding more new WBG to compare performance and understand their full potential

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Selected publication on Vertical GaN (Chowdhury group)

1. Dong Ji, Wenwen Li, and Srabanti Chowdhury, "A Study on the Impact of Channel Mobility on Switching Performance of Vertical GaN MOSFETs," *IEEE Transactions on Electron Devices*, vol. 64, no. 9, pp. 4271-4275, Sept. 2018
2. Dong Ji, Wenwen Li, Anchal Agarwal, Silvia H. Chan, Jeffrey Haller, Davide Bisi, Michelle Labrecque, Chirag Gupta, Bill Cruse, Rakesh Lal, Stacia Keller, Umesh K. Mishra, and Srabanti Chowdhury, "Improved Dynamic Ron of GaN vertical trench MOSFETs Using TMAH Wet Etch," *IEEE Electron Device Letters*, vol. 39, no. 7, July 2018
3. Dong Ji, Anchal Agarwal, Haoran Li, Wenwen Li, Stacia Keller, and Srabanti Chowdhury, "880V/2.7 mΩ· cm^2 MIS Gate Trench CAVET on Bulk GaN Substrates," *IEEE Electron Device Letters*, vol. 39, no. 6, pp. 863-865, June, 2018
4. Dong Ji, Chirag Gupta, Anchal Agarwal, Silvia H. Chan, Cory Lund, Wenwen Li, Stacia Keller, Umesh K. Mishra, and S. Chowdhury, "Large Area Normally Off In-Situ Oxide, GaN Interlayer Based Vertical Trench MOSFET (OG-FET)," *IEEE Electron Device Letters*, vol. 39, no. 5, pp. 711-715, May 2018
5. Dong Ji, Anchal Agarwal, Wenwen Li, Stacia Keller, and Srabanti Chowdhury, "Demonstration of GaN current aperture vertical electron transistor with aperture region formed using ion implantation," *IEEE Transactions on Electron Devices*, vol. 64, no. 2, pp. 483-487, Feb. 2018
6. Dong Ji, Matthew A. Laurent, Anchal Agarwal, Wenwen Li, Saptarshi Mandal, Stacia Keller and Srabanti Chowdhury, "Normally Off Trench CAVET With Active Mg-Doped GaN as Current Blocking Layer," *IEEE Transactions on Electron Devices*, vol. 64, no. 3, pp. 805-808, March, 2017
7. Wenwen Li, Dong Ji, Ryo Tanaka, Saptarshi Mandal, Matthew Laurent, and Srabanti Chowdhury, "Demonstration of GaN Static Induction Transistor (SIT) Using Self-Aligned Process," *IEEE Journal of the Electron Devices Society*, vol. 5, no. 6, pp. 485-490, Nov. 2017
8. Chirag Gupta, Dong Ji, Silvia H. Chan, Anchal Agarwal, William Leach, Stacia Keller, Srabanti Chowdhury, and Umesh K. Mishra, "Impact of Trench Dimensions on the Device Performance of GaN Vertical Trench MOSFETs," *IEEE Electron Device Letters*, vol. 38, no. 11, pp. 1559-1562, Nov. 2017
9. Saptarshi Mandal, Anchal Agarwal, Elaheh Ahmadi, Kanathila Mahadeva Bhat, Dong Ji, Matthew A. Laurent, Stacia Keller, and Srabanti Chowdhury, "Dispersion free 450V pGaN-gated CAVETs with Mg-ion implanted blocking layer," *IEEE Electron Device Letters*, vol. 38, no. 7, pp. 933-936, May 2017
10. Dong Ji, Jianyi Gao, Yuanzheng Yue, Srabanti Chowdhury, "Dynamic Modeling and Power Loss Analysis of High Frequency Power Switches Based on GaN CAVET," *IEEE Transactions on Electron Devices*, vol. 63, no. 10, pp. 4011-4017, Oct.2016
11. Dong Ji and Srabanti Chowdhury, "Design of 1.2kV Power Switches with Low Ron Using GaN-based Vertical JFET," *IEEE Transactions on Electron Devices*, vol. 62, no. 8, pp. 2571-2578, Aug. 2016
12. W. Li and S. Chowdhury, "Design and fabrication of a 1.2 kV GaN-based MOS vertical transistor for single chip normally off operation", *Phys. Status Solidi Appl. Mater. Sci.*, vol. 213, no. 10, pp. 2714-2720, 2016.
13. **[Invited]** S. Chowdhury and U. K. Mishra, "Lateral and vertical transistors using the Algan/GAN Heterostructure", *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp.3060-3066, 2013.
14. **[Invited]** S. Chowdhury, B. L. Swenson, M. H. Wong, and U. K. Mishra, "Current status and scope of gallium nitride-based vertical transistors for high-power electronics application", *Semicond. Sci. Technol.*, vol. 28, no. 7, pp. 074014, 2013,
15. S. Chowdhury, M. H. Wong, B. L. Swenson, and U. K. Mishra, "CAVET on bulk GaN substrates achieved with MBE-regrown AlGaN/GaN layers to suppress dispersion", *IEEE Electron Device Lett.*, vol. 33, no. 1, pp. 41-43, 2012.
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