NC STATE UNIVERSITY

Advances in Wide and Ultrawide Bandgap Semiconductor Materials for High Voltage, High Power Electronics

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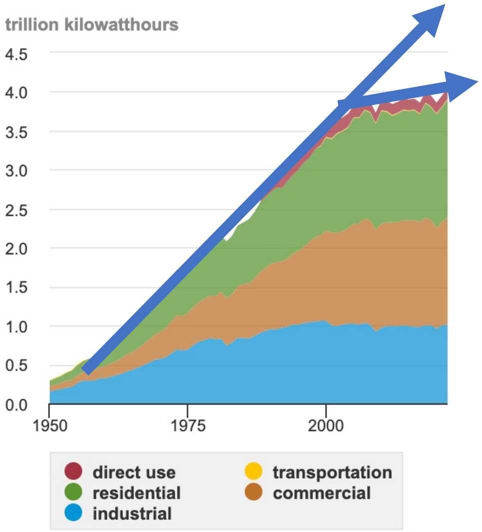
2023 Power Electronics & Energy Conversion Workshop
Albuquerque NM, August 2-3, 2023

Existential Reasons for Wide and Ultra Wide Bandgap Semiconductors

2022
- **industrial:** 1.0 trillion kilowatthours
- **commercial:** 1.4 trillion kilowatthours
- **residential:** 1.5 trillion kilowatthours
- **transportation:** 0.0 trillion kilowatthours
- **direct use:** 0.1 trillion kilowatthours

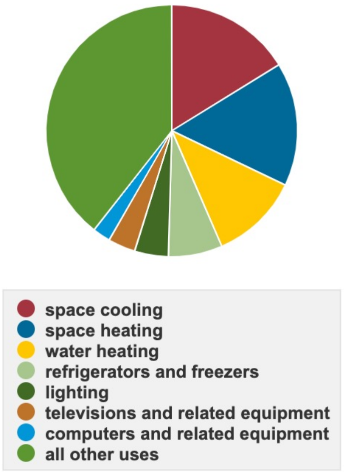
U.S. electricity retail sales to major end-use sectors and electricity direct use by all sectors, 1950-2022



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.6, March 2023, preliminary data for 2022

Space Cooling:
A leading driver of Electricity Demands
Impacts Grid
Significant Social, Human Health Issue

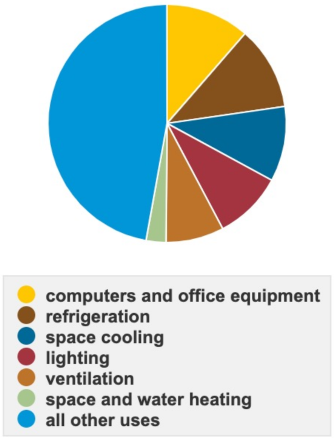
U.S. residential sector electricity consumption by major end uses, 2022



Data source: U.S. Energy Information Administration, *Annu Energy Outlook 2022*, Table 4, March 2023
Note: Space heating includes consumption for heat and operating furnace fans and boiler pumps. *All other uses* includes clothes washers and dryers, dishwashers, cookin equipment, miscellaneous electric and electronic devices, heating elements, and motors not included in other uses.

Motors Across all Sectors ~ 15 % of energy use.
Computation ~ 2%
EV ~ 0.5 % 2022
EV ~ 4 % 2030

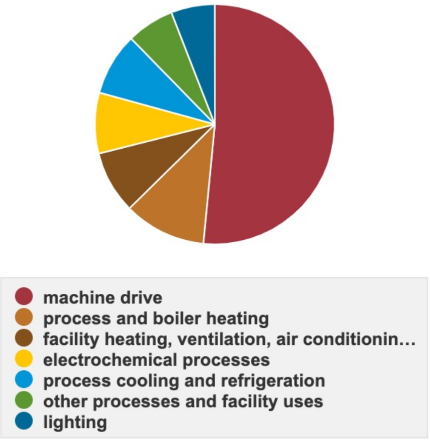
U.S. commercial sector electricity consumption by major end uses, 2022



Data source: U.S. Energy Information Administration, *Annual Energy Outlook 2023*, Table 5, March 2023
Note: Space cooling, and space and water heating includes fuel consumption for district services. *All other uses* includes (but is not limited to) cooking equipment and miscellaneous uses such as transformers, medical imaging and other medical equipment, elevators, escalators, off-road electric vehicles, laboratory fume hoods, laundry equipment, coffee brewers, and water services.

Machine Drives:
Many at Medium Voltage, 3.3k, 6.5 kV
Lighting, Cooling

U.S. manufacturing electricity consumption by major end uses, 2018



Data source: U.S. Energy Information Administration, *Manufact Energy Consumption Survey, 2018*, Table 5.1, February 2021

Click to enlarge

Connect Semiconductor Materials properties to the System Benefits.
The Challenges and Opportunities of Moving Beyond Silicon

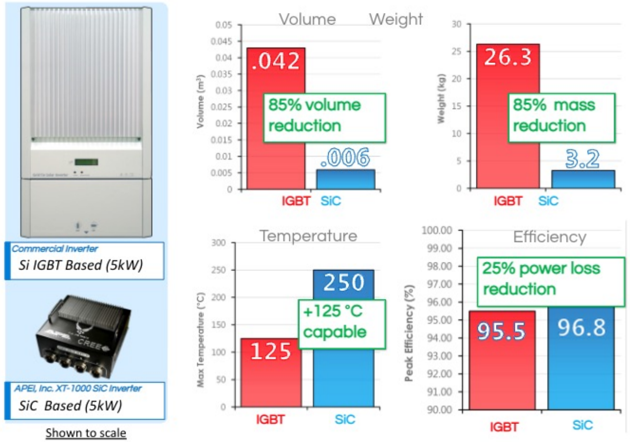
Reduction in Volume, Weight, Savings in Materials Costs

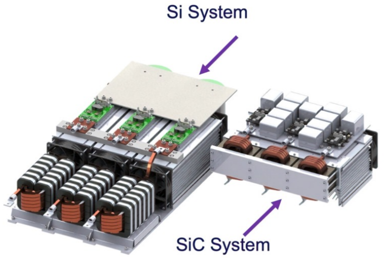
Improved Power Conversion Efficiency

Higher Temperature Operation

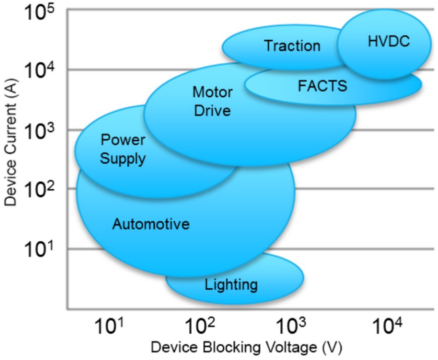
Reduce # of components,
Circuit complexity
(fewer devices in series)

Potentially Smarter Systems
Intelligent gate drivers
Monitoring Fault Protection
More Plug and Play





Wolfspeed website

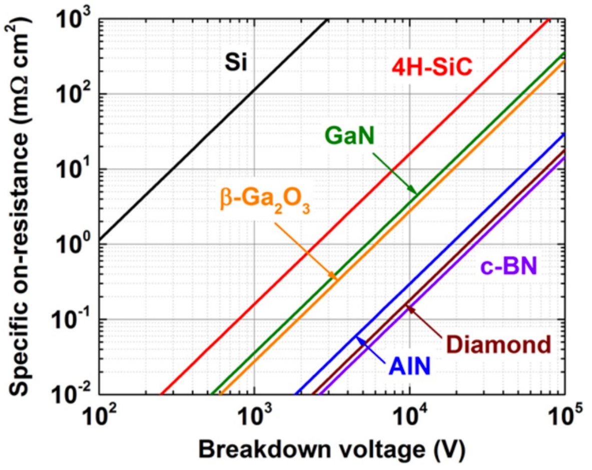


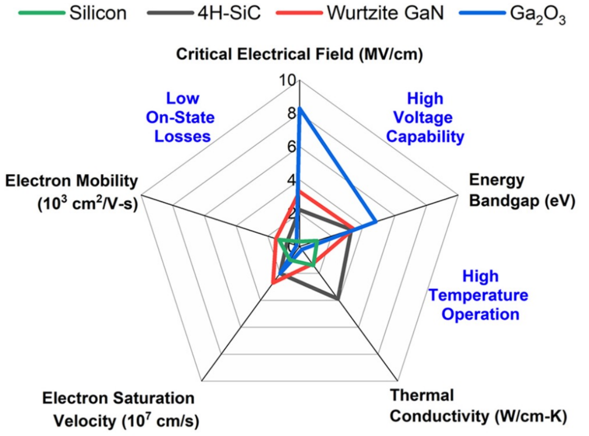
Kizilyalli, Wide Band-Gap Semiconductor Based Power Electronics for Energy Efficiency, ARPA-E DOE, 2018

M. K. Das, ICSCRM 2011

- **Operate w/ Higher Efficiency: translates to fuel savings + less waste-heat to manage**
- **Operate at Higher Temperature: smaller cooling system + "limp-home" margin**
- **Operate at Higher Frequency: reduce the size of passive circuit components**

The Fundamental Material Advantage





Ravinchandra et al. Journal of Power Electronics (2022) 22:1398–1413

With Improved Knowledge of Material Parameters

Kaplar, et al.,2022 6th IEEE Electron Devices Technology & Manufacturing Conference (EDTM)

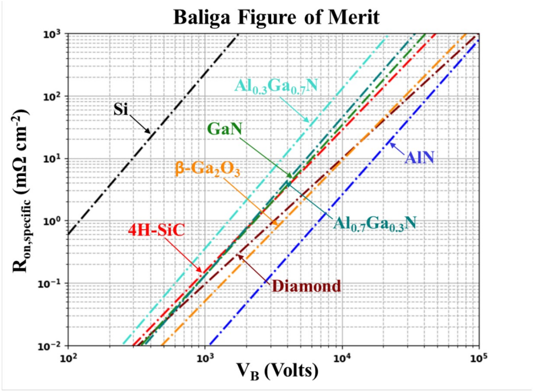
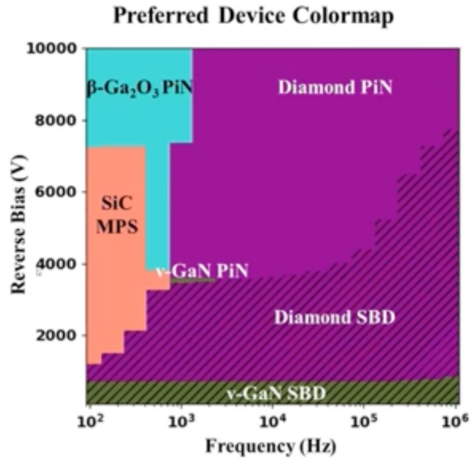


Figure 5. BFOM for representative UWBG semiconductors calculated considering relevant high- and low-field transport considerations.

Co-Design Approach Maps out Competing Technologies

Goodnick et al., 2022 PEEC Workshop



For PIN and SBD diodes

Adoption Consideration of Wide and Ultrawide Bandgaps

Identification of Early Enabling Applications

(Preferably with volume)

SiC Schottky barrier diode (SBD)

Fast Reverse Recovery

SiC junction barrier Schottky diode (JBS)

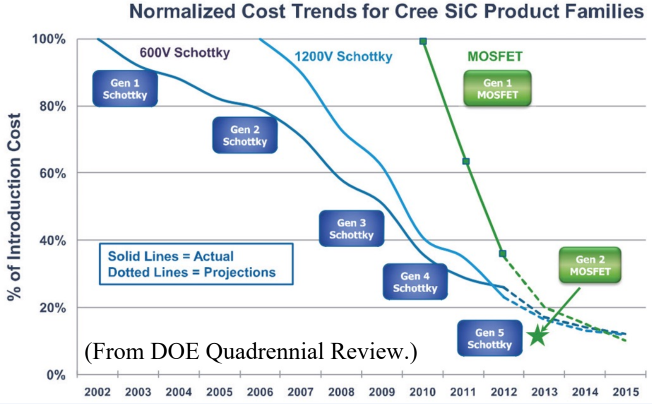
Control of fields for higher voltage

Still with Fast Reverse Recovery

SiC PIN Diode

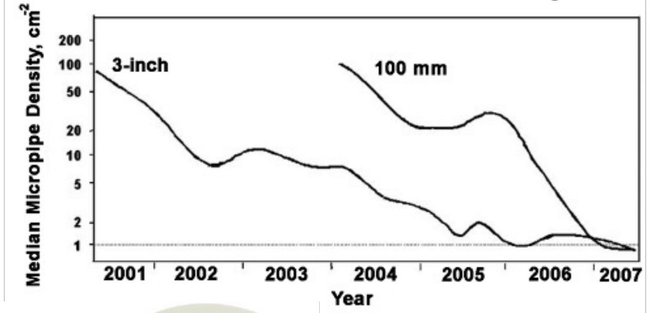
HV – with Conductivity modulation

A scalable and Improving Cost Structure



(From DOE Quadrennial Review.)

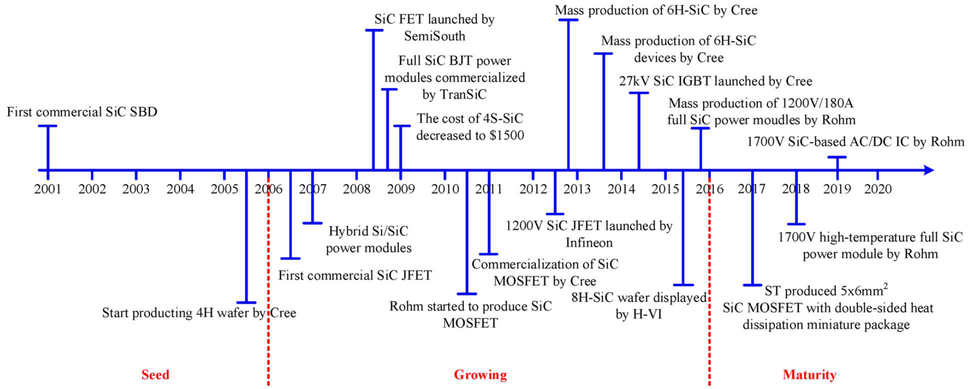
Wafer Size and Problem Solving



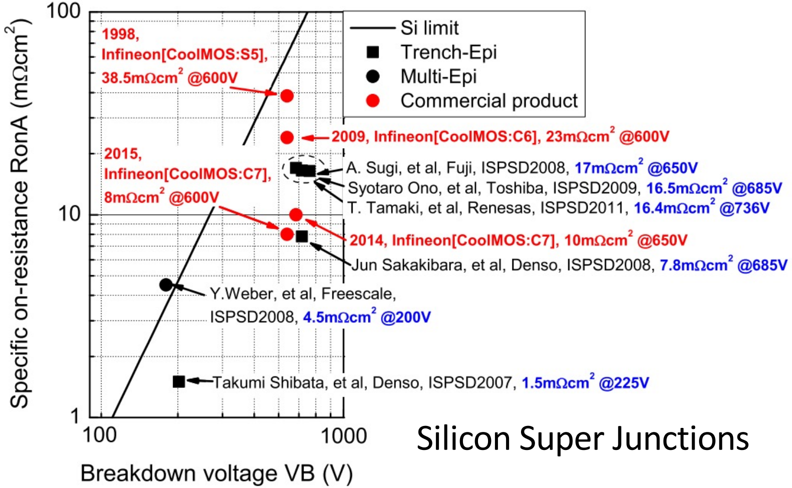
- First Need Availability of Materials – Learning Cycles
- Cost of component vs design for system level performance.
- Comfort with legacy designs: not just a substitute
  - Education of designers about Wide band Gap
- Packaging: Not just thermal but EMI and Gate drivers
- Reliability and Standards
- Hard to displace Legacy investments.

Lessons Learned from SiC - Some Patience is Necessary

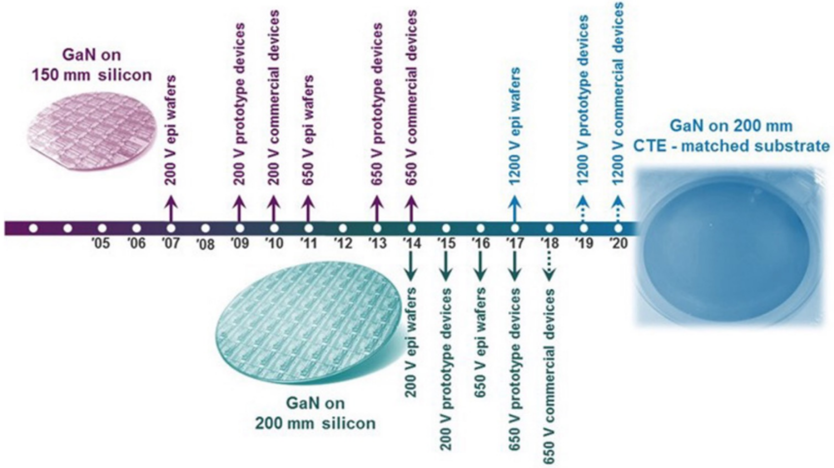
Note Time Between Commercial Diodes and Commercial Transistors



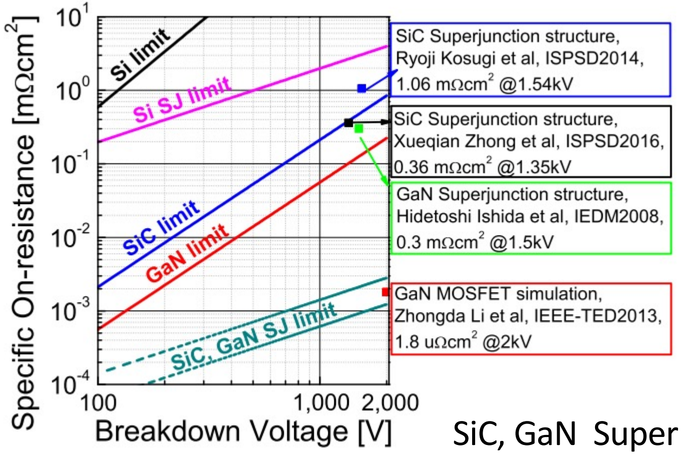
Gao et al. Micromachines 2019, 10(6), 406; https://doi.org/10.3390/mi10060406



Silicon Super Junctions



H Amano et al 2018 J. Phys. D: Appl. Phys. 51 163001



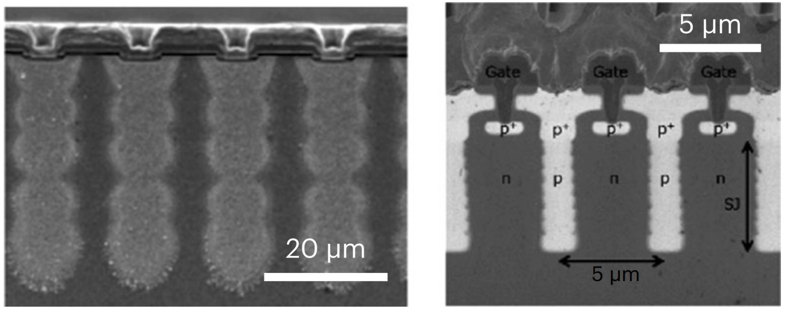
SiC, GaN Super Junctions

Udrea, et al, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 64, NO. 3, MARCH 2017

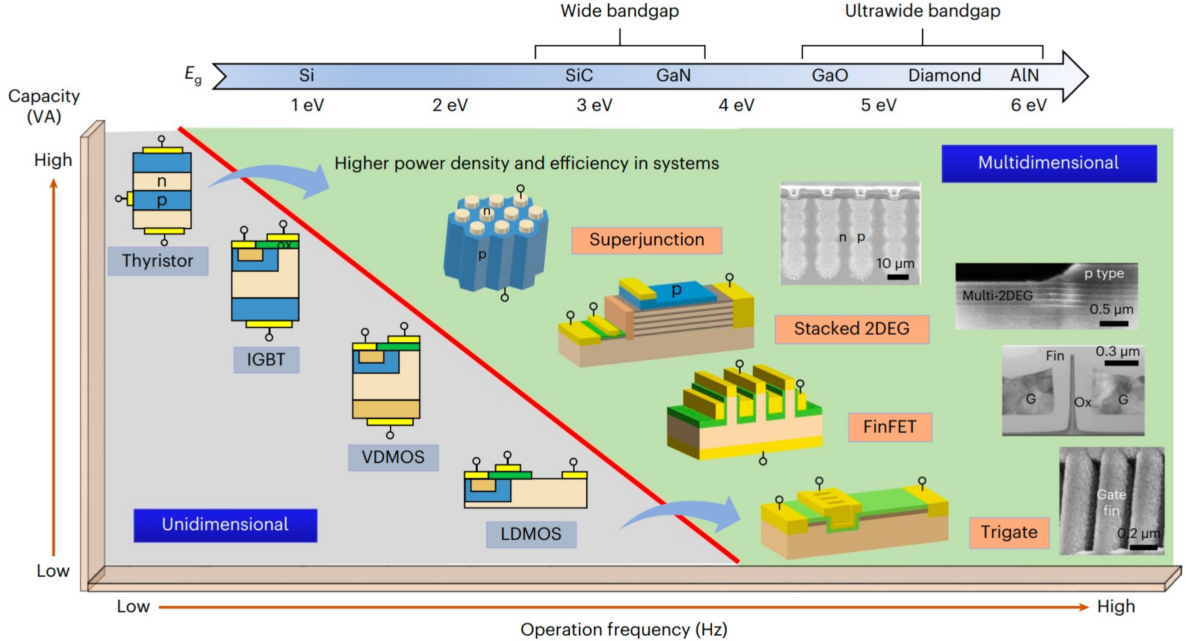
Innovations in Device Geometries

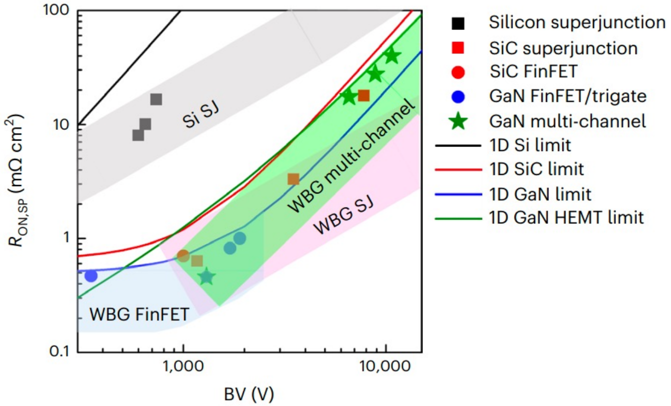
Challenges for Ultra and wide bandgap semiconductors:

- Trench Etching,
- Ion Implantation, High Temperature, Channeling
- Etch and Regrowth
- Field Control for breakdown, Control of D or E mode operation
- Increased Doping, and Dopant Activation still a problem



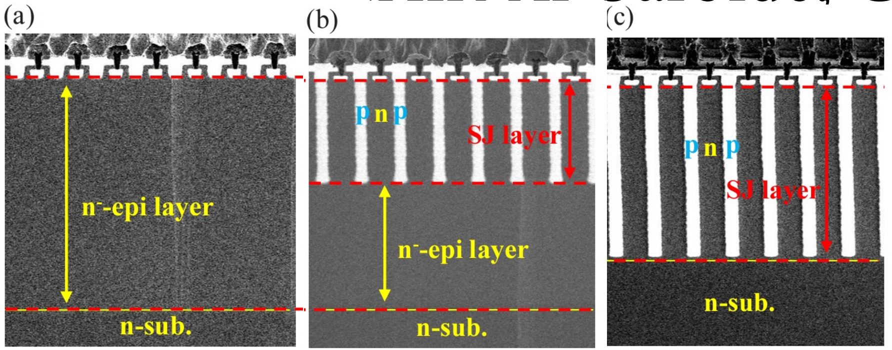
Silicon (left) SiC right Super Junction Examples





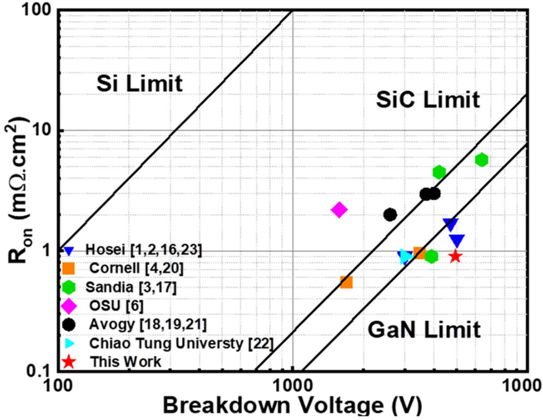
Zhang, Y., Udrea, F. & Wang, H. Multidimensional device architectures for efficient power electronics. *Nat Electron* **5**, 723–734 (2022). https://doi.org/10.1038/s41928-022-00860-5

Silicon Carbide, GaN Vertical Devices

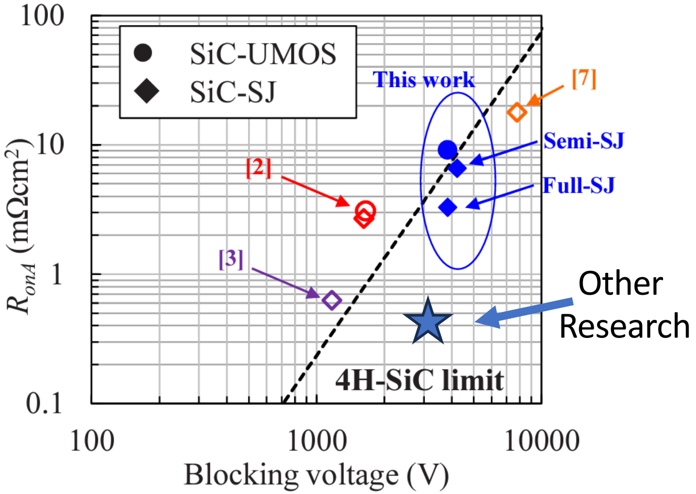


SiC- UMOS. Semi- SJ. Full SJ

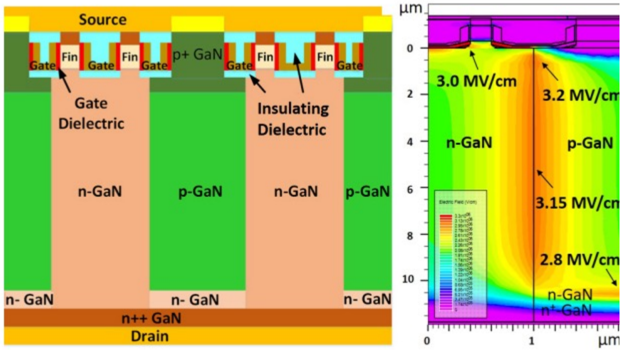
GaN-on-GaN pn power diodes with a breakdown voltage of 4.9 kV and BFOM of 27 GW/cm2 using a relative thin 28 um drift layer with a doping concentration of 1 10^{15} cm^3.



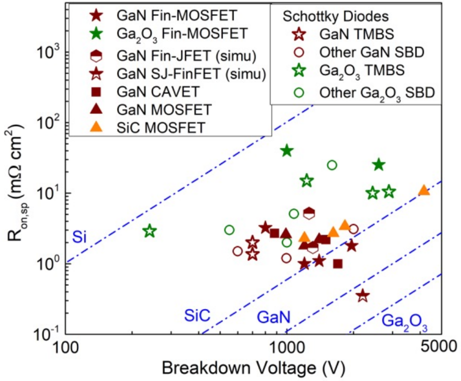
Talesara,Appl.Phys.Lett.122,123501(2023);doi:10.1063/5.013531



Baba, et al., Ultra-Low Specific on-Resistance Achieved in 3.3 kV-Class SiC Superjunction MOSFET, 33rd International Symposium on Power Semiconductor Devices and ICs (ISPSD) (2021)



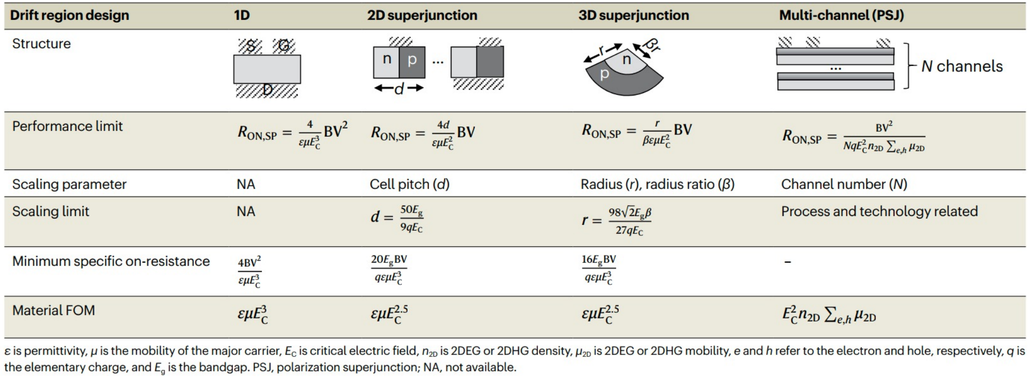
Left: schematic of an SJ-FinFET where each SJ unit cell accommodates two fin channels. Right: E-field distribution in an SJ-FinFET unit cell at a forward blocking bias of 2200 V, showing an almost constant E-field along the p-n junction in the SJ drift region.



RON, versus BV of GaN/Ga2O3 TMBS diodes and power FinFETs compared with other WBG/UWBG high-voltage SBD and transistor technologies.

More Figures of Merit:

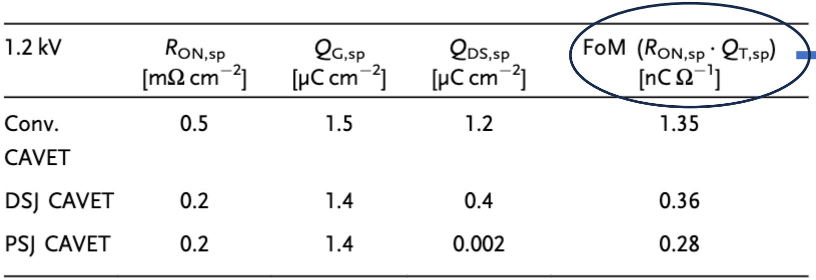
Table 1 | Performance limit, scaling parameter and limit, minimum specific on-resistance, and material FOM of 1D vertical unipolar devices, 2D and 3D superjunction devices and the multi-channel lateral devices with precisely matched polarization charges



Drift region design	1D	2D superjunction	3D superjunction	Multi-channel (PSJ)
Structure	S G D	n p … d	r βr n p	… N channels
Performance limit	$R_{\mathrm{ON,SP}} = \frac{4}{\varepsilon\mu E_C^3}\mathrm{BV}^2$	$R_{\mathrm{ON,SP}} = \frac{4d}{\varepsilon\mu E_C^2}\mathrm{BV}$	$R_{\mathrm{ON,SP}} = \frac{r}{\beta\varepsilon\mu E_C^2}\mathrm{BV}$	$R_{\mathrm{ON,SP}} = \frac{\mathrm{BV}^2}{NqE_C^2 n_{2D}\sum_{e,h}\mu_{2D}}$
Scaling parameter	NA	Cell pitch (d)	Radius (r), radius ratio (β)	Channel number (N)
Scaling limit	NA	$d = \frac{50E_g}{9qE_C}$	$r = \frac{98\sqrt{2}E_g\beta}{27qE_C}$	Process and technology related
Minimum specific on-resistance	$\frac{4\mathrm{BV}^2}{\varepsilon\mu E_C^3}$	$\frac{20E_g\mathrm{BV}}{q\varepsilon\mu E_C^3}$	$\frac{16E_g\mathrm{BV}}{q\varepsilon\mu E_C^3}$	–
Material FOM	$\varepsilon\mu E_C^3$	$\varepsilon\mu E_C^{2.5}$	$\varepsilon\mu E_C^{2.5}$	$E_C^2 n_{2D}\sum_{e,h}\mu_{2D}$

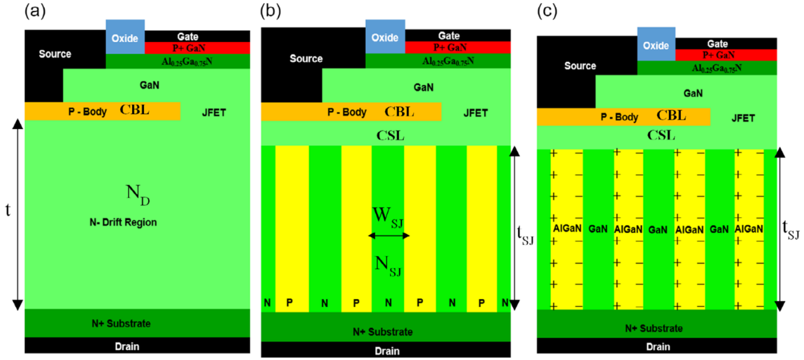
ε is permittivity, μ is the mobility of the major carrier, E_C is critical electric field, n_{2D} is 2DEG or 2DHG density, μ_{2D} is 2DEG or 2DHG mobility, e and h refer to the electron and hole, respectively, q is the elementary charge, and E_g is the bandgap. PSJ, polarization superjunction; NA, not available.

Zhang, Y., Udrea, F. & Wang, H. Multidimensional device architectures for efficient power electronics. *Nat Electron* **5**, 723–734 (2022). https://doi.org/10.1038/s41928-022-00860-5

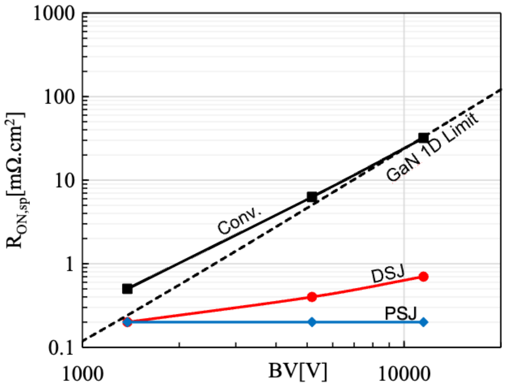


1.2 kV	$R_{\mathrm{ON,sp}}$ [mΩ cm^{-2}]	$Q_{\mathrm{G,sp}}$ [μC cm^{-2}]	$Q_{\mathrm{DS,sp}}$ [μC cm^{-2}]	FoM ($R_{\mathrm{ON,sp}} \cdot Q_{\mathrm{T,sp}}$) [nC Ω^{-1}]
Conv. CAVET	0.5	1.5	1.2	1.35
DSJ CAVET	0.2	1.4	0.4	0.36
PSJ CAVET	0.2	1.4	0.002	0.28

M. Torky, M.S. Thesis, Rensselaer Polytech. Inst., Troy, NY2022

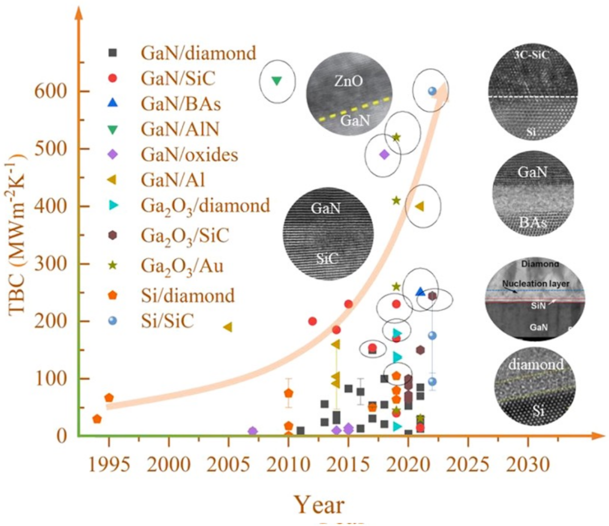


f-cell schematic cross sections of a) conventional and b) DSJ, and c) PSJ CAVETs.

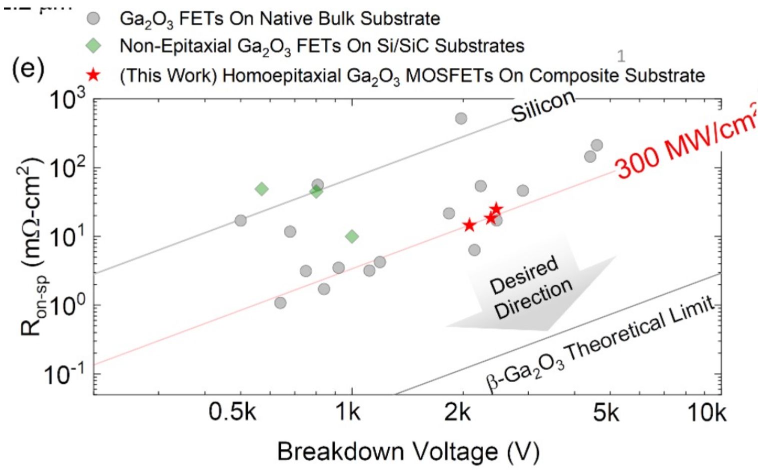


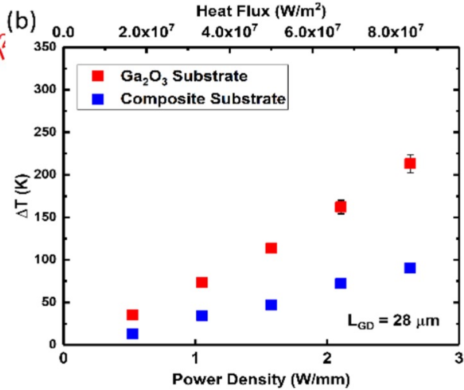
Torky, et al., Comparative Performance Evaluation for 1.2–10kV Conventional and Superjunction GaN Current Aperture Vertical Electron Transistors, Phys. Status Solidi A2023,

Innovations in Thermal Management



Feng, et al., ACS Applied Materials & Interfaces 2023 15 (25), 29655-29673
DOI: 10.1021/acsami.3c02507





Fusion Bonding, With 15 nm SiN layer to SIC
($A_{l2}O_3$ could be alternative to SiN layer)
Bonding to Diamond instead of SiC also a
future choice.

Ultra-Wide Band Gap Ga2O3-on-SiC MOSFETs, Yiwen Song, et al., ACS Applied Materials & Interfaces 2023 15 (5), 7137-7147
DOI: 10.1021/acsami.2c21048

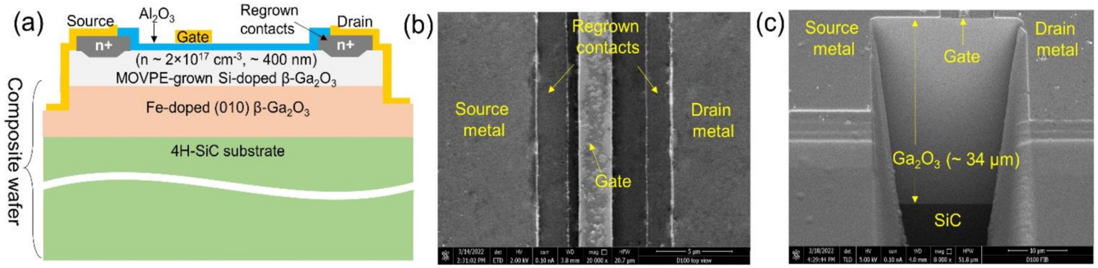


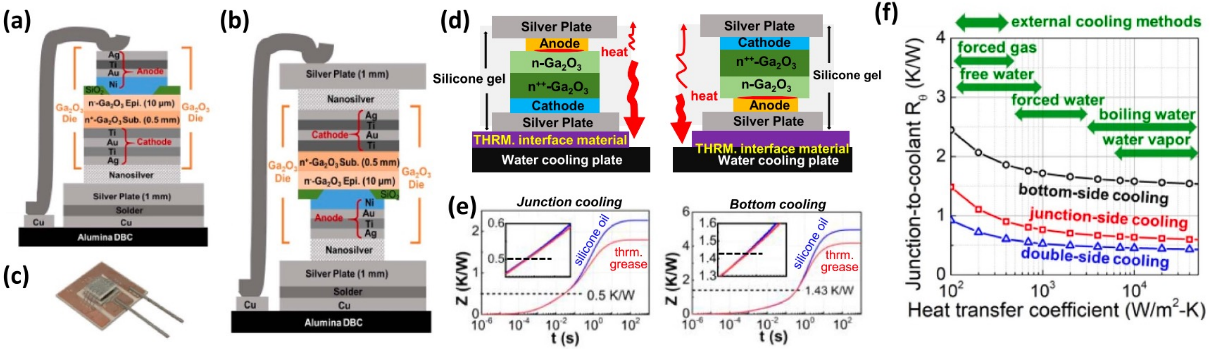
Figure 2: **(a)** A cross-sectional schematic of a Ga_2O_3 MOSFET fabricated on the composite substrate. **(b)** Plan-view SEM image of a final device structure. **(c)** Cross-sectional SEM image of the same device showing the thickness of Ga_2O_3 layer.

Packaging and Double Side Cooling Approaches

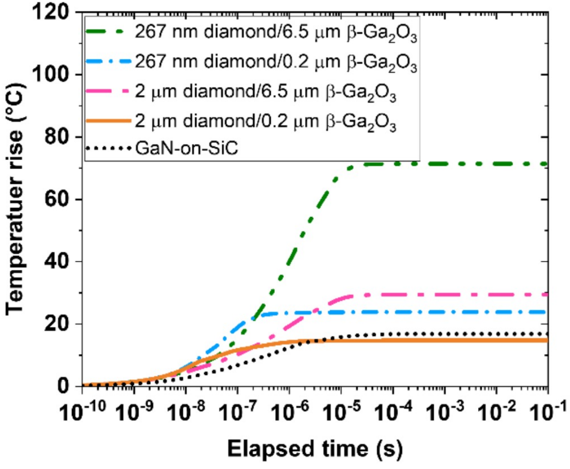
For all UWBG Semiconductors There are Challenges with Thermal Expansion Coefficient Matching, Creep, Dielectric Breakdown etc. but substantial Innovation.

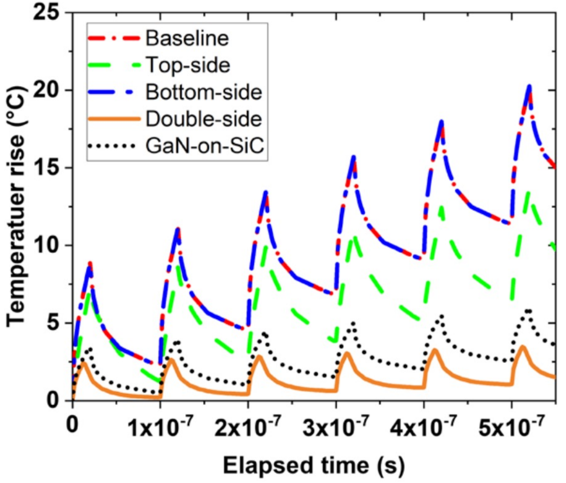
As alternatives to heterogeneous large-area packaged Ga_2O_3 devices are now allowing for probing Ga_2O_3 thermal management beyond the device level.

Modeling (Diamond/Ga_2O_3/Diamond) shows that due to the low thermal diffusivity of Ga_2O_3 that Top side cooling is advantageous and, in some cases, may be necessary.



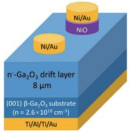
Yuan Qin et al 2023 J. Phys. D: Appl. Phys. 56 093001





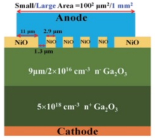
Kim et al., IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 70, NO. 4, APRIL 2023

Nickle Oxide/Gallium Oxide Structures



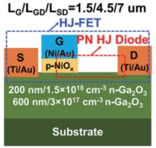
2019. 12

The first 1-kV NiO/β-Ga_2O_3 heterojunction diode [27]
Breakdown voltage: 1059 V
BFOM: 0.32 GW/cm^2



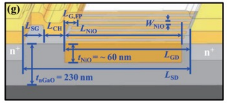
2020. 09

The first NiO/β-Ga_2O_3 heterojunction JBS diode [3
Breakdown voltage: 1715 V
BFOM: 0.85 GW/cm^2



2021. 01

The first NiO/β-Ga_2O_3 heterojunction JFET [33]
Breakdown voltage: 1190 V
BFOM: 0.33 GW/cm^2



2021. 07

The first β-Ga_2O_3 superjunction MOSFET [35]
Breakdown voltage: 1326 V
BFOM: 39.1 MW/cm^2

Lu et al., Recent advances in NiO/Ga2O3 heterojunctions for power electronics, Journal of Semiconductors
doi: 10.1088/1674-4926/44/6/061802

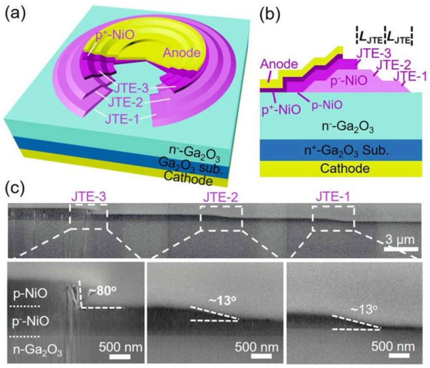


FIG. 1. (a) 3D and (b) cross-sectional schematics of the NiO/Ga_2O_3 p–n diode with the proposed NiO JTE. (c) Cross-sectional SEM images of the entire JTE region fabricated in this work and the edge of each JTE layer.

Xiao, et al., NiO junction termination extension for high-voltage (>3 kV) Ga2O3 devices
Appl. Phys. Lett. 122, 183501 (2023)
https://doi.org/10.1063/5.0142229

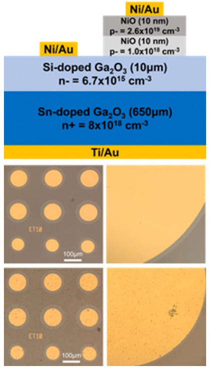


Fig. 1 (top) Schematic of the structures and images of devices (center) before and (bottom) after operation at 600 K.

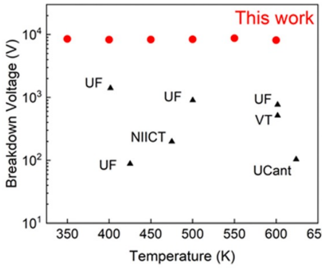
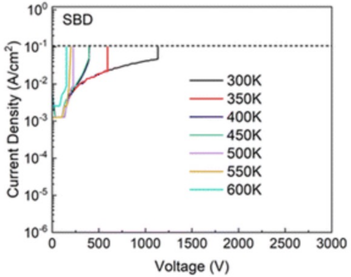
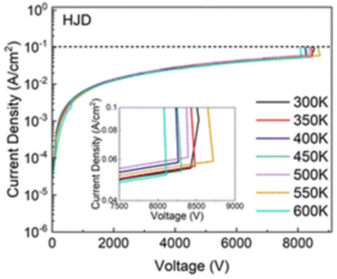


Fig. 5 Compilation of maximum operation temperature *versus* V_B for vertical Ga_2O_3 rectifiers. Previous data comes from Virginia Tech[37], University of Canterbury[39], University of Florida[38] and NIICT[40].

Li et al., Superior high temperature performance of 8 kV NiO/Ga2O3 vertical heterojunction rectifiers, J. Mater. Chem. C, 2023, 11, 7750





For 100 µm diameter devices, the power figure of merit (VB)2/RON, where RON is the on-state resistance, was 9.1 GW cm−2 at 300 K and 3.9 GW cm−2 at 600 K. By sharp contrast, Schottky rectifiers fabricated on the same wafers show VB of ~1100 V at 300 K, with a negative temperature coefficient of breakdown of 2 V K−1. The corresponding figures of merit for Schottky rectifiers were 0.22 GW cm−2 at 300 K and 0.59 MW cm−2 at 600 K.

Other Interesting Trends In Wide and Ultra Wide Bandgap Power Electronics

- Diamond Electronics

- Optical Control of Switches – Smart gate drivers

- Exploiting the Speed of of Wide bandgap Electronics
  - Ride through Transients
  - Protection from Fast Faults
    - What are the critical time scales, and magnitudes of currents for different applications.

- Still a lot of need for fundamental research in understanding materials, (e.g., defects, doping, impact ionization parameters) fabrication (e.g., ion Implantation, regrowth).

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