Gallium Oxide – Taking over from SiC ?

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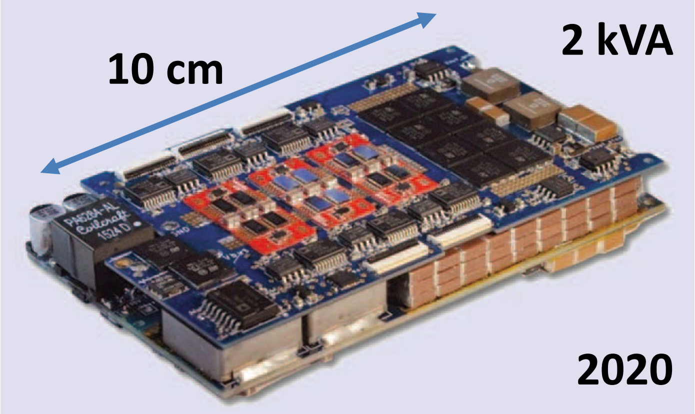
http://www.bristol.ac.uk/physics/research/cdtr/

Pathway from Si to wide to ultrawide bandgap semiconductors

	Narrow	Wide		ULTRAs – New class of materials			
	Si	4H-SiC	GaN	ß-Ga_2O_3	Diamond	h-AlN	h-BN
Bandgap (eV)	1.12	3.26	3.4	4.9	5.5	6.2	6.4
Breakdown Field (MV/cm)	0.3	2.5	3.8	8	10	16	12
Baliga's figure of merit (FOM)	**1**	**183**	**535**	**3444**	**9000**	**9797**	**1678**
	Traditional	New		Emerging Technology			

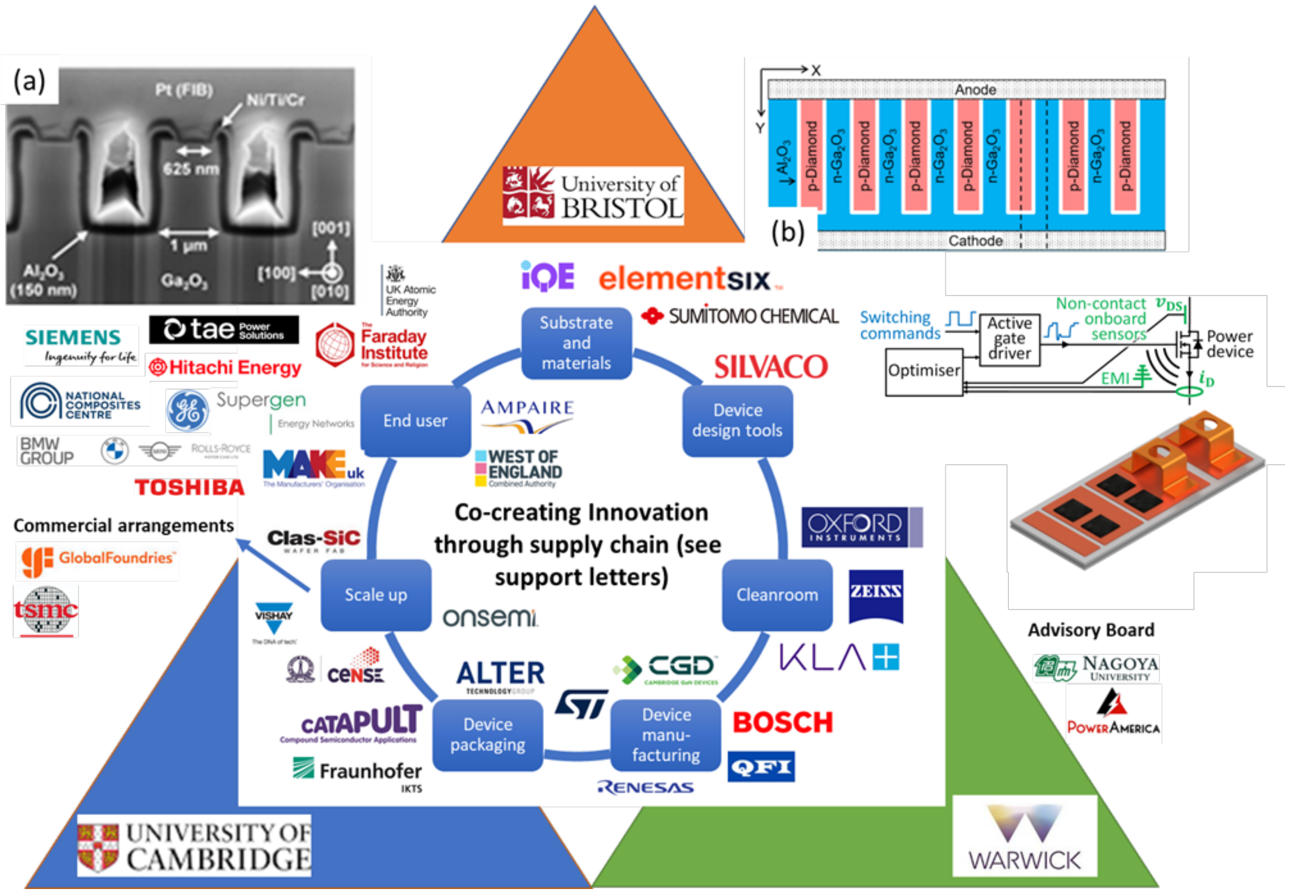
Emerging technology

- **>20% energy savings**
- Smaller size
- Higher voltage rating
- …

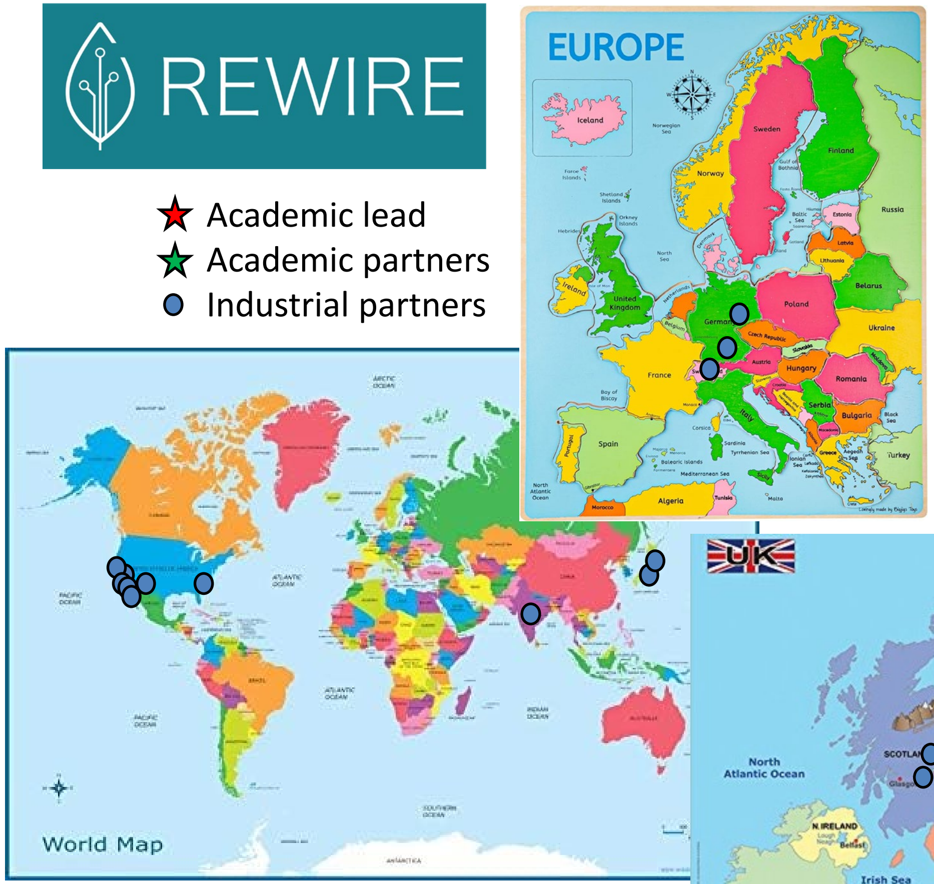


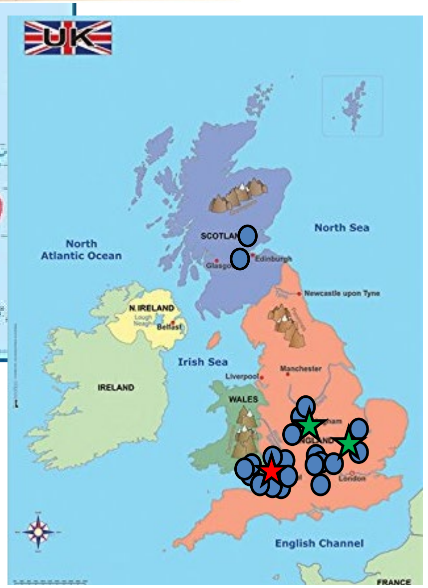
Match box size but more powerful!

High voltage power electronics: Co-innovation to commercialization



Power device technology through supply chain

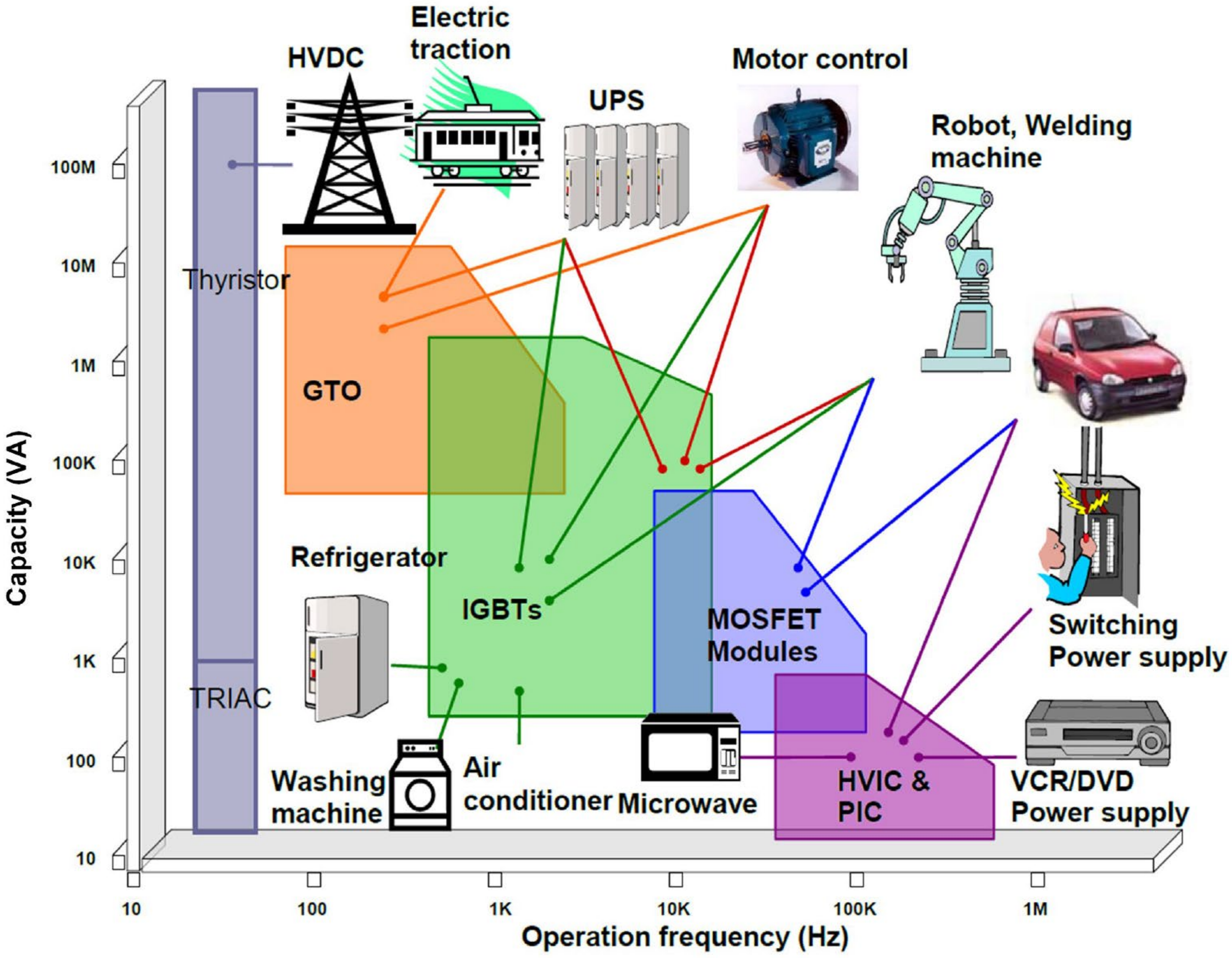


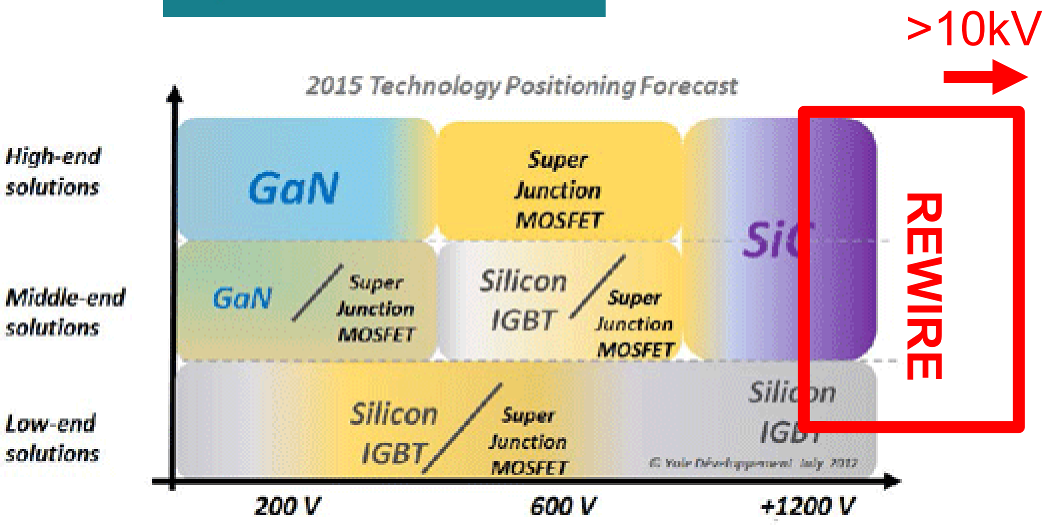


£11M UK program with 35 industrial partners with contributions of >£3M

High voltage power electronics

REWIRE

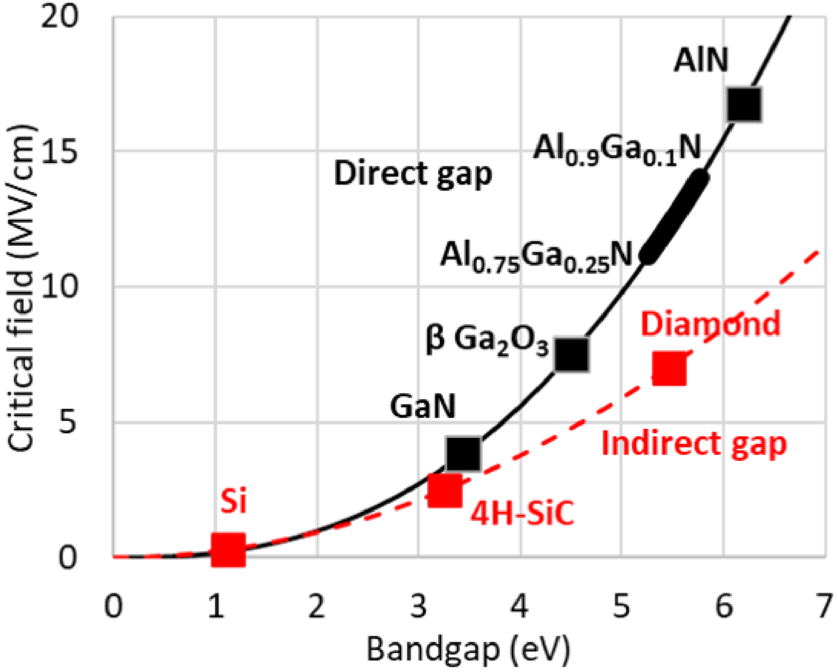




Co-develop devices and applications with industry; wide and ultra-wide bandgap semiconductors

Power electronics is a major technology sector internationally.

Ga_2O_3 of great potential for power electronics

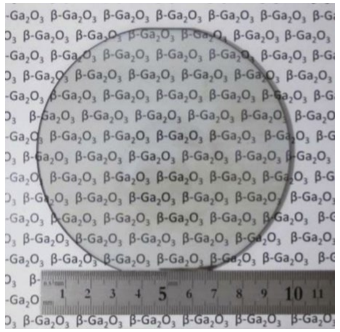


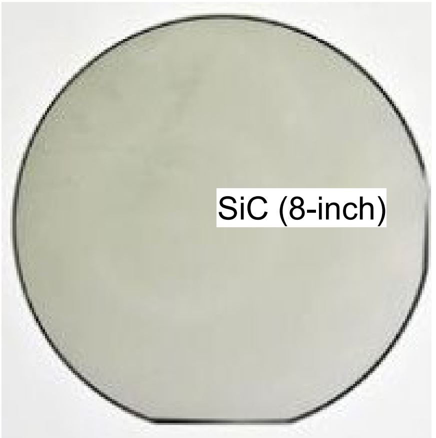
	Si	GaN	SiC	Diamond	Ga_2O_3
E_g(eV)	1.1	3.4	3.3	5.5	4.9
μ(cm^2/V.s)	1400	1200	1000	2000	300
E_c(MV/cm)	0.3	3.3	2.5	10	8
ε_{REL}	11.8	9	9.7	5.5	10
λ(W/m.K)	250	130	370	2000	20
BFOM($\mu\varepsilon E_c^3$)	1	870	340	24661	3444

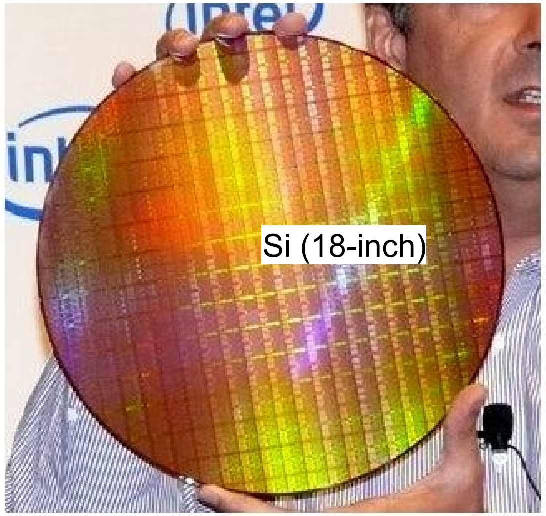
Baliga Figure of Merit


SCD (6 mm)


AlN (2-inch)


Ga_2O_3 (4 - 6-inch)

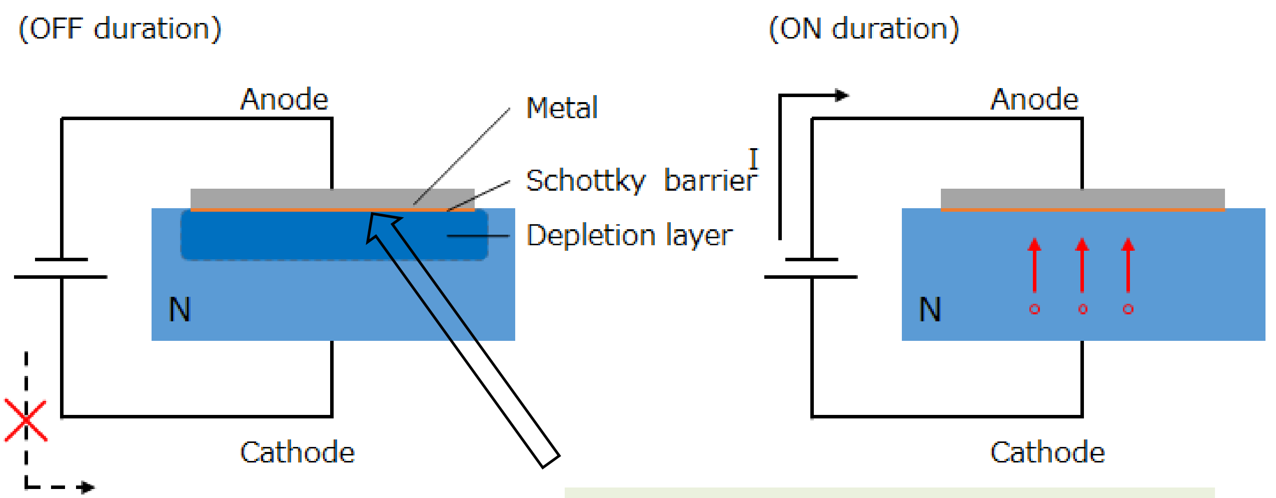




Cleanroom facilities for device prototyping

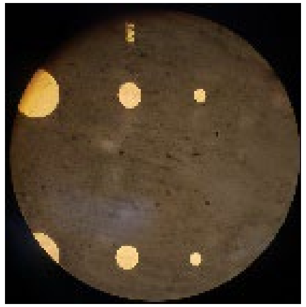
Example, Bristol cleanroom

How do increase breakdown voltage in power devices ?

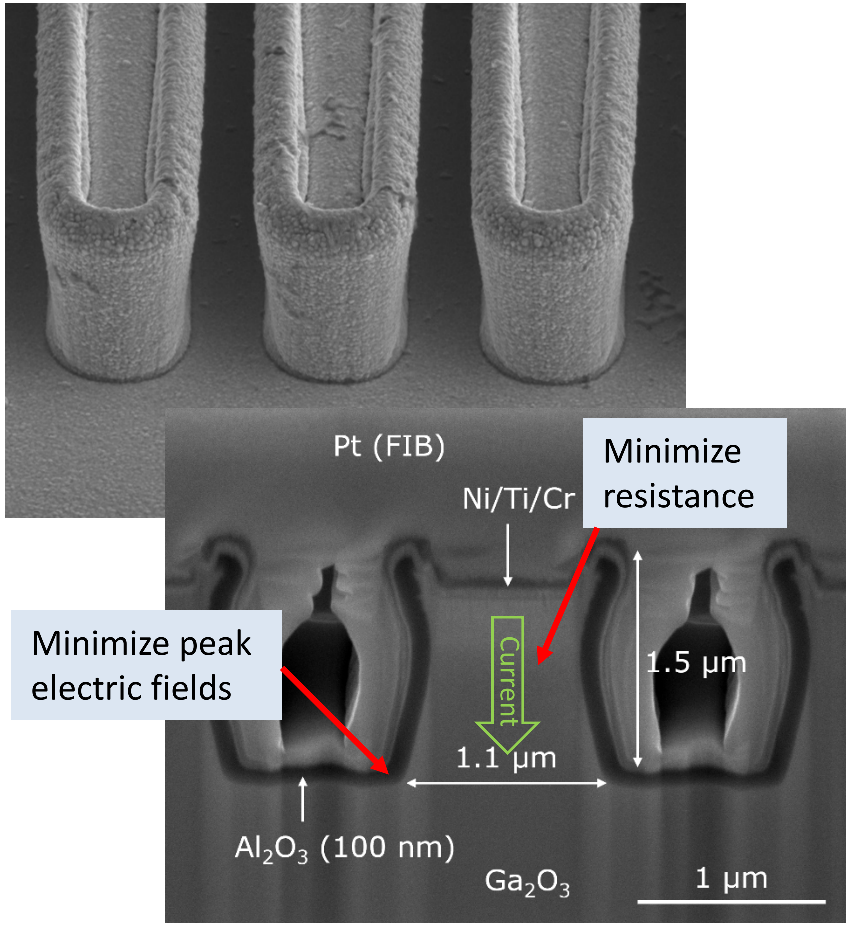


I:Current does not flow.

https://toshiba.semicon-storage.com

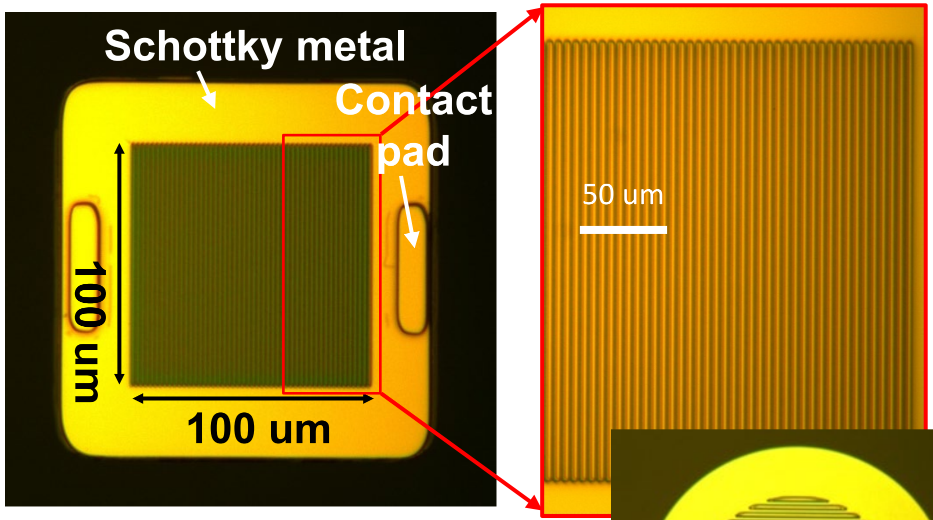


Most of the electrical field generated by the voltage applied near surface which limits the voltage these device can sustain!

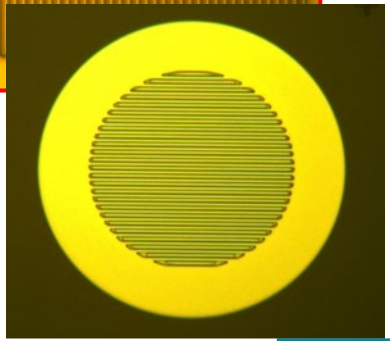


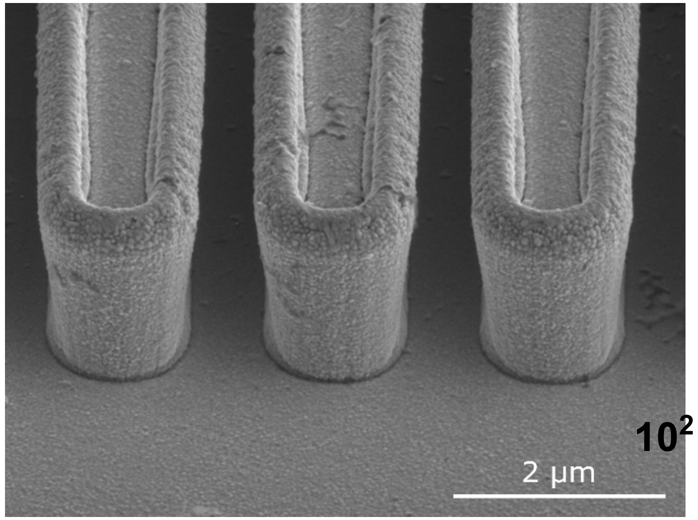
3D semiconductor structures move the electric field inside the semiconductor and increase breakdown voltage

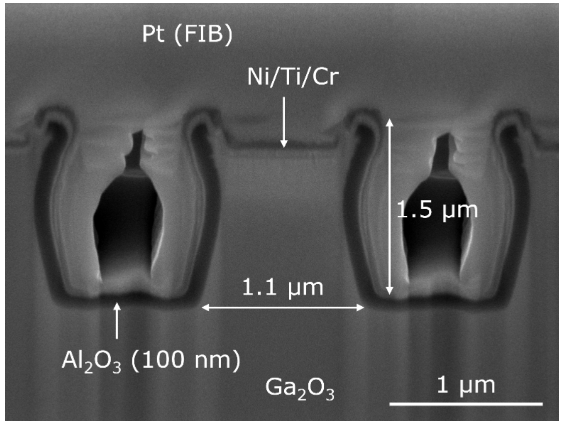
Bristol fabrication of Ga_2O_3 trench Schottky Barrier Diodes

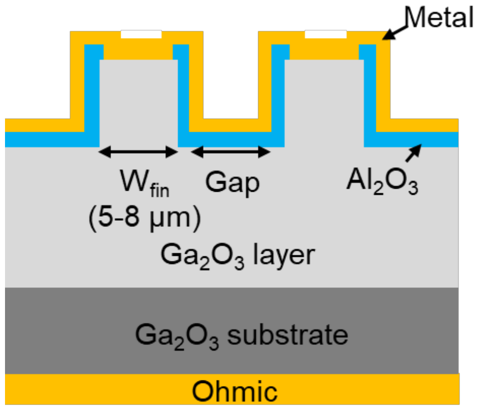


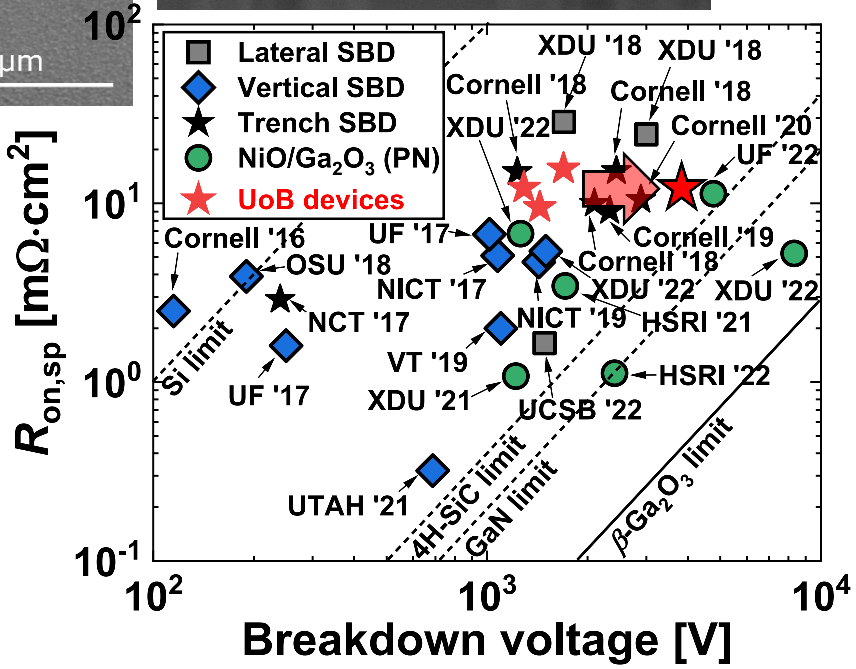
[W_{fin} 1 um / W_{gap} 1 um]







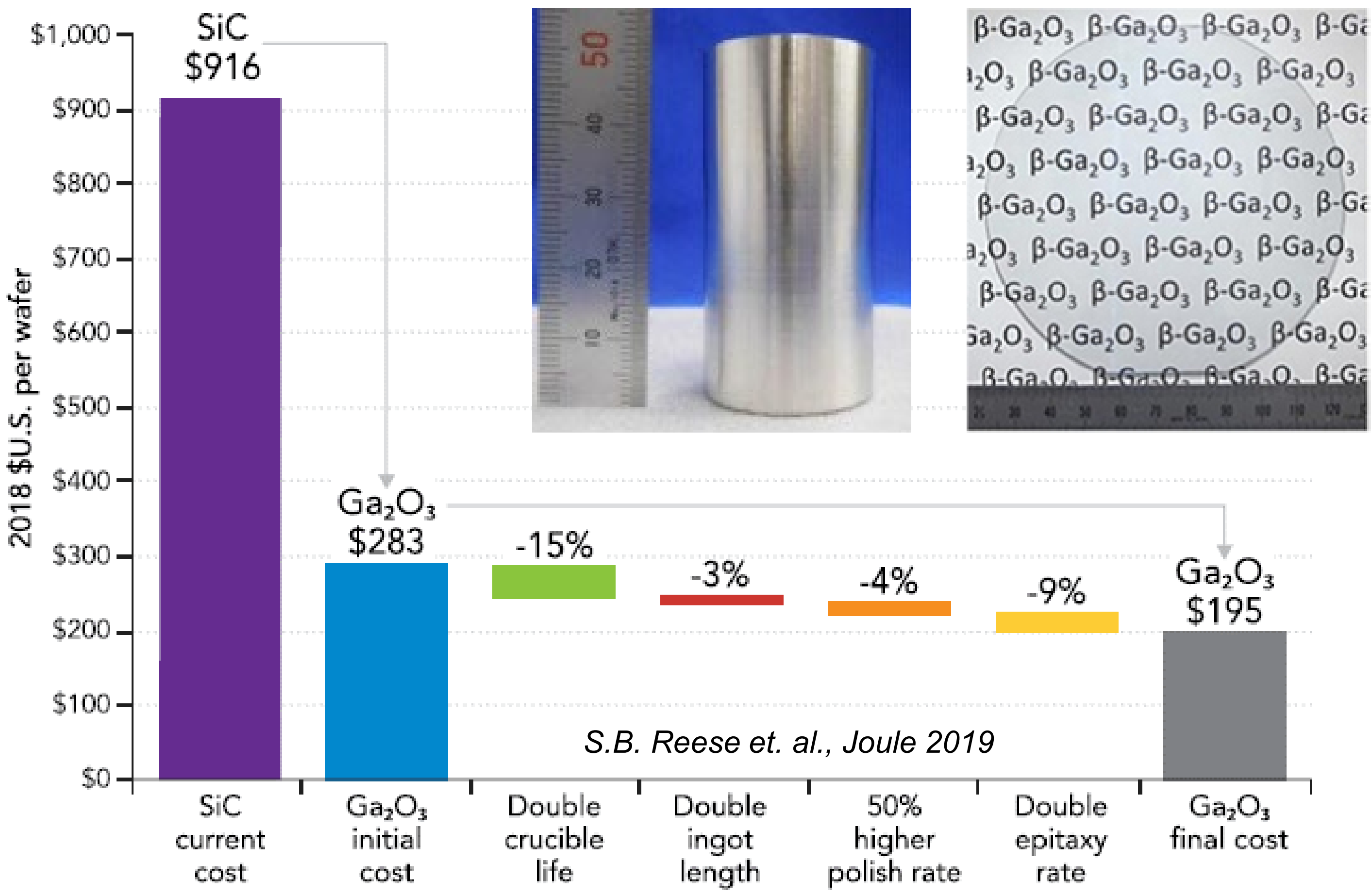




Ga_2O_3 versus SiC device technology

Why Ga_2O_3?
Cost Comparison

- Modelled 6-inch wafer costs comparison for Ga_2O_3 and SiC wafers
- Ga_2O_3 wafers would cost 3x less than SiC wafers

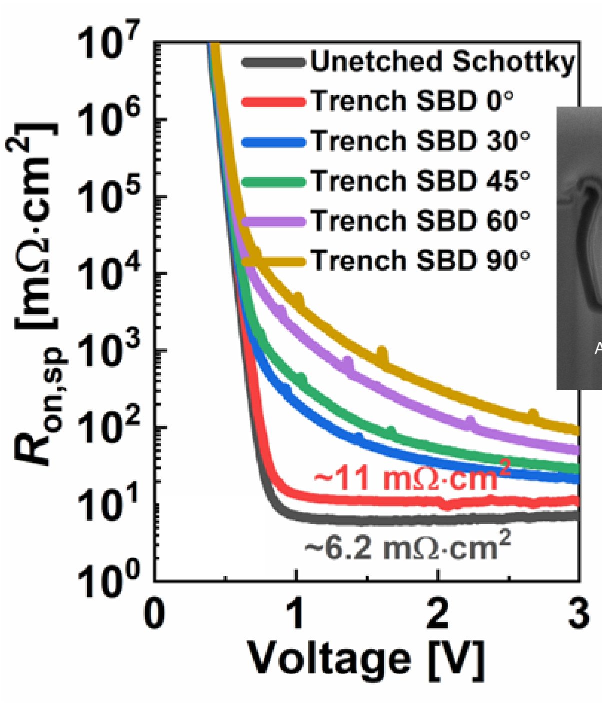


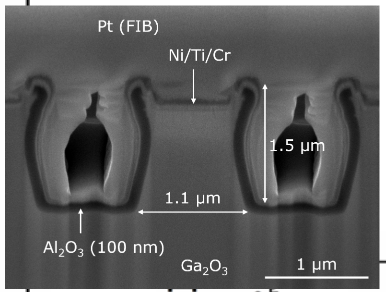
S.B. Reese et. al., Joule 2019

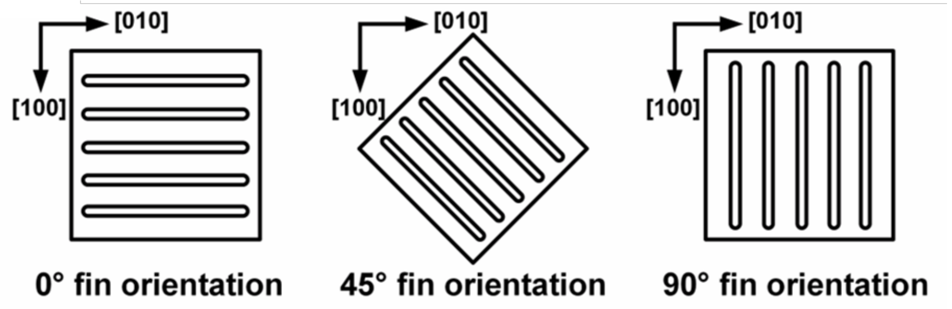
K.Hoshikawa et. al, Journal of Crystal Growth, 2016; M. Higashiwaki et al 2017 J. Phys. D: Appl. Phys.

In contrast to SiC, Ga_2O_3 has large in-plane anisotropy

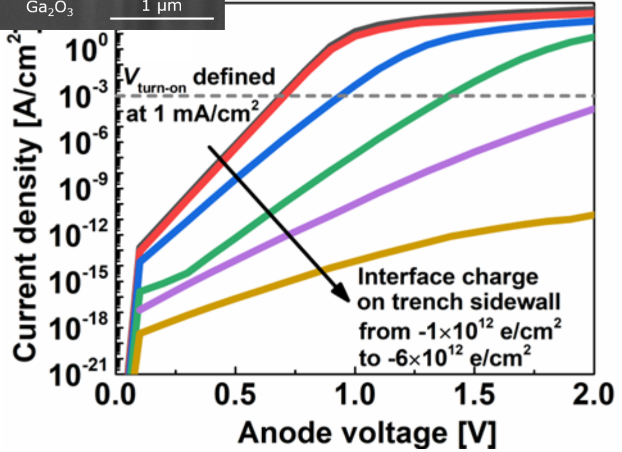
Orientation dependence of trench SBDs

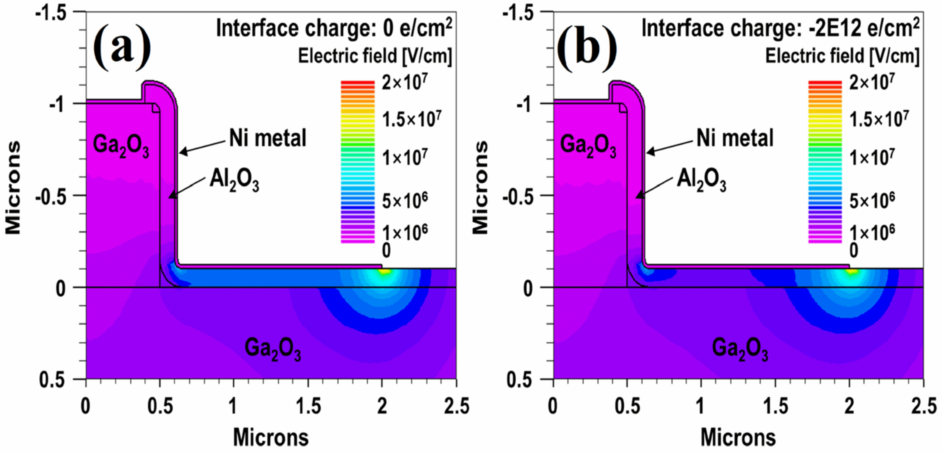






H.S. Kim et al, accepted in IEEE Trans. Electron Dev.

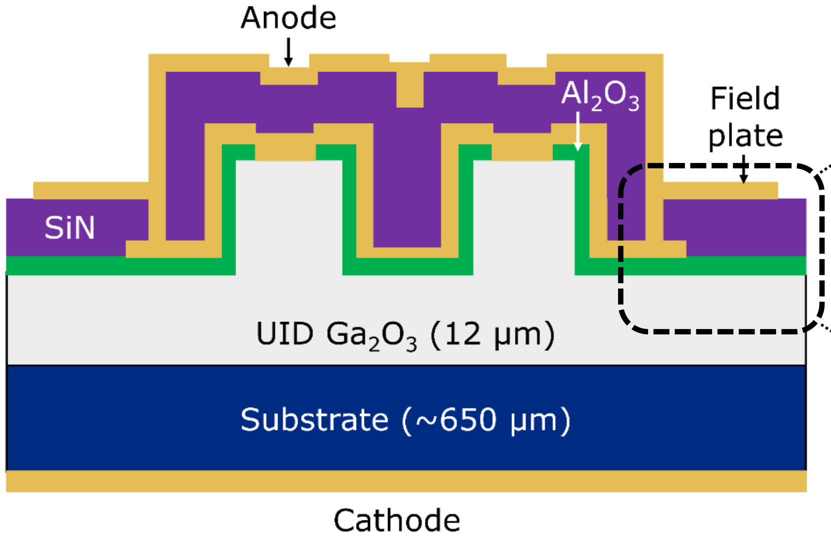




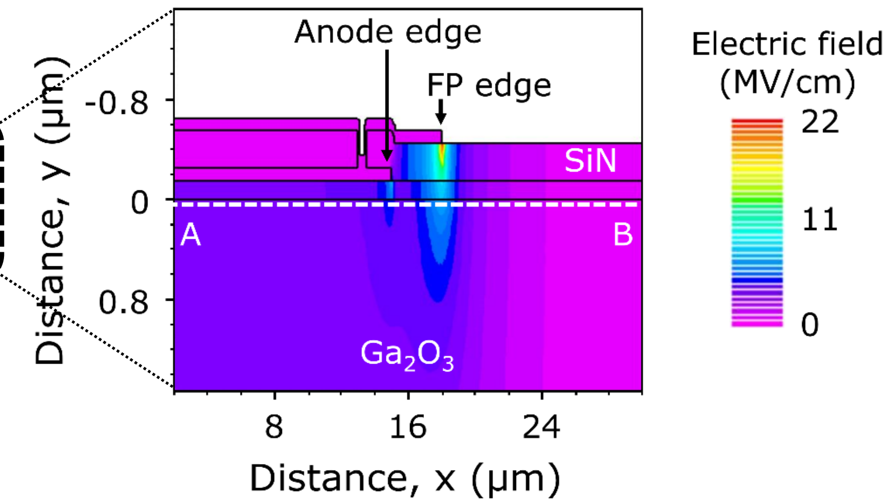
Anisotropy (e.g. sidewall traps) needs to be considered in Ga_2O_3 device design, though breakdown voltage is not affected in this case; also Ga_2O_3 exhibits a **low thermal conductivity** and **can not be well p-doped**.

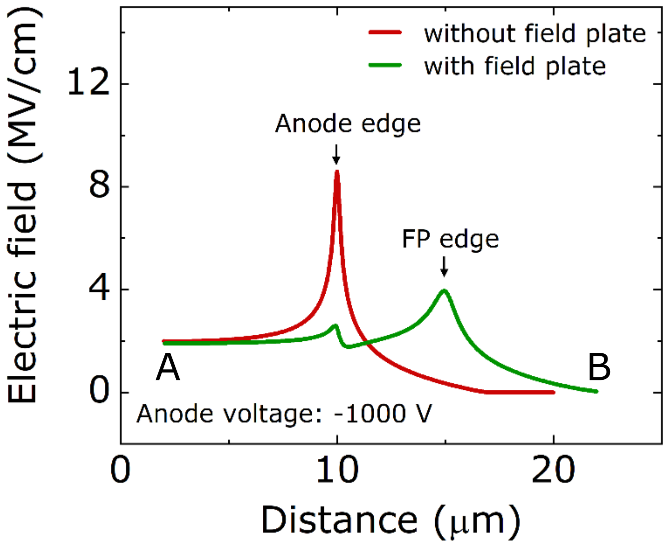
Considerable thoughts into edge termination using field plates

TSBD with field plate



Simulated electric field

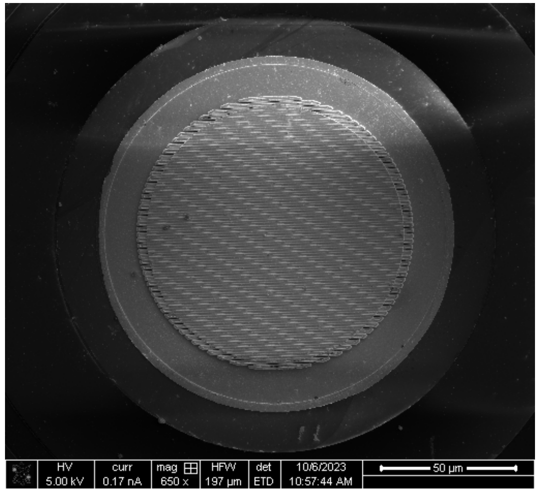


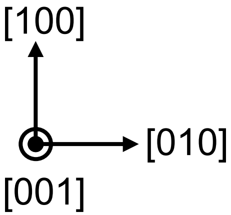


Field plate minimizes the electric field crowding at the edge by distributing the field between anode edge and field plate edge

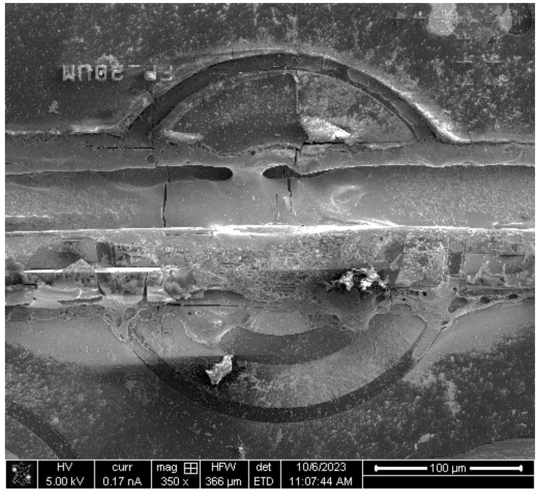
Reliability of Ga_2O_3 trench FETs: More work needs to be done

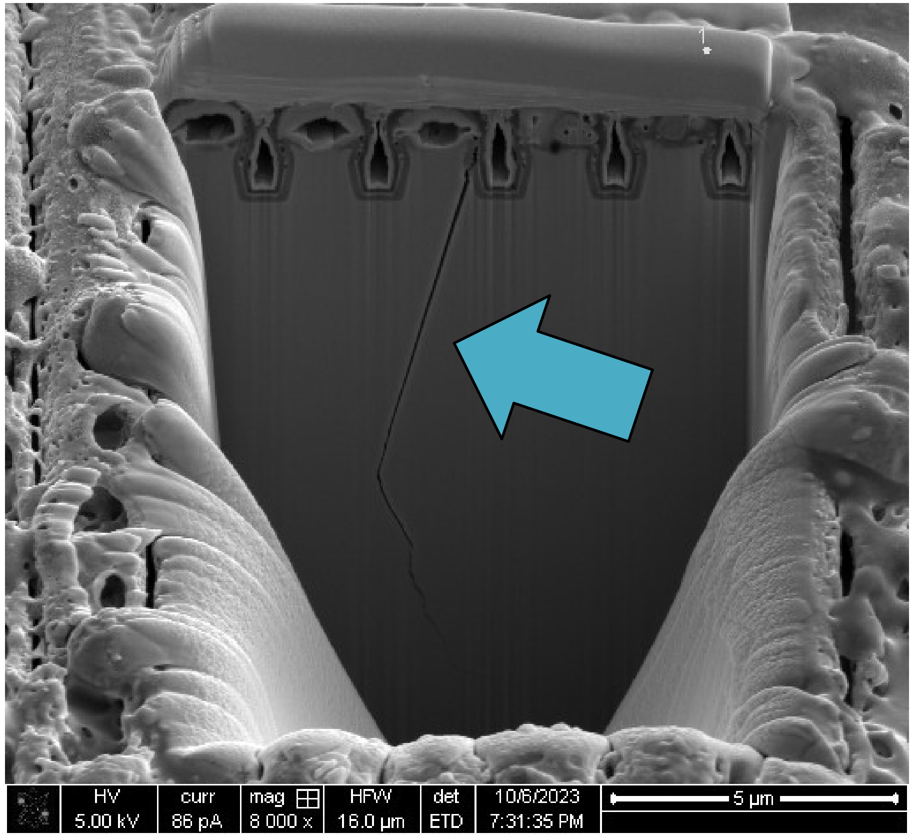
As fabricated





After breakdown



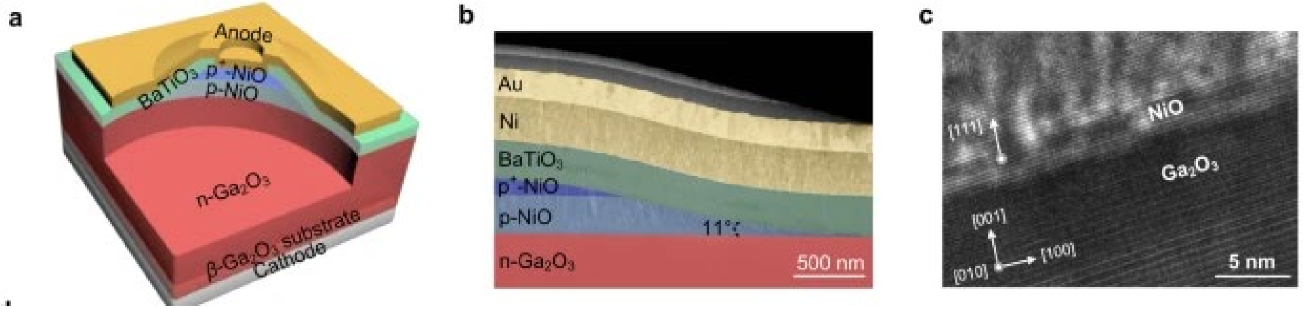


- Substrate orientation: (001) out-of-plane
- Breakdown is always observed along [010] direction

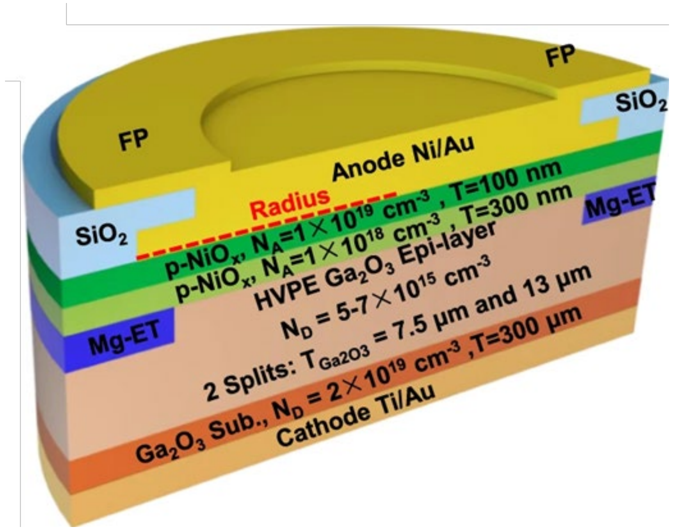
Killer defects still need to be identified

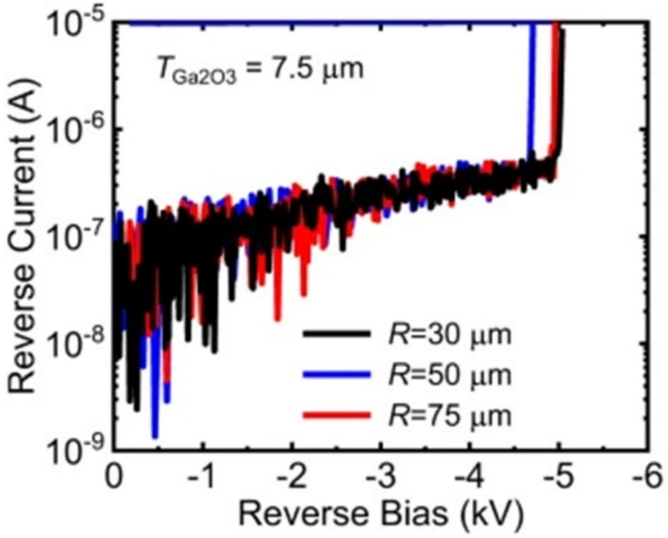
Nickel Oxide - Ga_2O_3 integrated devices

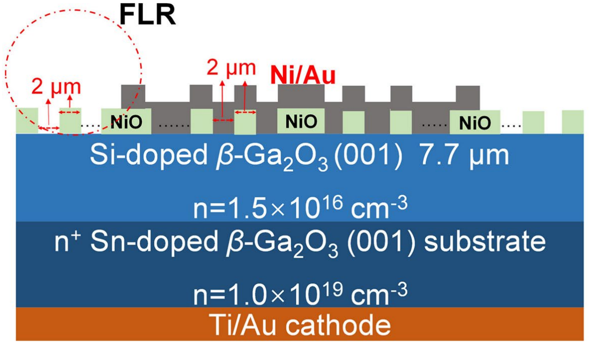
Avalanche and surge robustness, high breakdown voltage

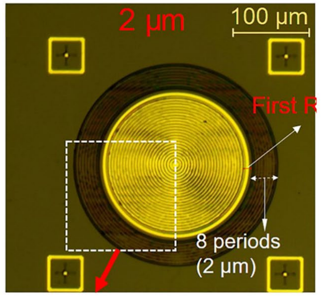


*F. Zhou et al, Nat Commun **14**, 4459 (2023) – Nanjing, Virginia Polytech, ANU*

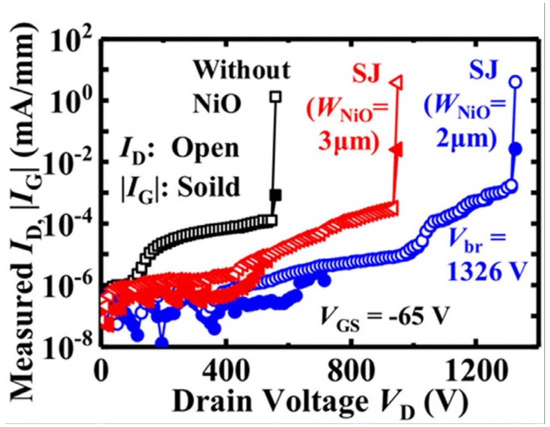








This addresses the lack of good p-doping of Ga_2O_3.

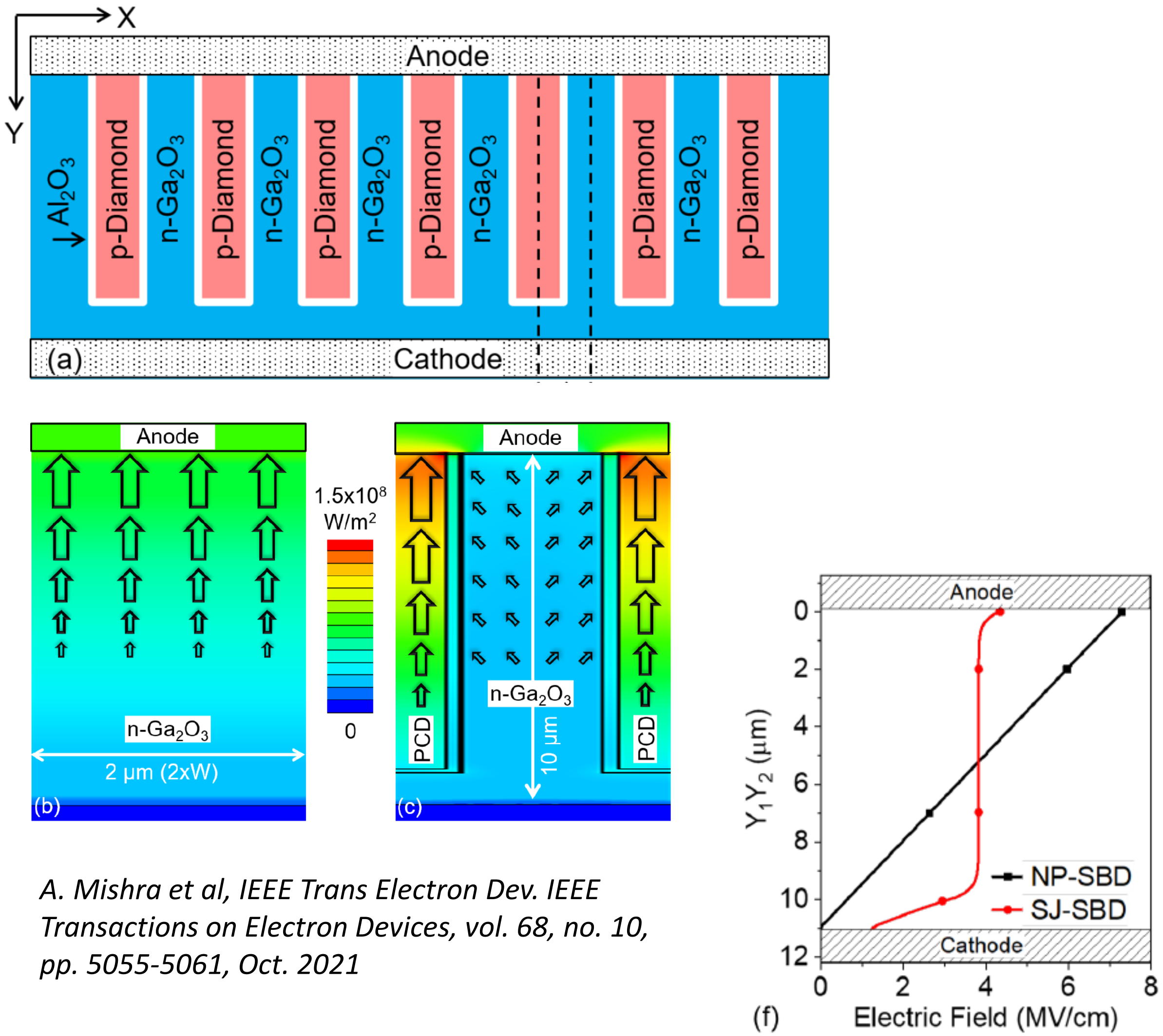


B. Li et al., Fundamental Research, 2023 (in press) - Xidian, CAS, Nanjing.

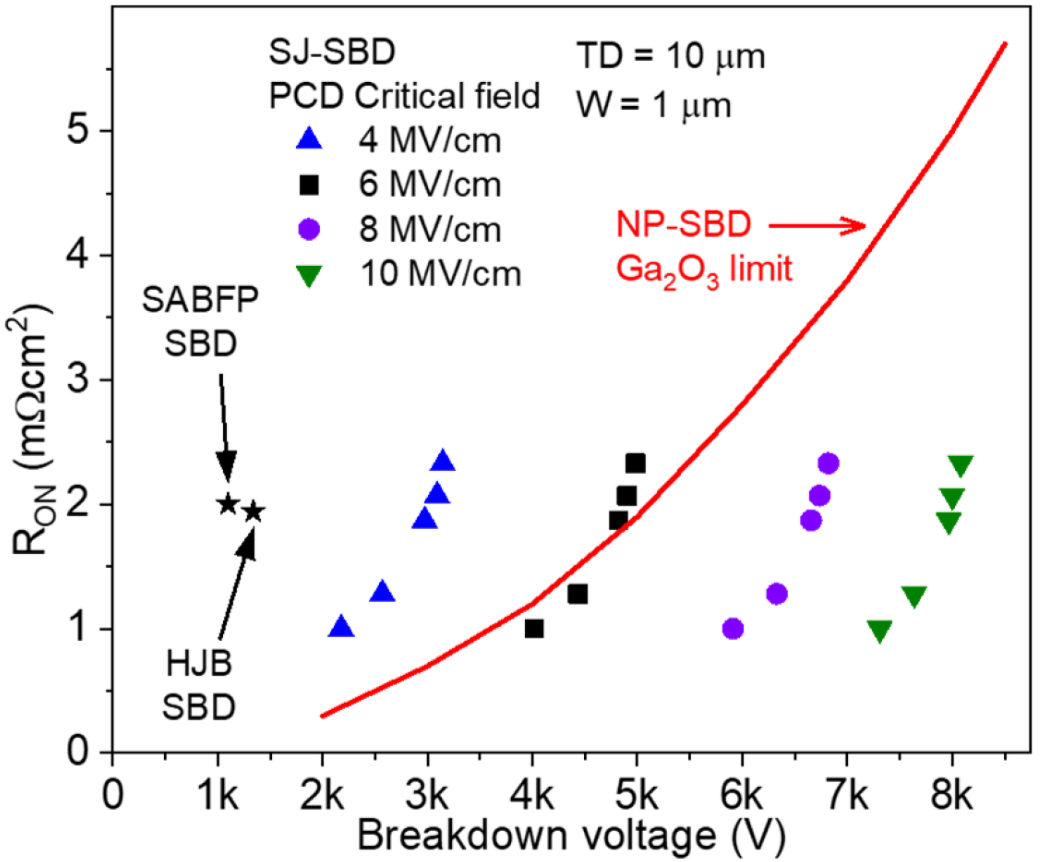
*J. Zhang, et al., Nat Commun. **13**, 3900 (2022) – Xidian, Shanghai Jiao Tong, UEST*

Corresponding work from University of Florida; generally up to 8kV devices

Integrated Ga_2O_3 – diamond device technology

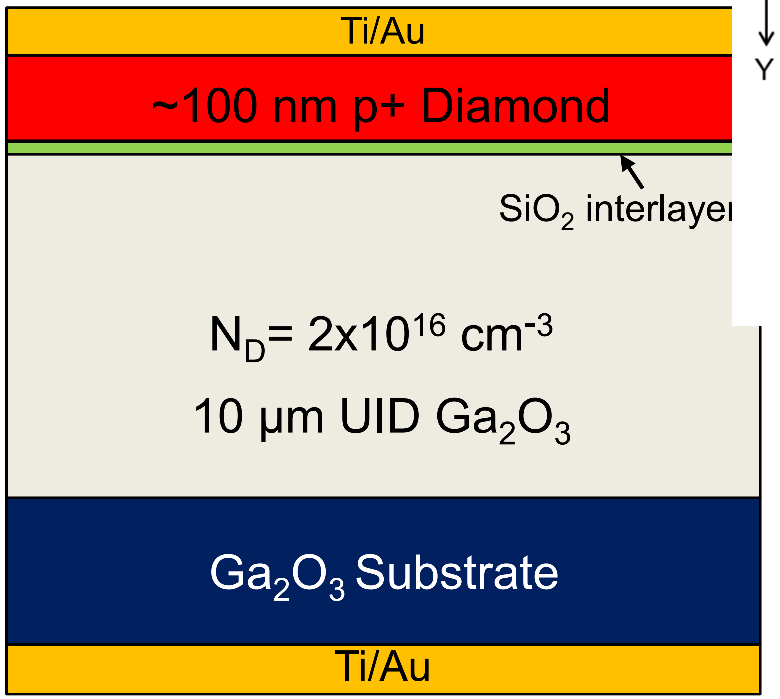


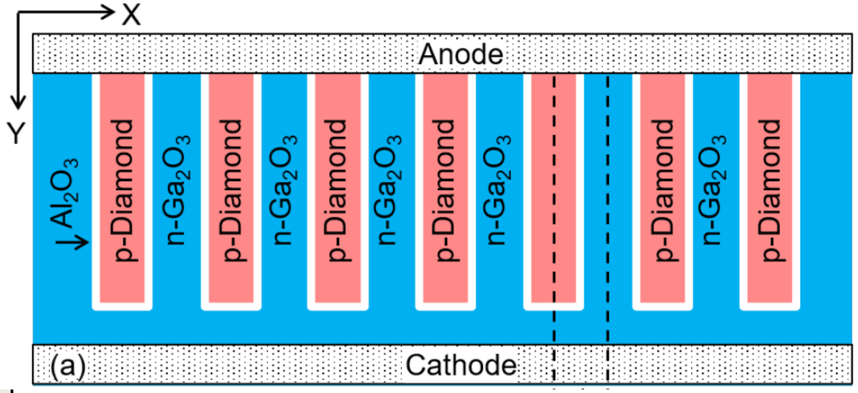
A. Mishra et al, IEEE Trans Electron Dev. IEEE Transactions on Electron Devices, vol. 68, no. 10, pp. 5055-5061, Oct. 2021

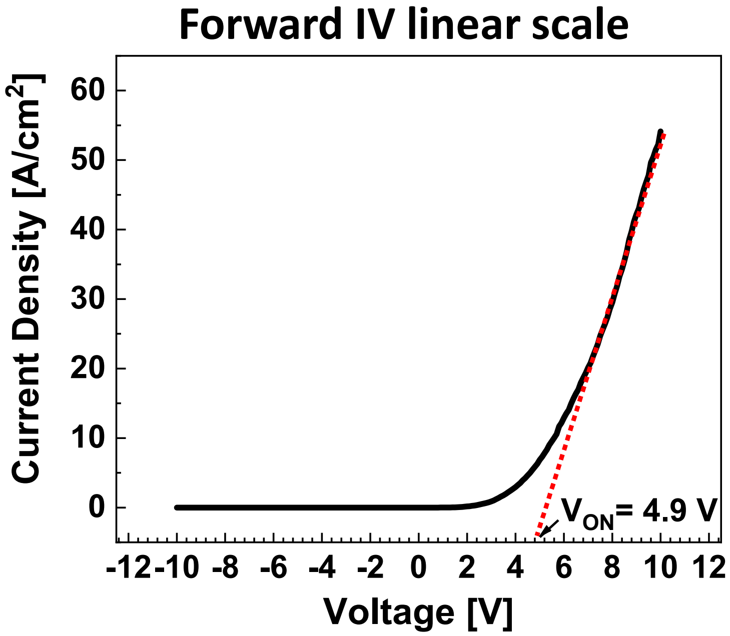


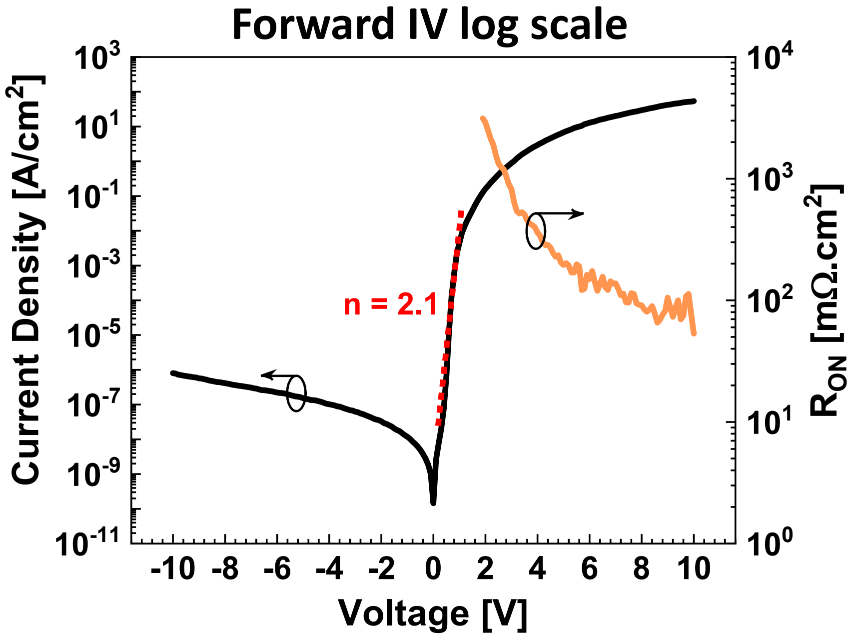
Use of p-diamond increases breakdown voltage, and improves heat sinking

Initial steps for diamond – Ga_2O_3 integration





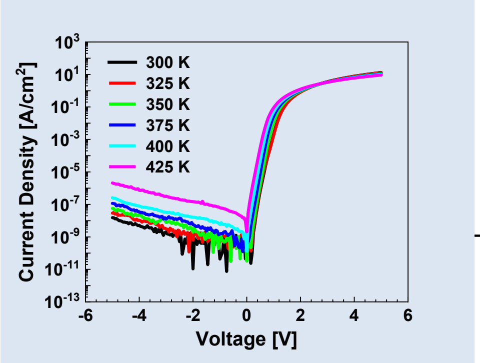




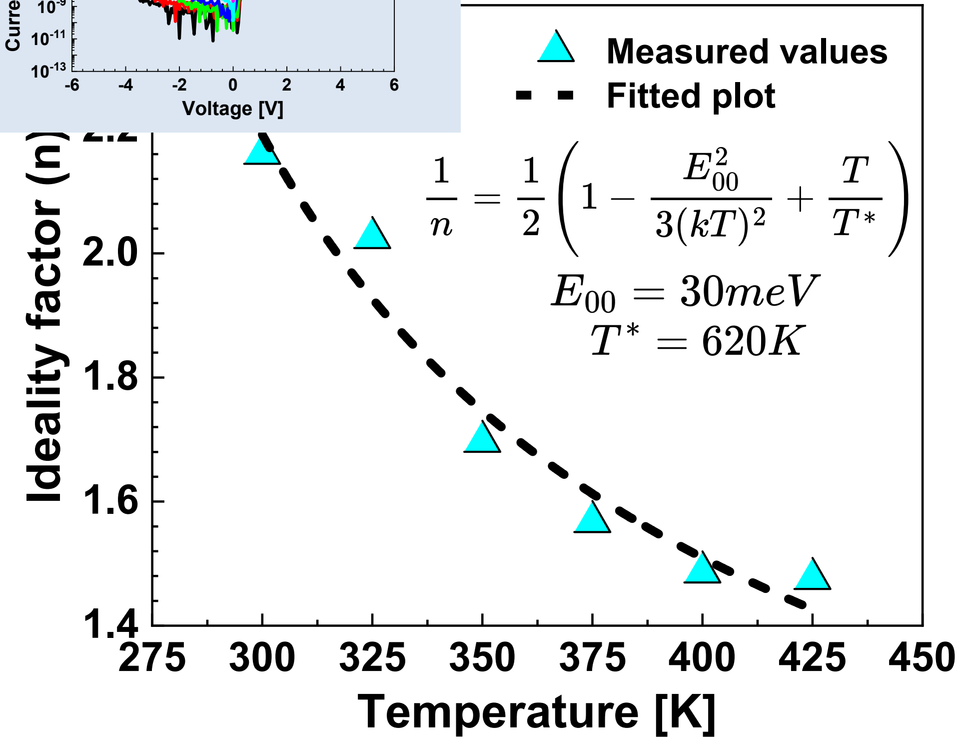
On-Off ratio 10^8 → SiO_2 interlayer protects surface of Ga_2O_3

A. Bhat et al (Bristol-Stanford collaboration), submitted to EDL

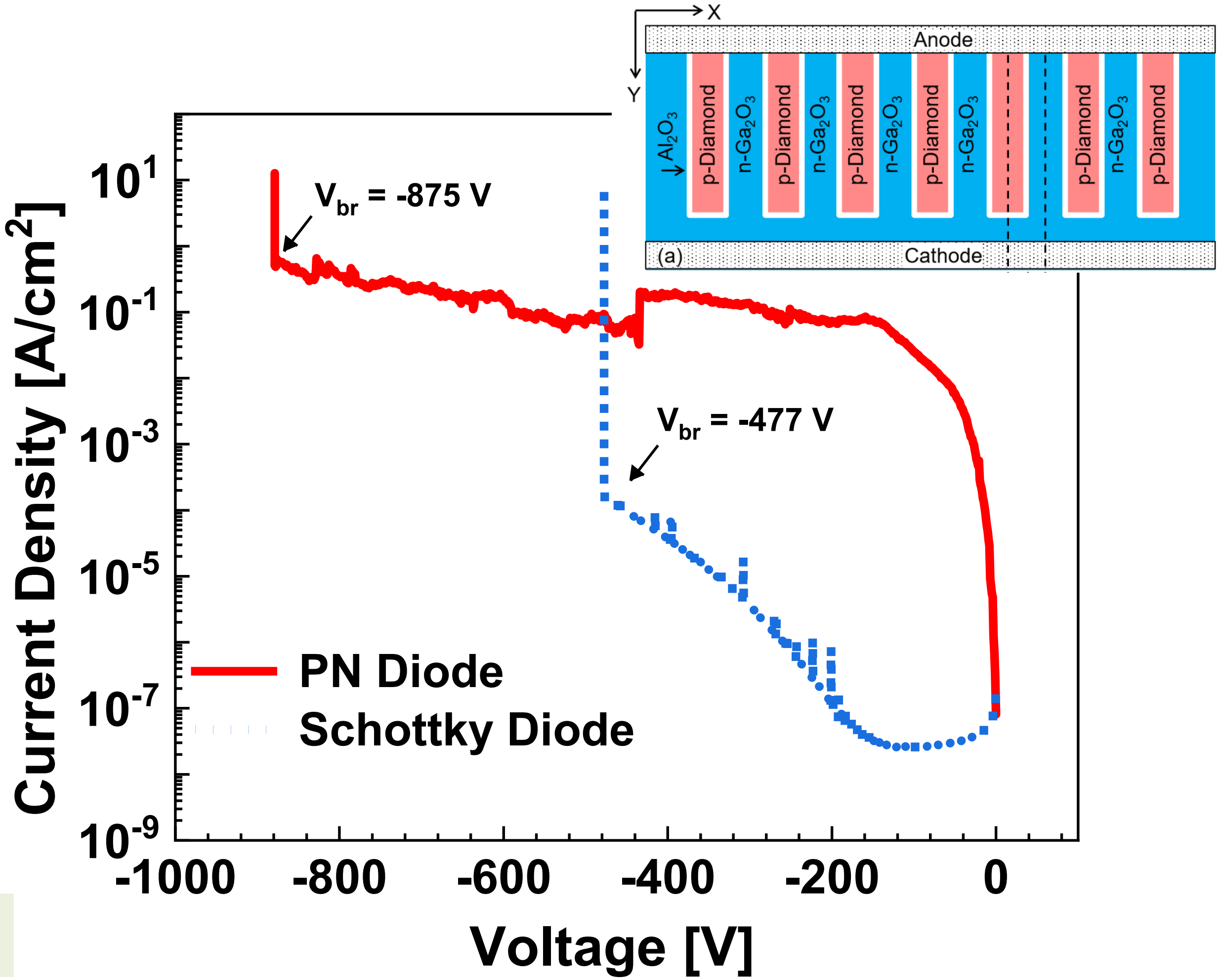
Conduction mechanisms & breakdown



Tunneling assisted recombination

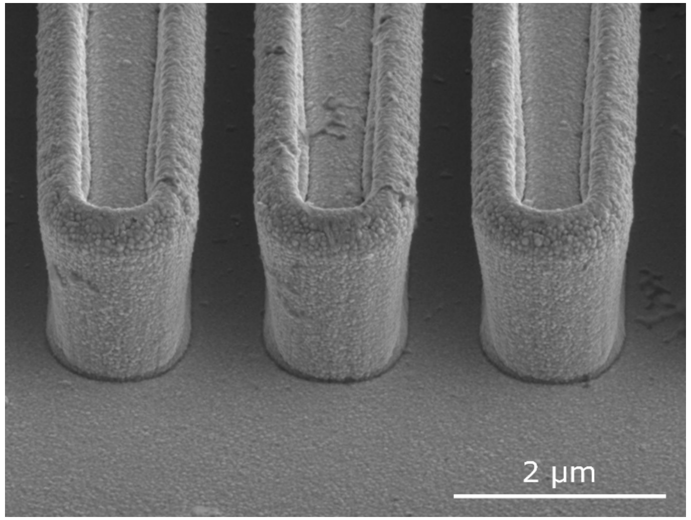


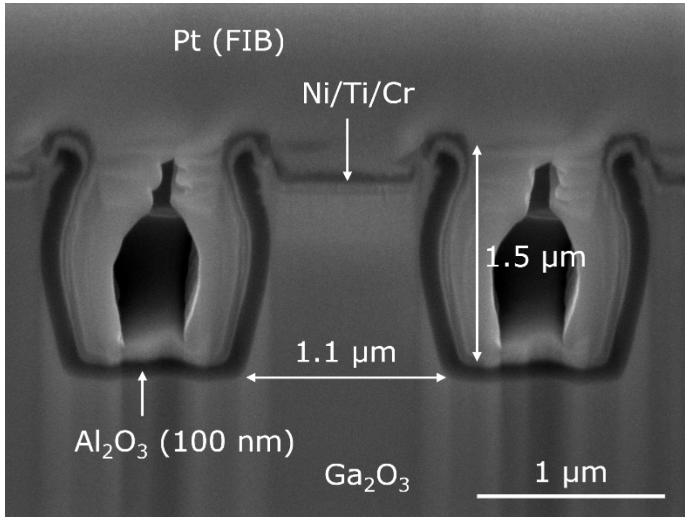
A breakdown of 875 V, without edge termination!

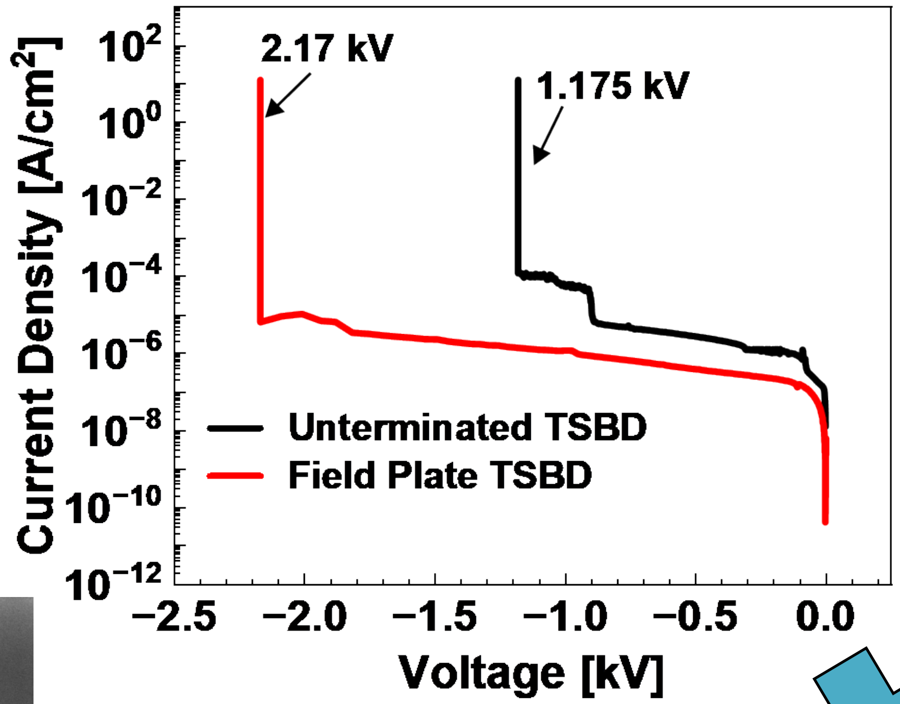


Should result into >3-5kV superjunction devices

Next steps

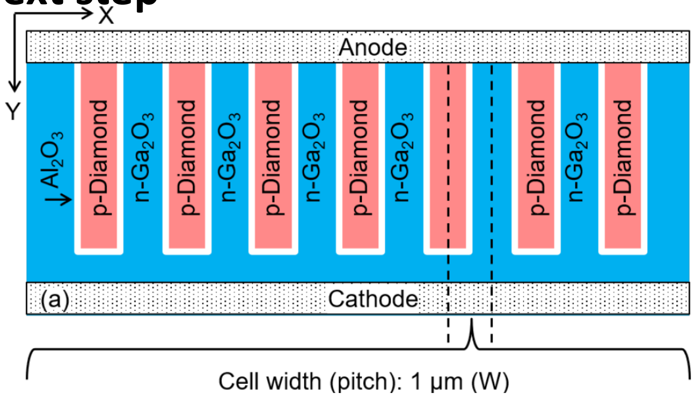






Latest Bristol fabricated Trench Schottky Barrier diode

Next step

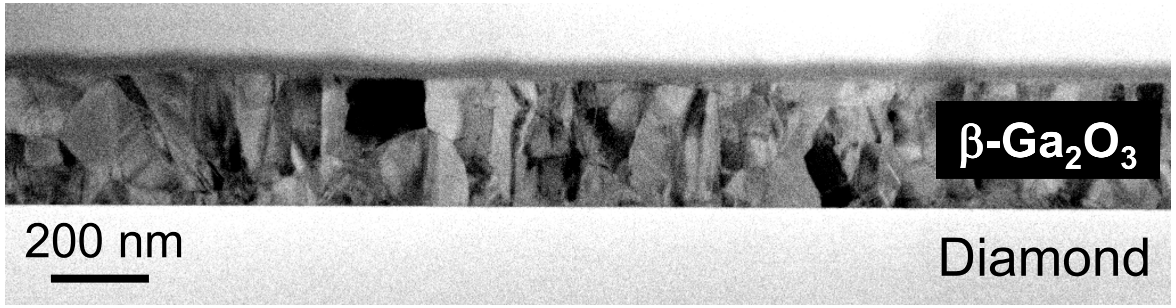


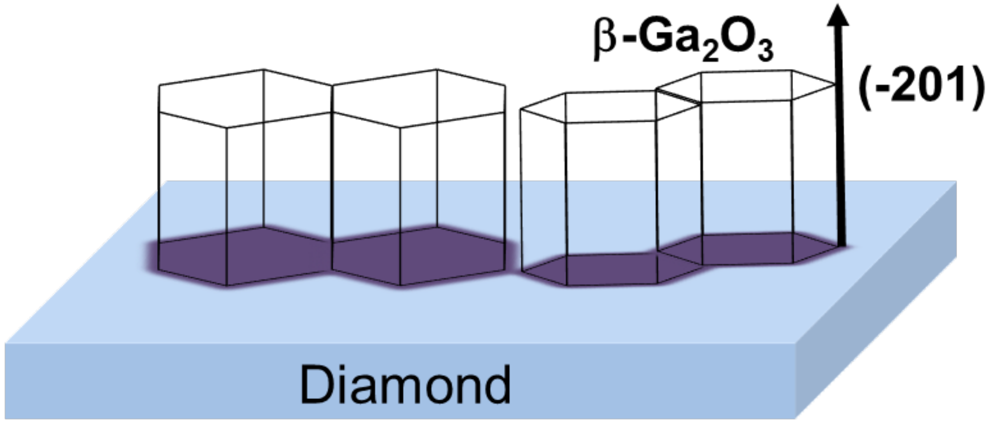
Ability to make next generation materials …

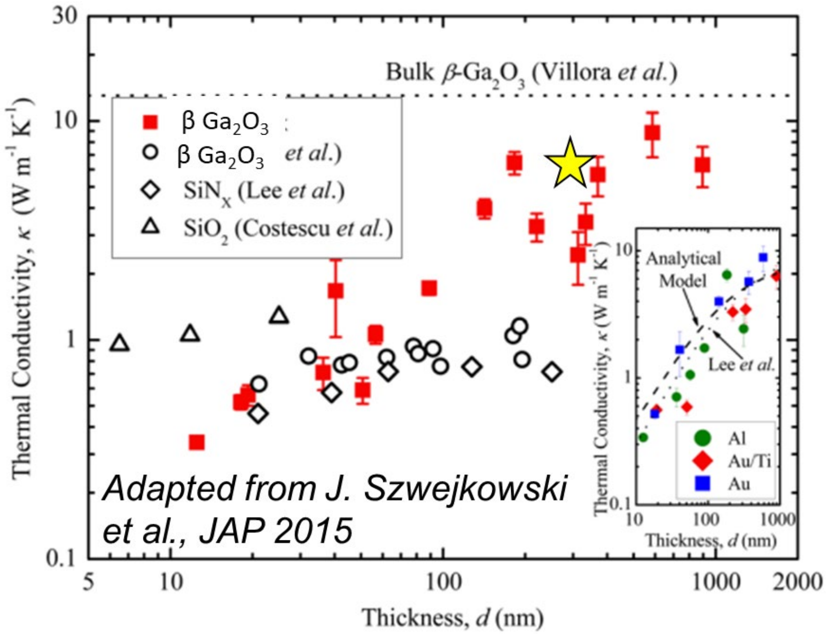
REWIRE

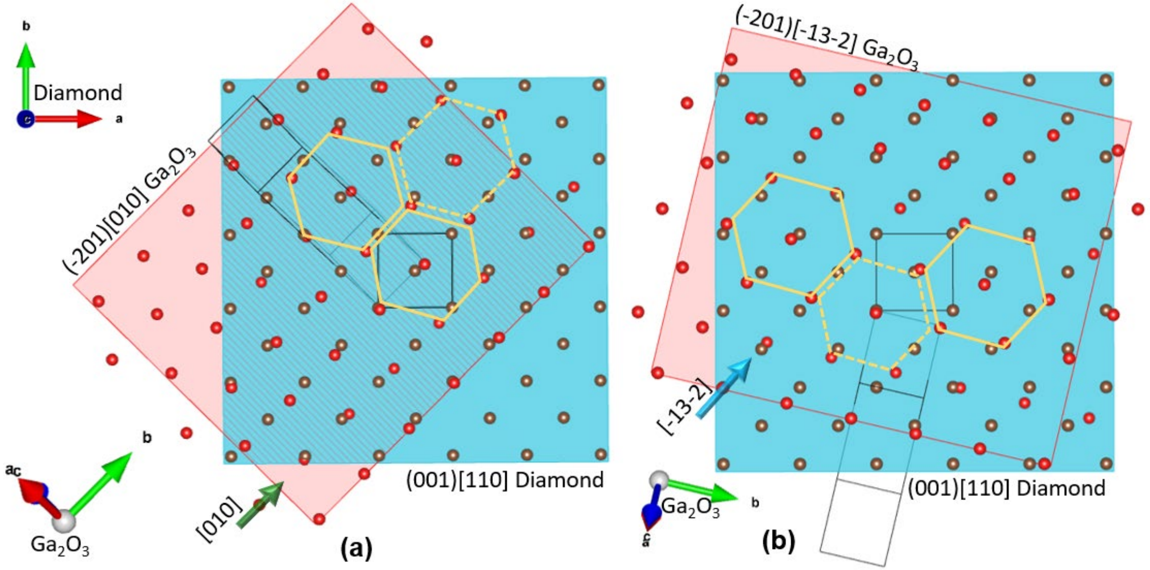
Bristol Gallium Oxide Agnitron MOCVD system

Alternative for heat sinking: Growth of Ga_2O_3 on diamond



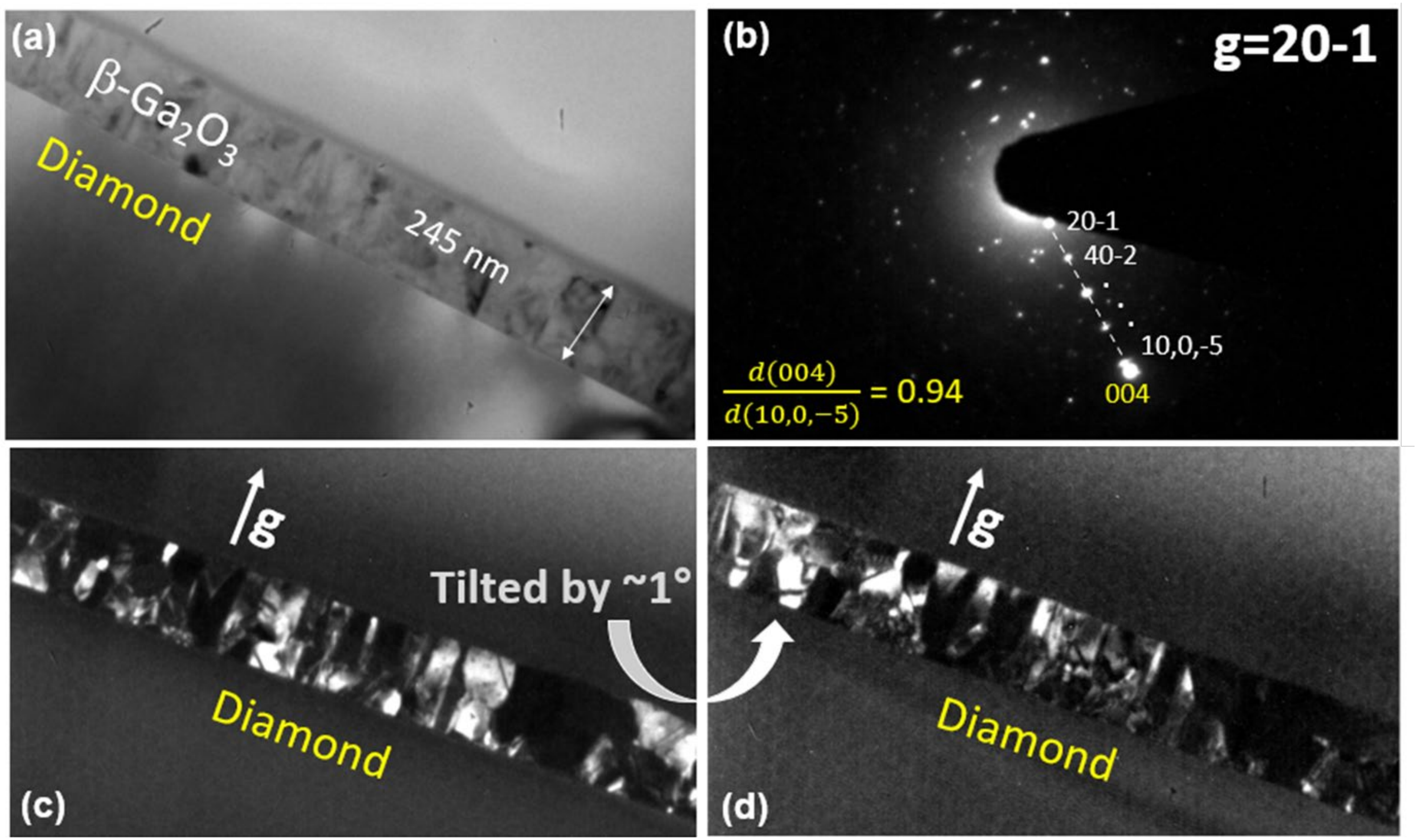




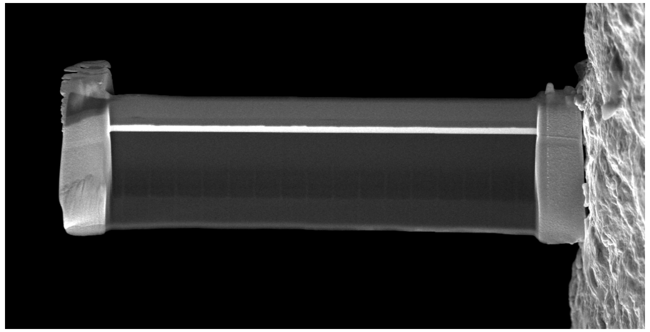


A. Nandi et al., Cryst. Growth Des. **23**, 8290–8295 (2023)

TEM: Ga_2O_3 on diamond



A. Nandi et al., Cryst. Growth Des. ***23****, 8290–8295 (2023)*

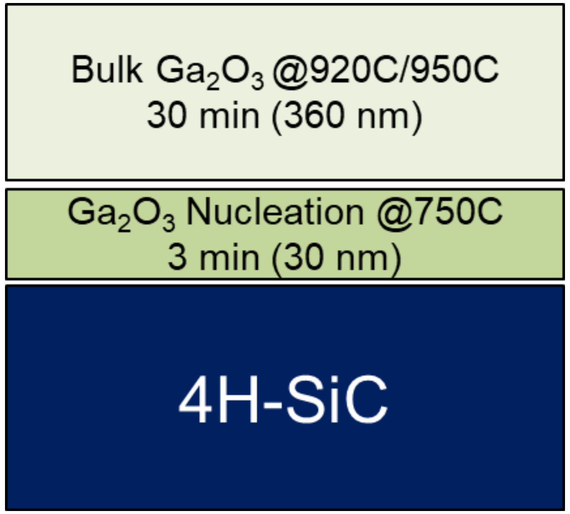


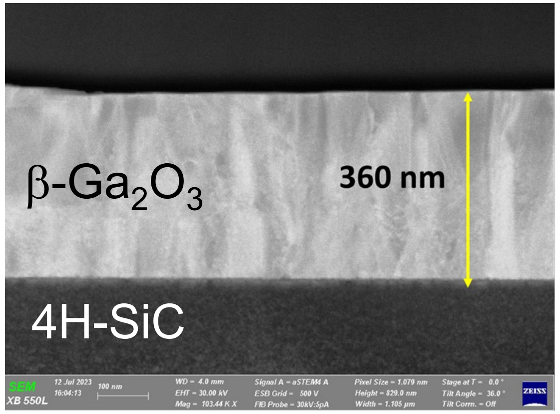
Lamella prepared by Zeiss

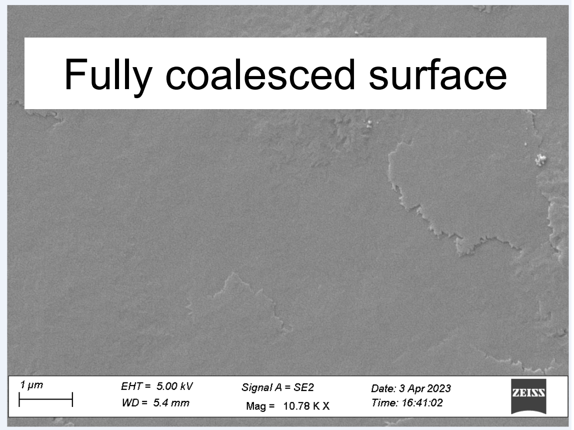
- Alignment of (20-1) Ga_2O_3 with (001) diamond
- Minor tilts show closely related mis-oriented grains

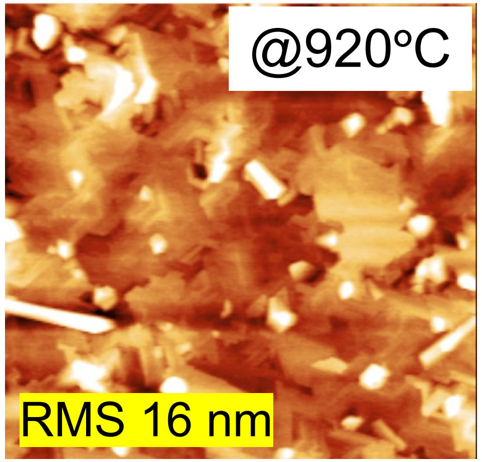
β-Ga_2O_3 epitaxy on SiC also possible

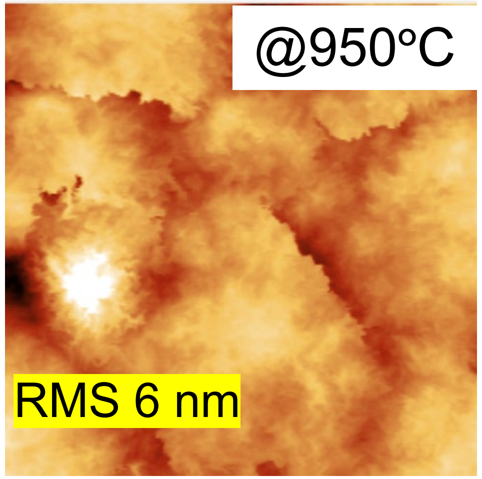
High quality β-Ga_2O_3 hetero-epitaxy on SiC substrates:





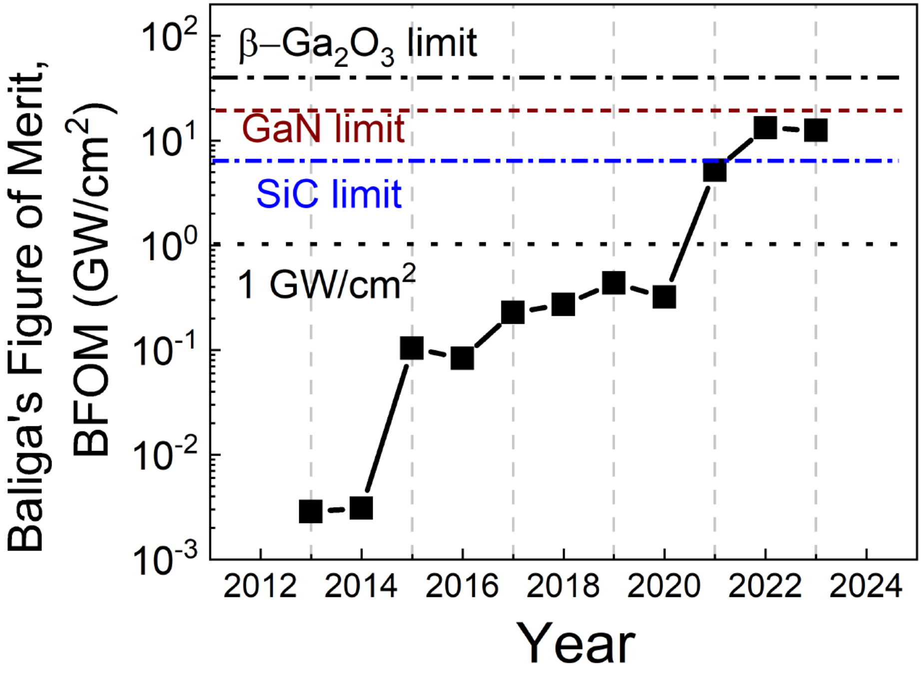


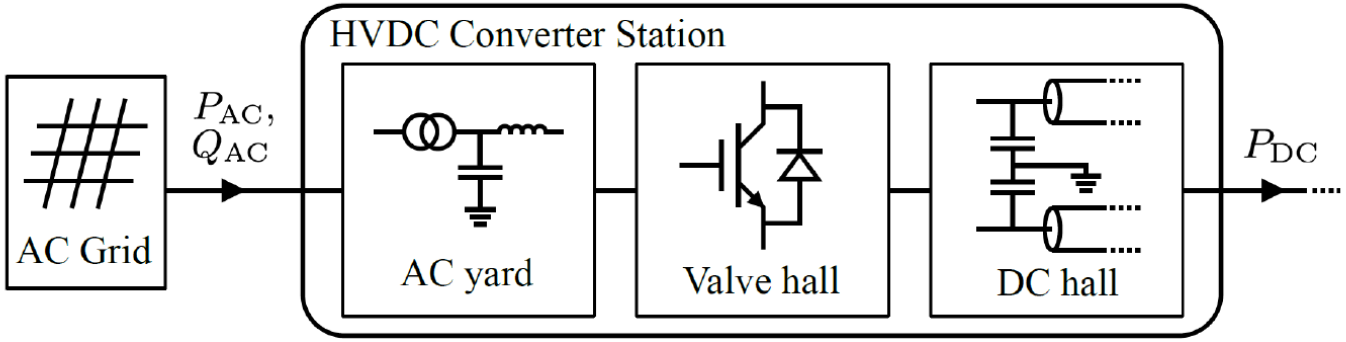


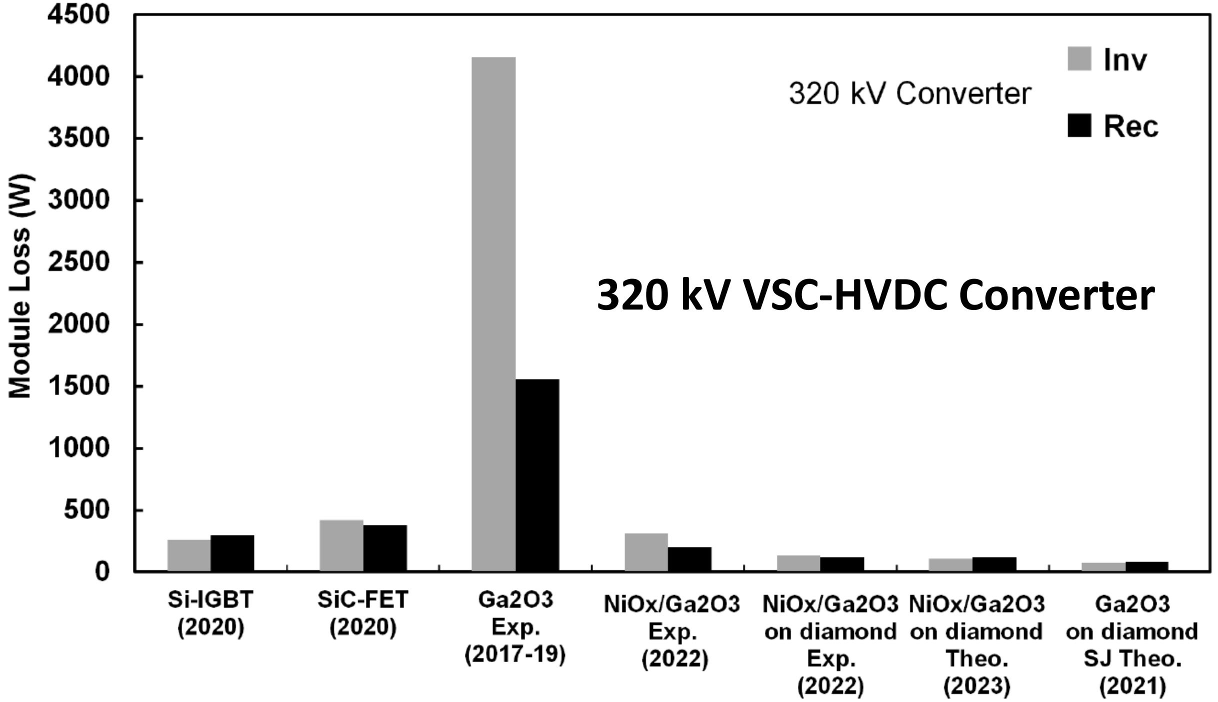


I. Sanyal, submitted to Appl. Phys. Lett.

Are we chasing Ga_2O_3 power electronics ghosts ?







Ga_2O_3 could already now provide system benefits, with reduced converter losses.

Jahdi, Kumar, Deacon, Taylor, Kuball, submitted to IEEE Open Journal of Power Electronics

Conclusions

- **Ga_2O_3 power electronics has already exceeded many performance parameters of GaN and SiC power electronic devices.**
- **Device prototyping and commercialization pathways (for Ga_2O_3, SiC, GaN, AlGaN, diamond, BN etc) within the £11M UK funded Innovation and Knowledge Centre (IKC) REWIRE.**
- Huge opportunities for Ga_2O_3, though challenge of **low thermal conductivity** and **lack of workable p-type doping** need to be addressed**; integration of Ga_2O_3 with e.g. nickel oxide or diamond** can overcome some of Ga_2O_3's limitations; superjunctions, MOCVD growth on diamond and SiC substrates.
- **Good quality Ga_2O_3 Schottky Barrier Diodes (SBD)** demonstrated; some failure modes of Ga_2O_3 devices discussed. **Early power systems analysis shows Ga_2O_3 enables reduced converter losses.**
- **Ga_2O_3 could become a serious competitor to SiC in the high voltage power market.**

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