University of BRISTOL

CDTR

ROYAL ACADEMY OF ENGINEERING

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

Gallium Oxide – The next revolution in power electronics

Professor Martin Kuball

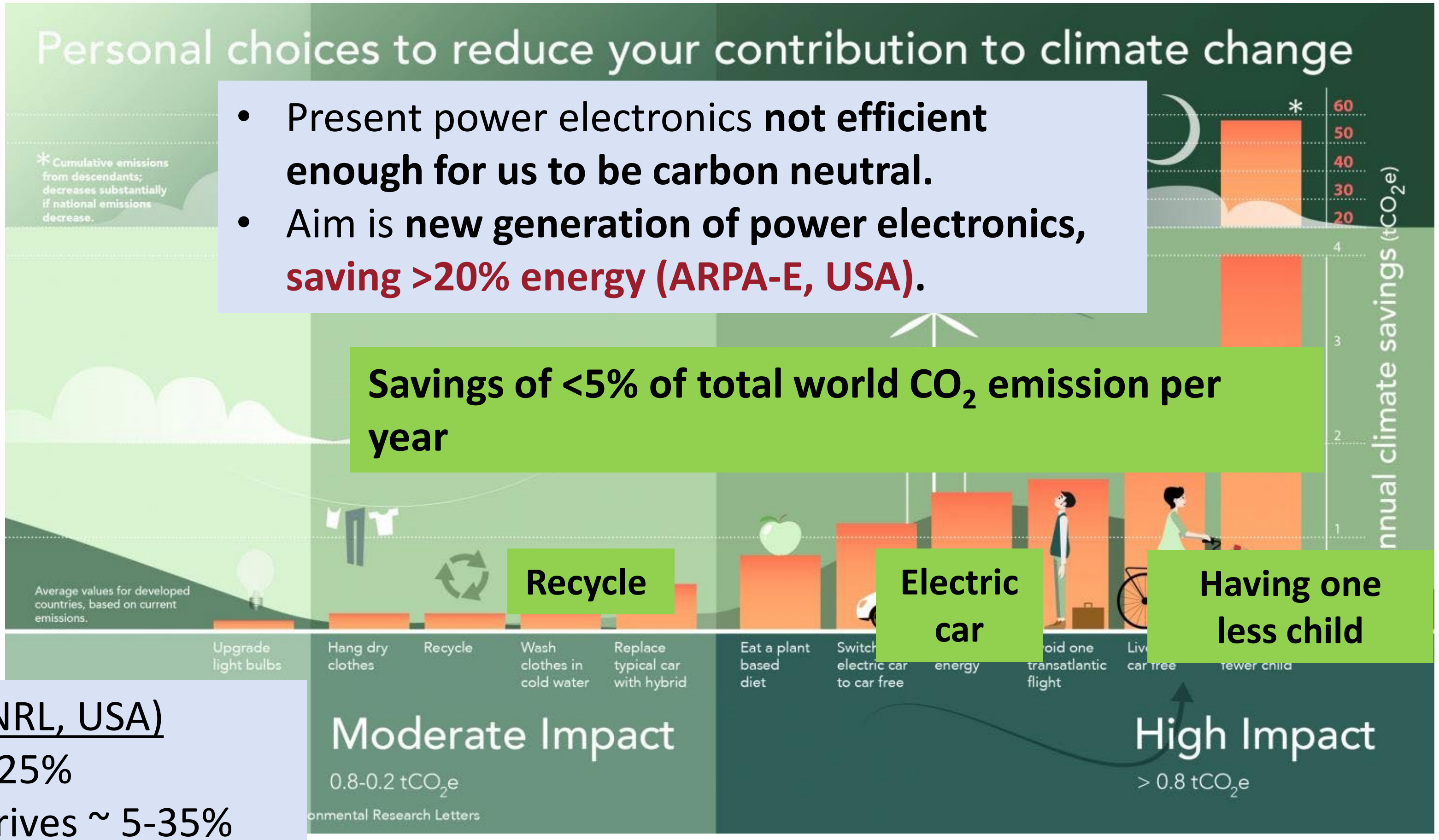
Royal Academy of Engineering Chair in Emerging Technologies

Abhishek Mishra, Arpit Nandi, Indraneel Sanyal,
Zeina Abdallah, James W. Pomeroy

University of Bristol, United Kingdom

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

The VISION – Transform energy savings



- Present power electronics **not efficient enough for us to be carbon neutral.**
- Aim is **new generation of power electronics, saving >20% energy (ARPA-E, USA).**

Savings of <5% of total world CO$_2$ emission per year

Recycle

Electric car

Having one less child

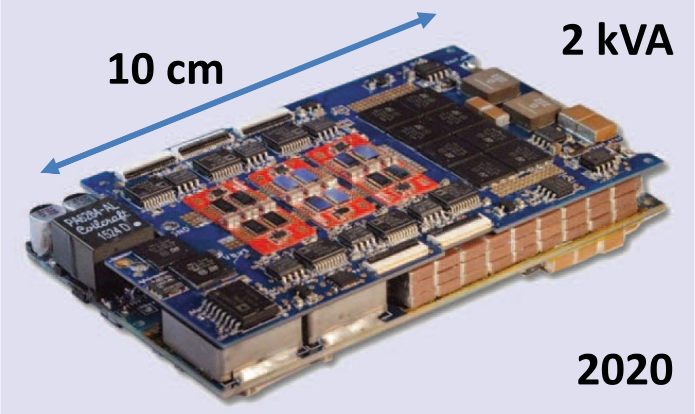
<u>Energy savings (ONRL, USA)</u>
Data centres ~ 20-25%
Industrial motor drives ~ 5-35%
Electric vehicles & trains ~ 10-15%
Renewable grids ~ 10-15%

Pathway from Si to wide to ultrawide bandgap semiconductors

	Narrow	Wide		ULTRAs – New class of materials			
	Si	4H-SiC	GaN	β-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			

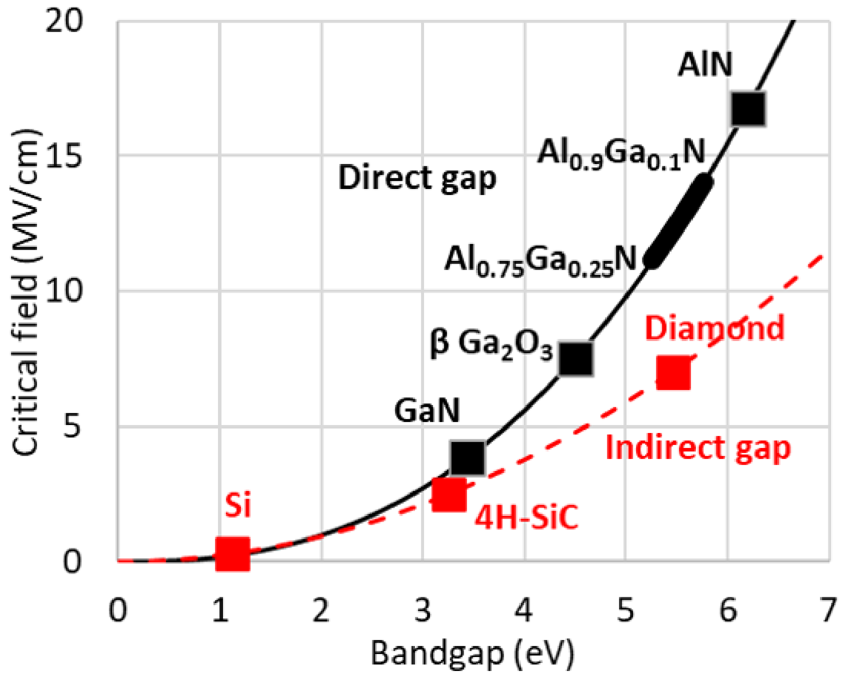
Emerging technology

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



Match box size but more powerful!

Ga_2O_3 of great potential for power electronics

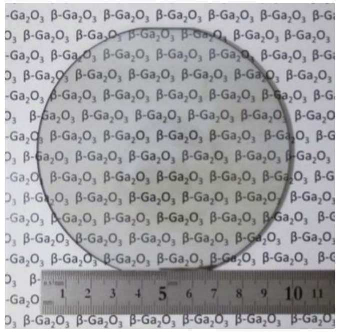


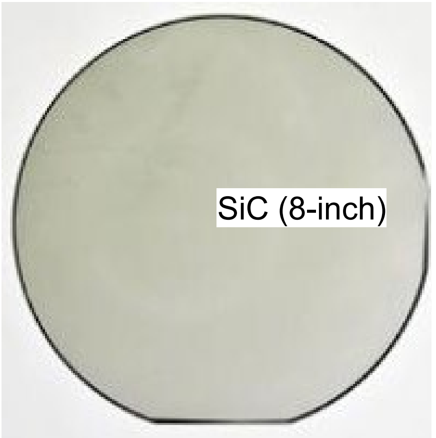
	Si	GaN	SiC	Diamond	Ga_2O_3
E_g(eV)	1.1	3.4	3.3	5.5	4.9
μ(cm^2/V.s)	1400	1200	1000	2000	300
E_c(MV/cm)	0.3	3.3	2.5	10	8
ε_{REL}	11.8	9	9.7	5.5	10
λ(W/m.K)	250	130	370	2000	20
BFOM($\mu\varepsilon E_c^3$)	1	870	340	24661	3444

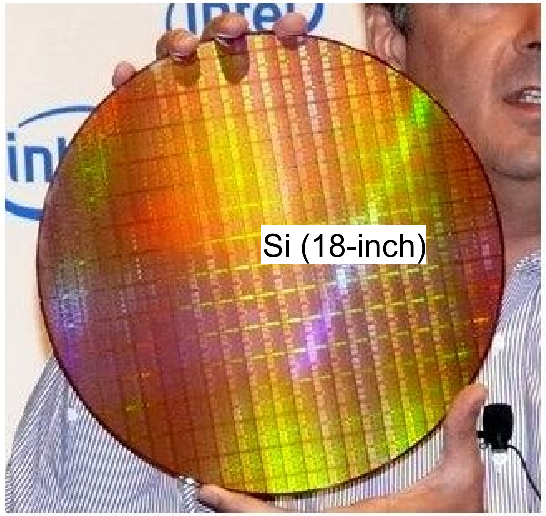
Baliga Figure of Merit


SCD (6 mm)

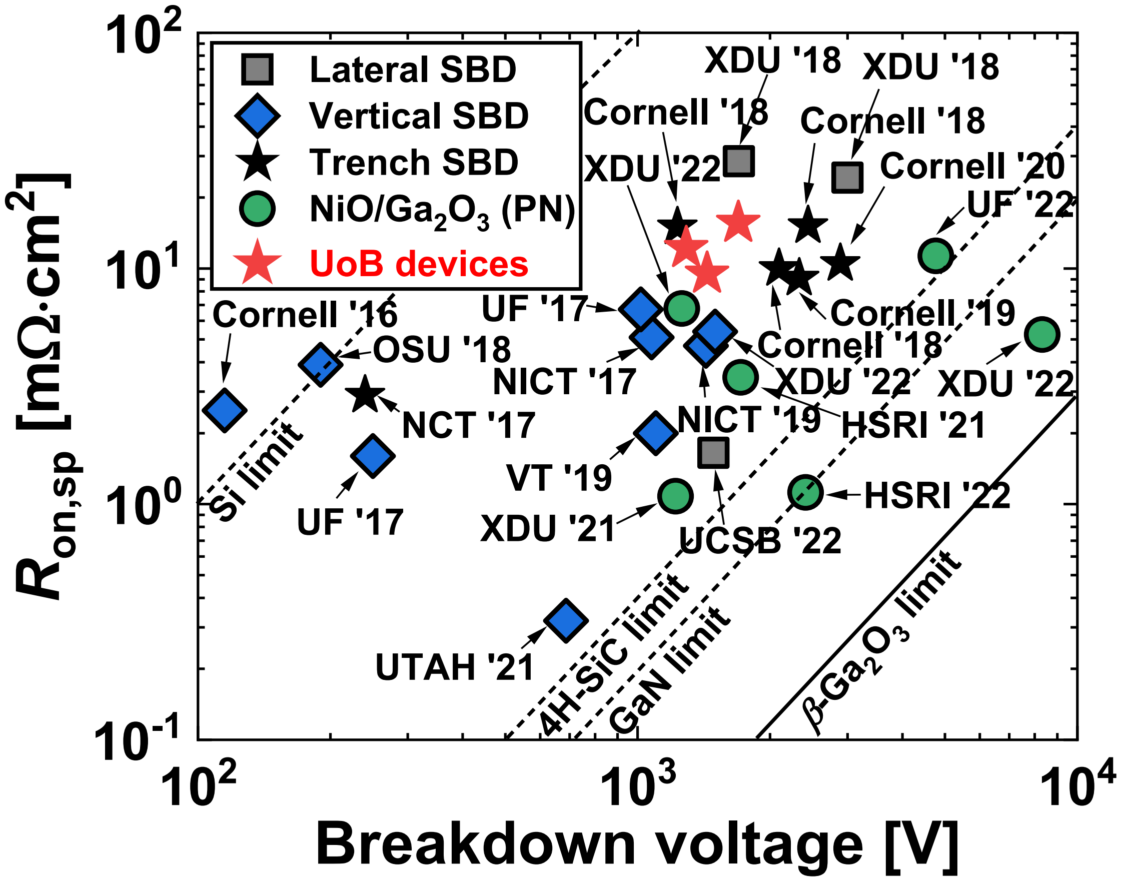

AlN (2-inch)

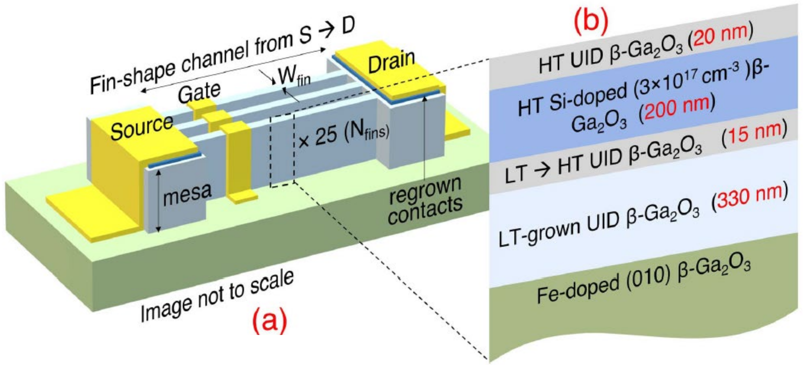

Ga_2O_3 (4 - 6-inch)


SiC (8-inch)

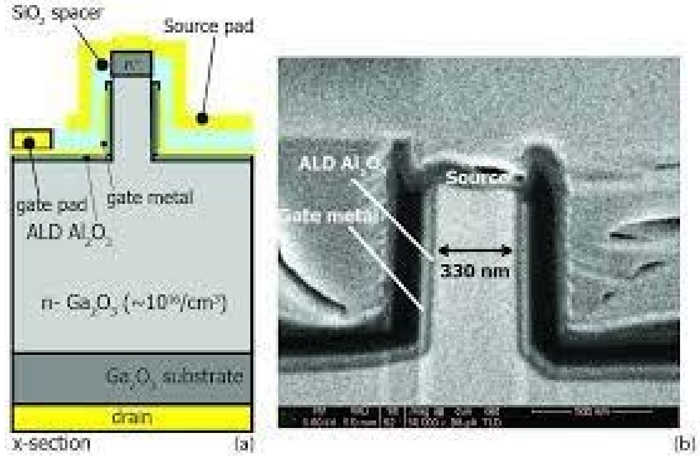

Si (18-inch)

Major progress in Ga_2O_3 power devices in recent years





Bhattacharyya et al, IEEE Electron Dev. Lett. 43, 1637 (2022)



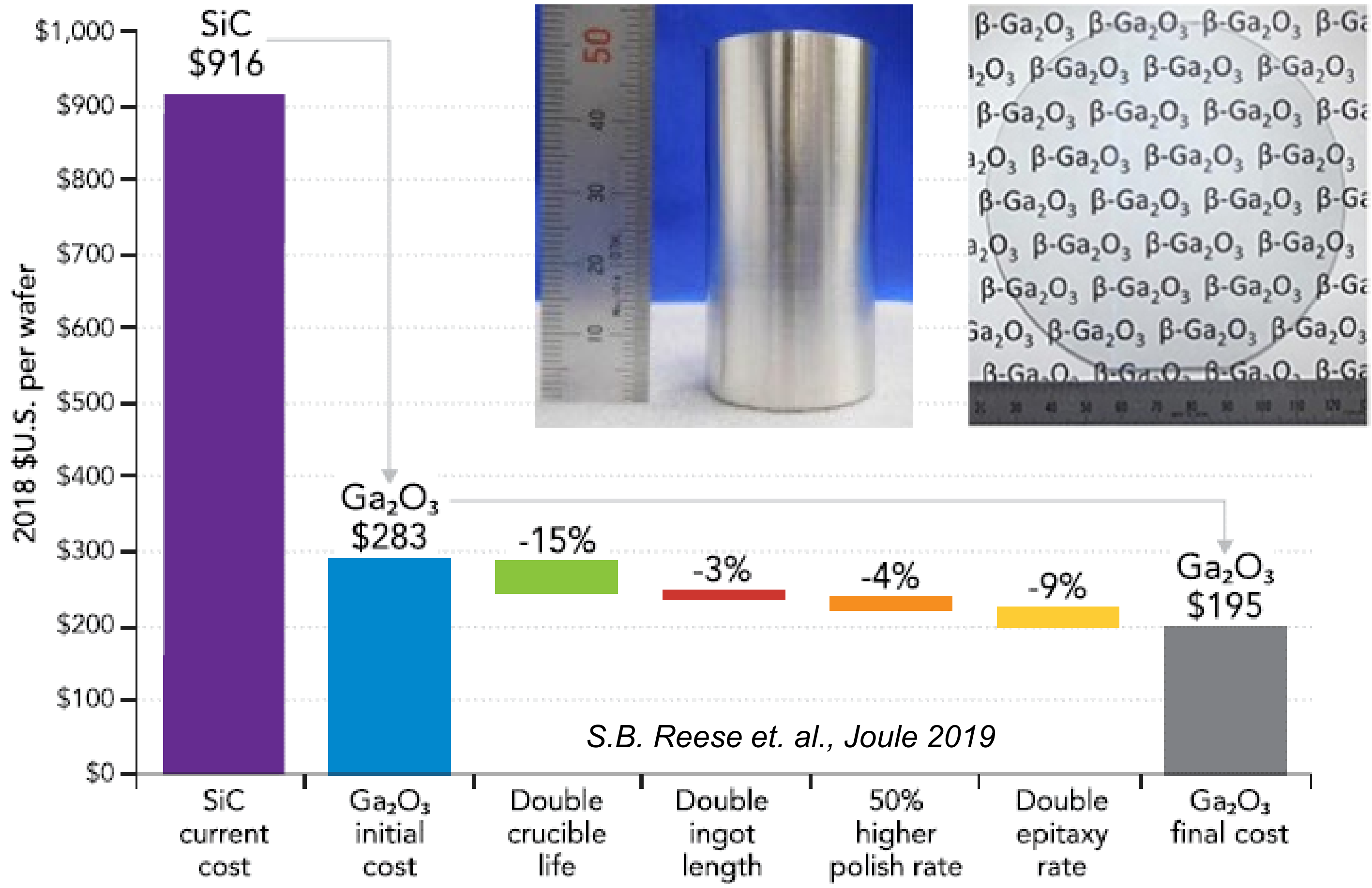
https://news.cornell.edu/stories/2018/06/vertical-gallium-oxide-transistor-high-power-efficiency

Ga_2O_3 devices start reaching beyond SiC and GaN, but many open questions remain

Ga_2O_3 versus SiC device technology

Why Ga_2O_3?
Cost Comparison

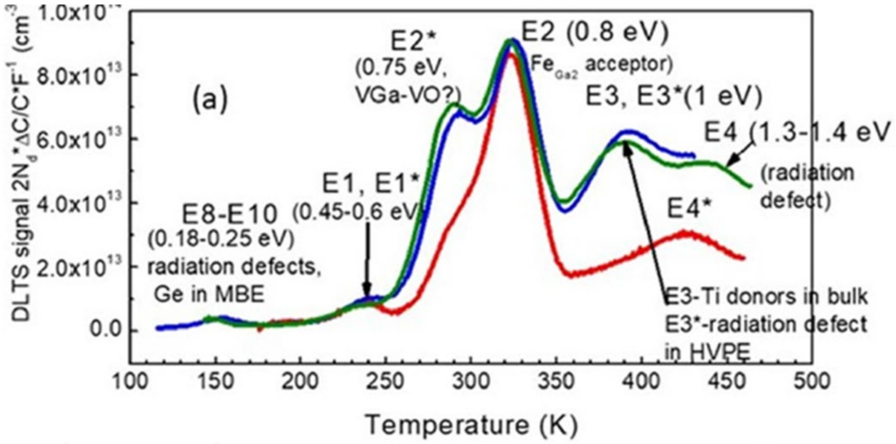
- Modelled 6-inch wafer costs comparison for Ga_2O_3 and SiC wafers
- Ga_2O_3 wafers would cost 3x less than SiC wafers

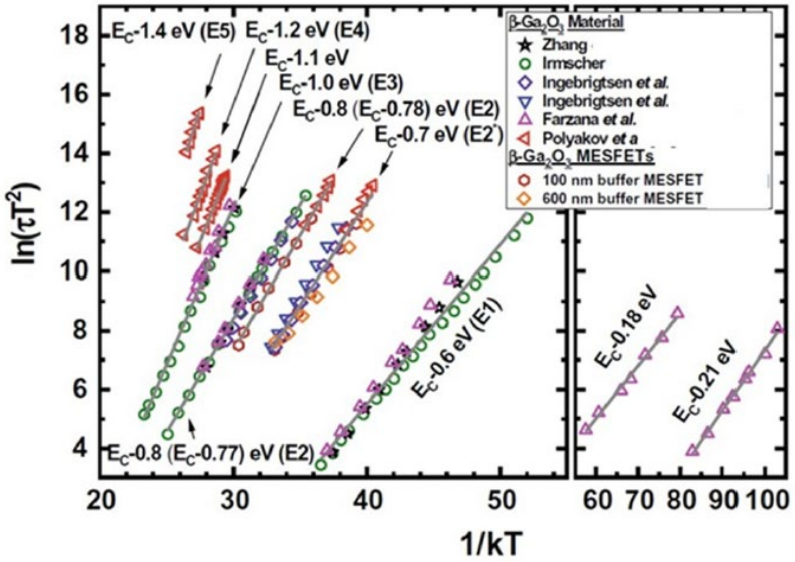


S.B. Reese et. al., Joule 2019

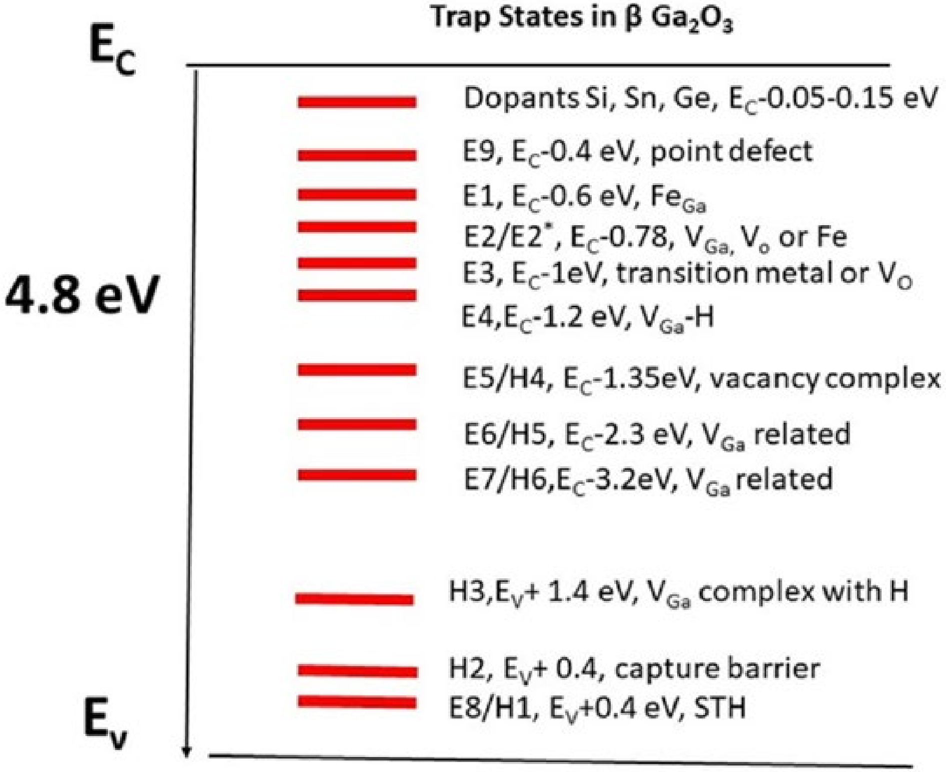
K.Hoshikawa et. al, Journal of Crystal Growth, 2016; M. Higashiwaki et al 2017 J. Phys. D: Appl. Phys.

Still plenty of defects in Ga_2O_3 – e.g. DLTS data





A. R. Arehart et al. Springer Series in Materials Science Vol. 293



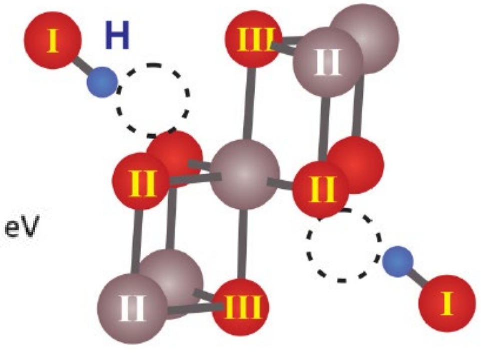
Trap States in β Ga_2O_3

E_C

4.8 eV

E_V

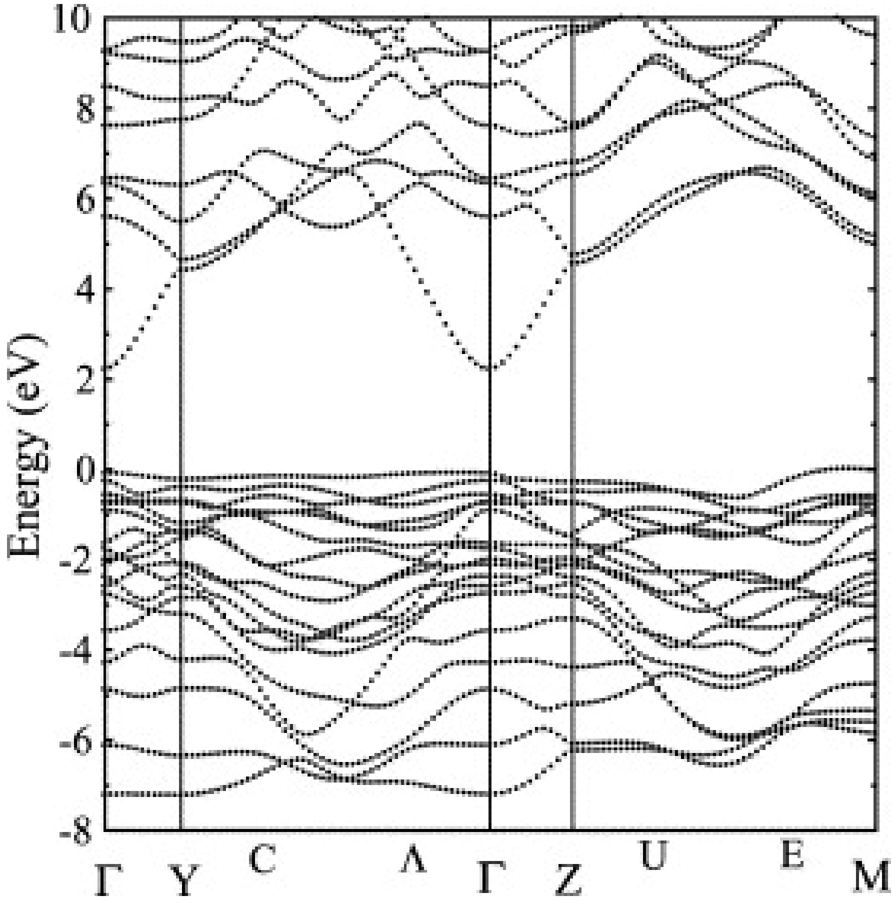
- Dopants Si, Sn, Ge, E_C-0.05-0.15 eV
- E9, E_C-0.4 eV, point defect
- E1, E_C-0.6 eV, Fe_{Ga}
- E2/E2*, E_C-0.78, V_{Ga}, V_o or Fe
- E3, E_C-1eV, transition metal or V_O
- E4,E_C-1.2 eV, V_{Ga}-H
- E5/H4, E_C-1.35eV, vacancy complex
- E6/H5, E_C-2.3 eV, V_{Ga} related
- E7/H6,E_C-3.2eV, V_{Ga} related
- H3,E_V+ 1.4 eV, V_{Ga} complex with H
- H2, E_V+ 0.4, capture barrier
- E8/H1, E_V+0.4 eV, STH



$V_{Ga}2H$

What are killer defects for Ga_2O_3 devices is largely still unknown.

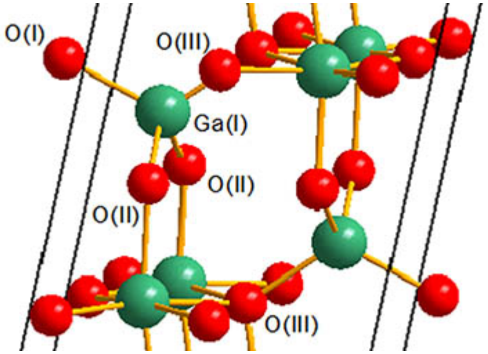
Challenges for β-Ga_2O_3: Low thermal conductivity and p-doping



*K. Yamaguchi, Solid State Communications **131**, 739 (2004)*

Very low thermal conductivity → Device overheating

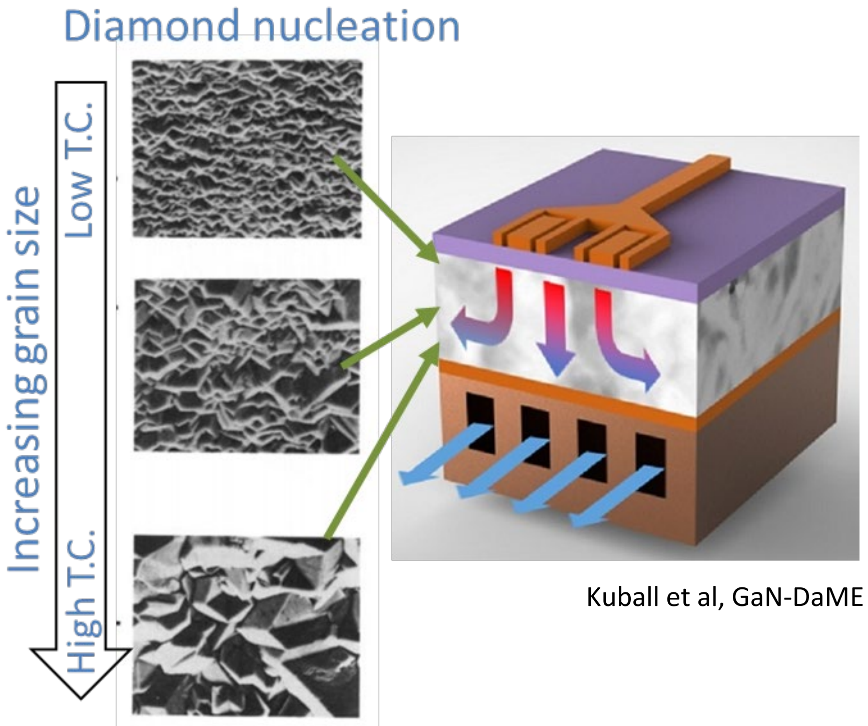
Very high hole mass making **p-type Ga_2O_3 not viable for real application** (hole trapping).



*BE Kananen et al, JAP **122**, 215703 (2017)*

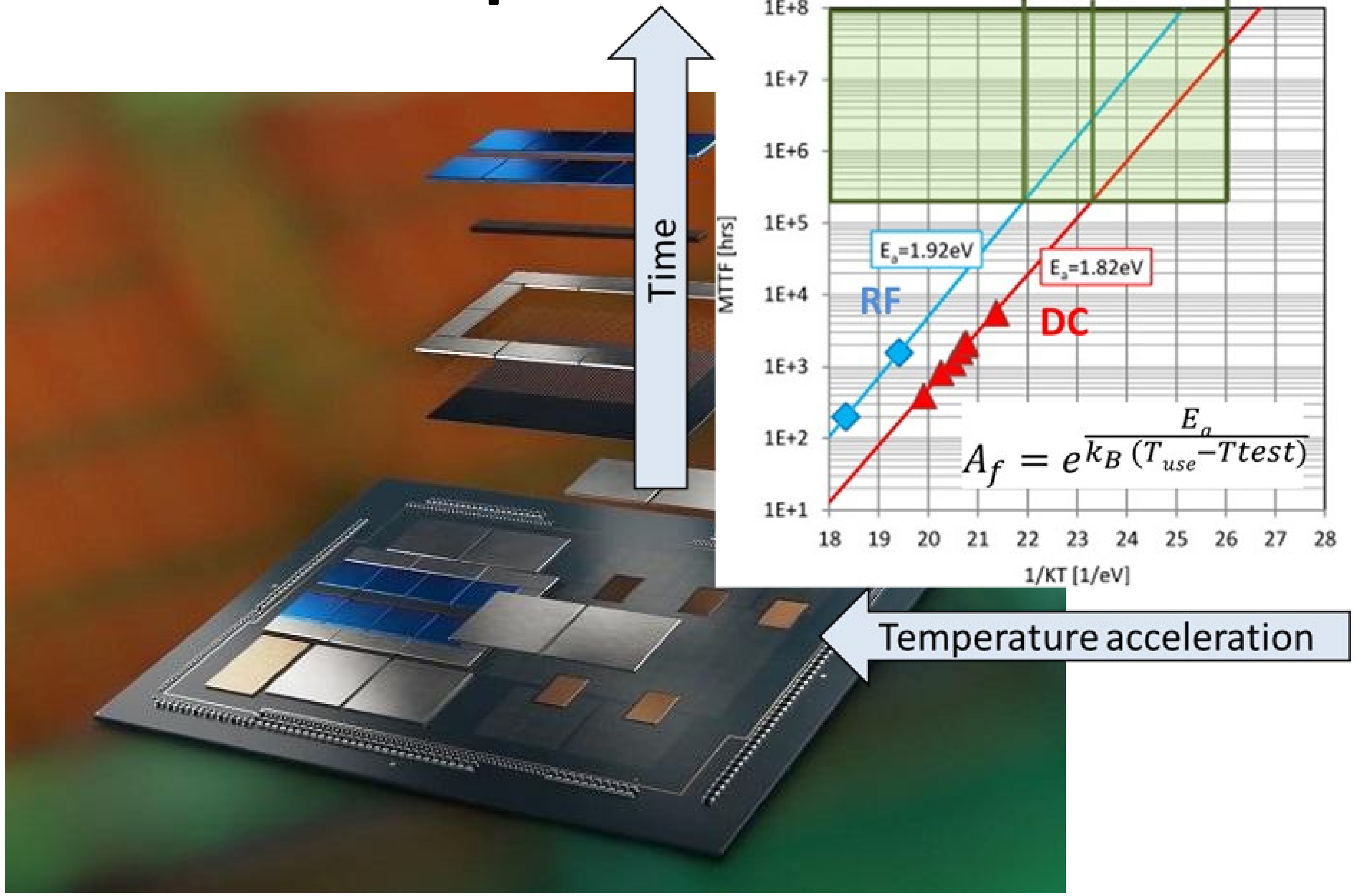
N-type Ga_2O_3: Si, Sn, Ge (30meV deep).

Can integration of Ga_2O_3 with diamond help ?



Kuball et al, GaN-DaME

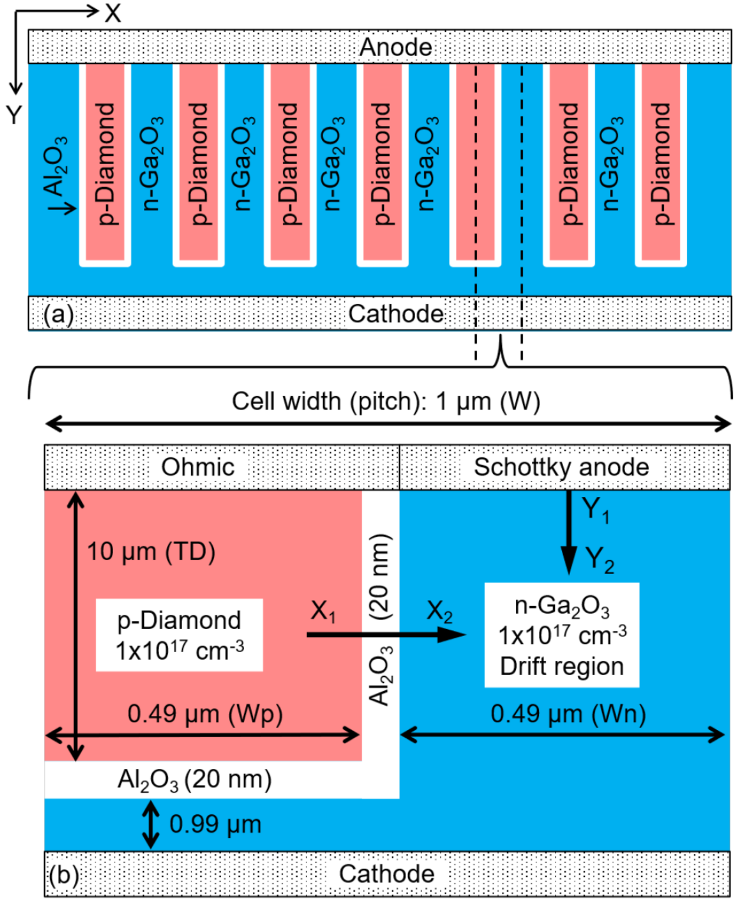
J. E. Graebner, *et al.*, Diamond and Related Materials 2, pp.1059-1063 (1993)

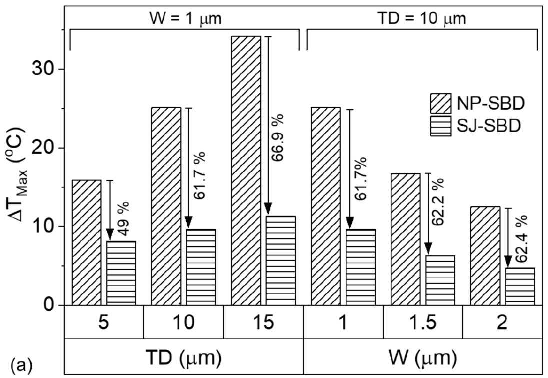


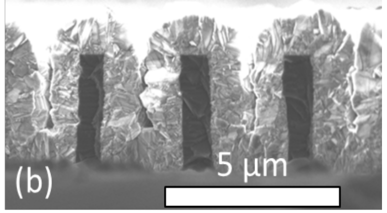
Example of GaN-on-Diamond RF devices

https://www.semi.org/en/blogs/technology-trends/intel-sets-out-to-tackle-power-delivery-challenges-for-heterogeneous-systems

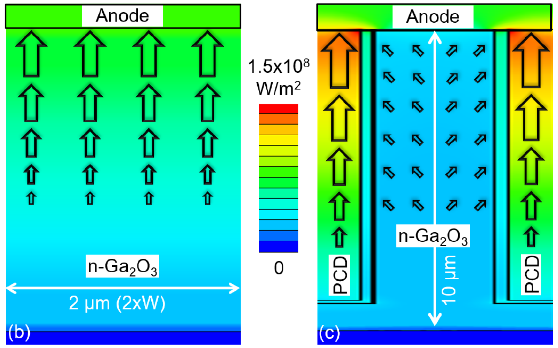
Integrated Ga_2O_3 – diamond device technology







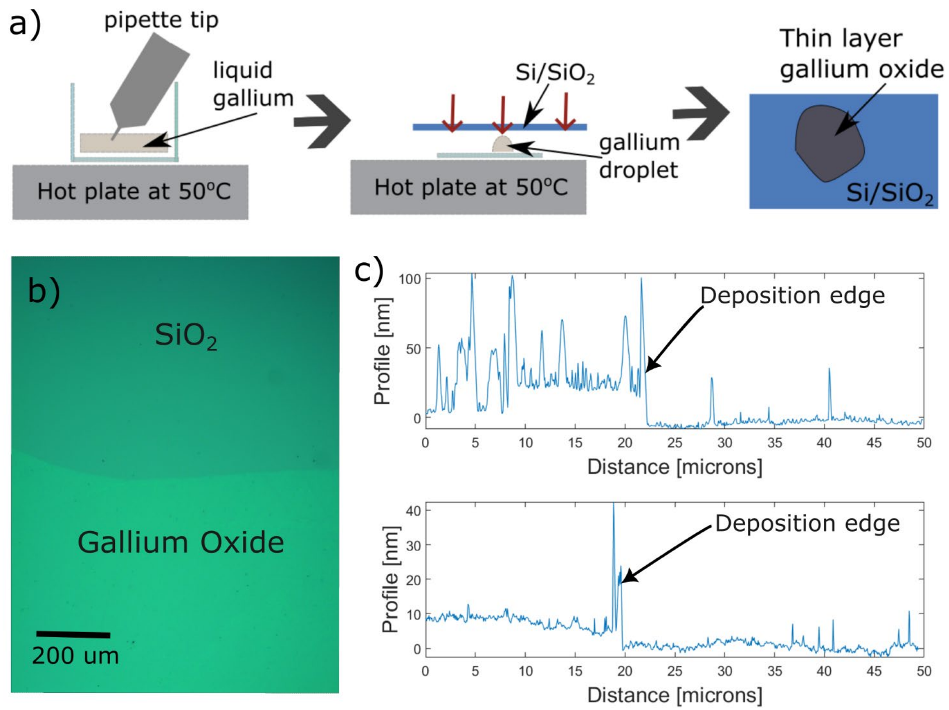
A. Mishra et al, IEEE Trans Electron Dev. IEEE Transactions on Electron Devices, vol. 68, no. 10, pp. 5055-5061, Oct. 2021



Diamond provides good heat sinking, but it can do more: In addition, the use of p-diamond provides electrical control of the devices.

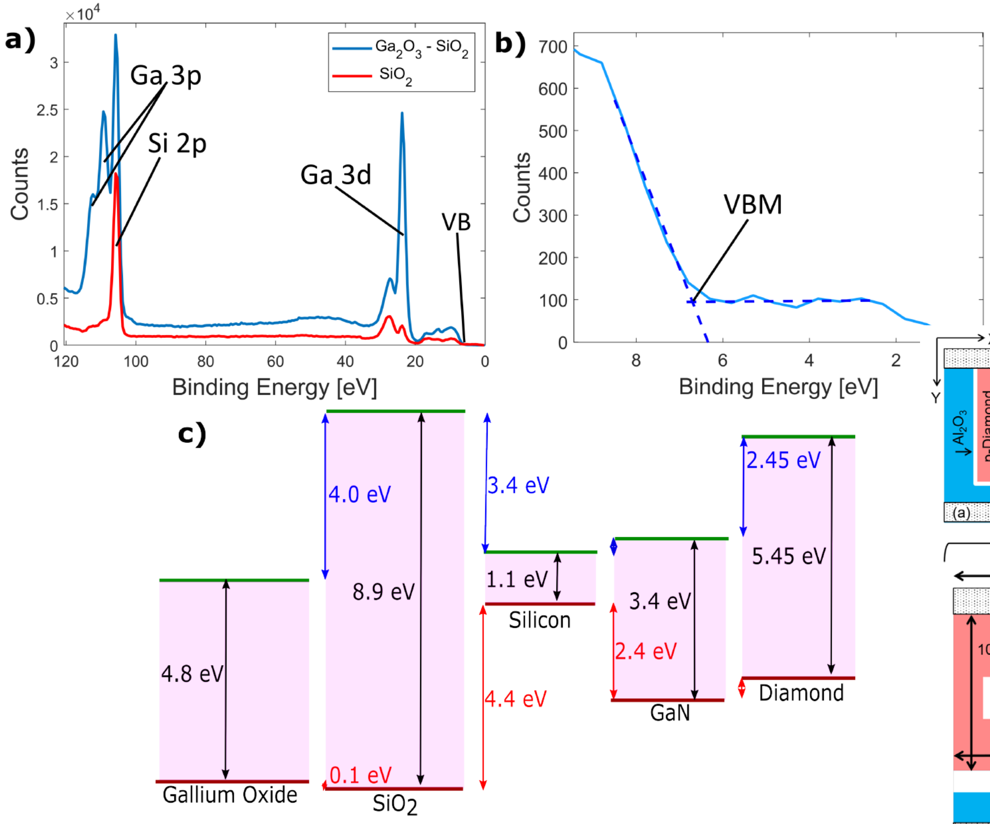
Band alignment Ga_2O_3 to other materials

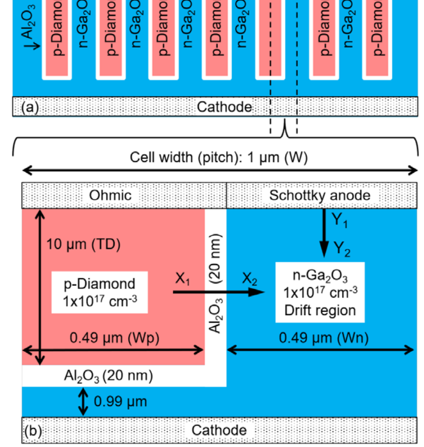
Test system: Ultra-thin Ga_2O_3 from liquid gallium



Integration with other p-type (wide-bandgap) semiconductors can address lack of suitable p-doping in Ga_2O_3.

Nano-ESCA experiments

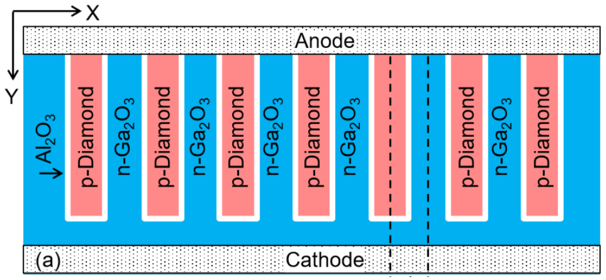


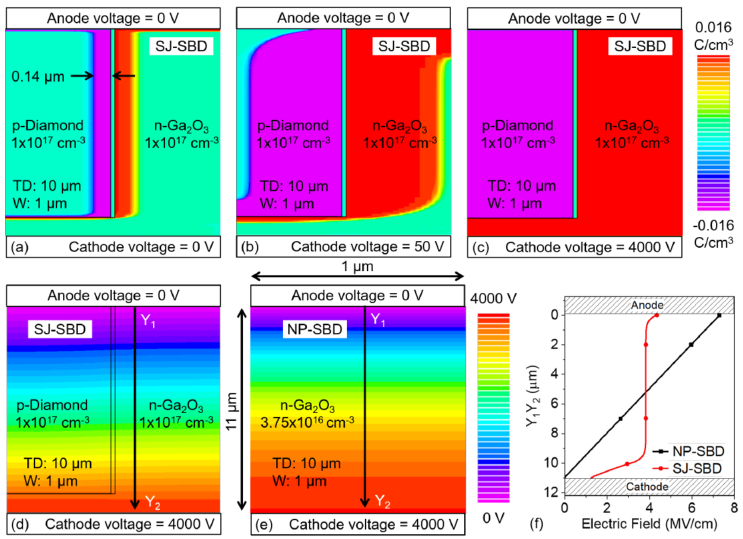


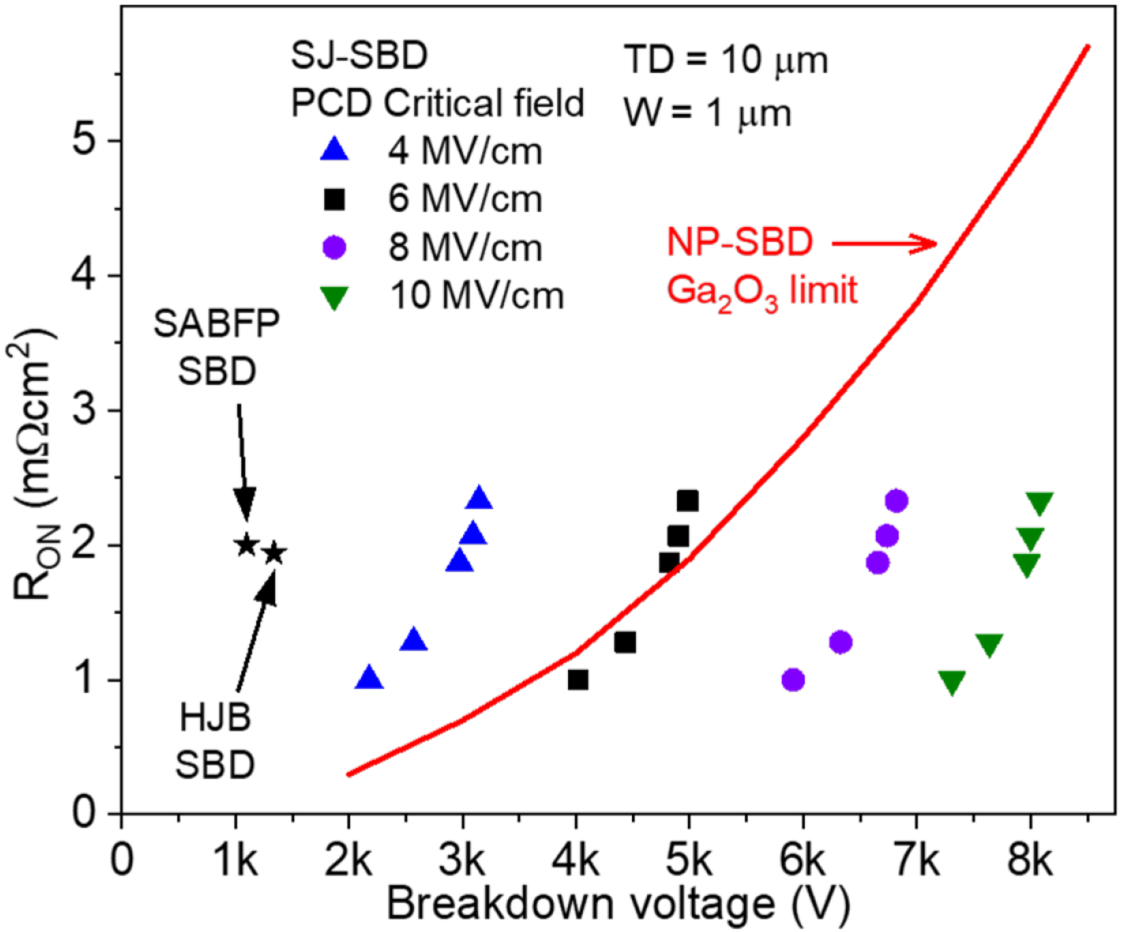
A. Petkov et al, Scientific Reports 13, 3437 (2023)

Integrated Ga_2O_3 – diamond device technology

This is a superjunction device !

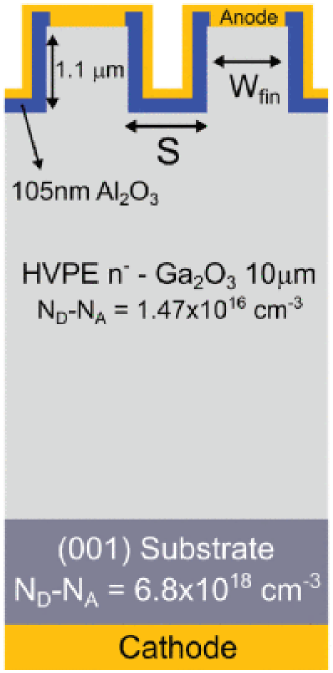


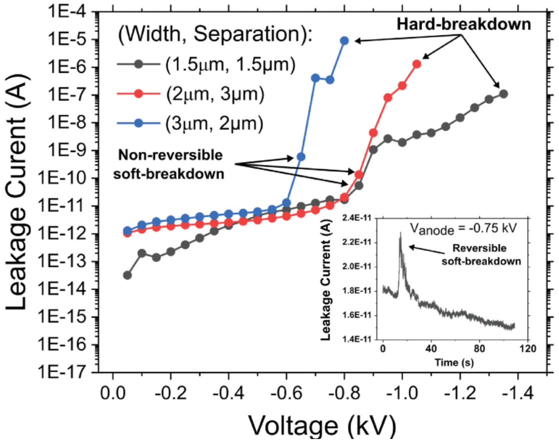


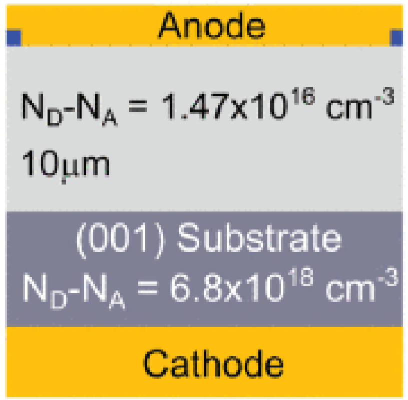


Use of p-diamond increases electrical performance i.e. breakdown voltage if the diamond breakdown voltage can be engineered high enough !

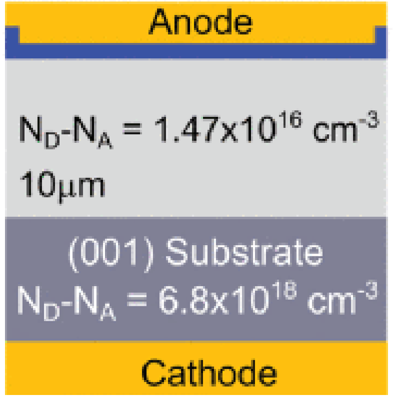
Reliability of Ga_2O_3 trench FETs: Oxide breakdown





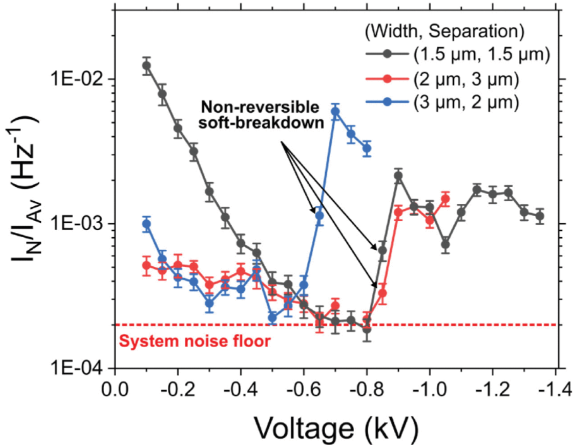


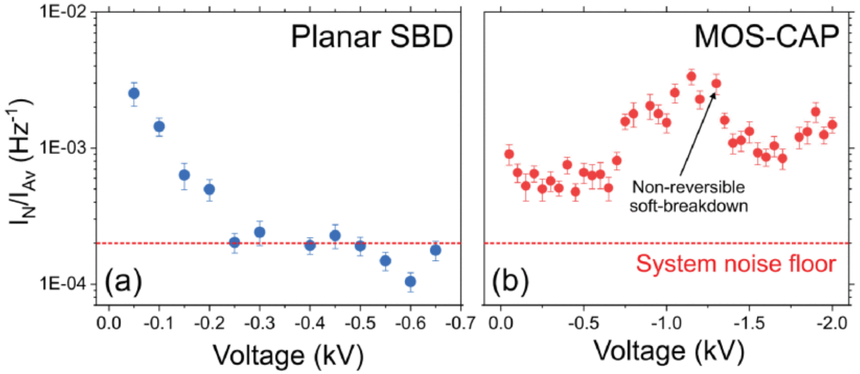
Planar SBD



Planar MOS-CAP

Devices studied in Bristol supplied by Cornell University

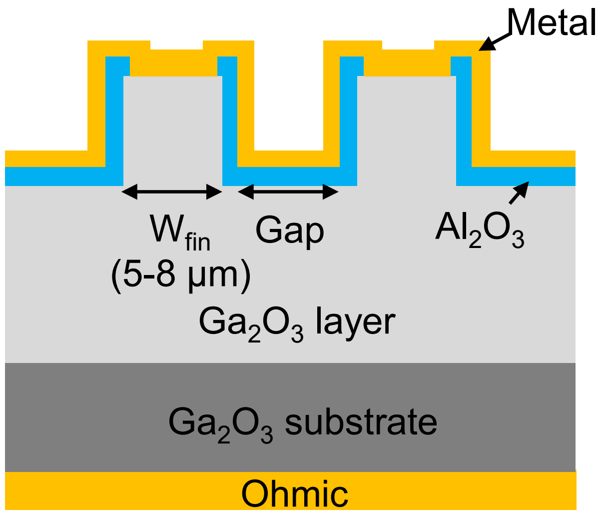




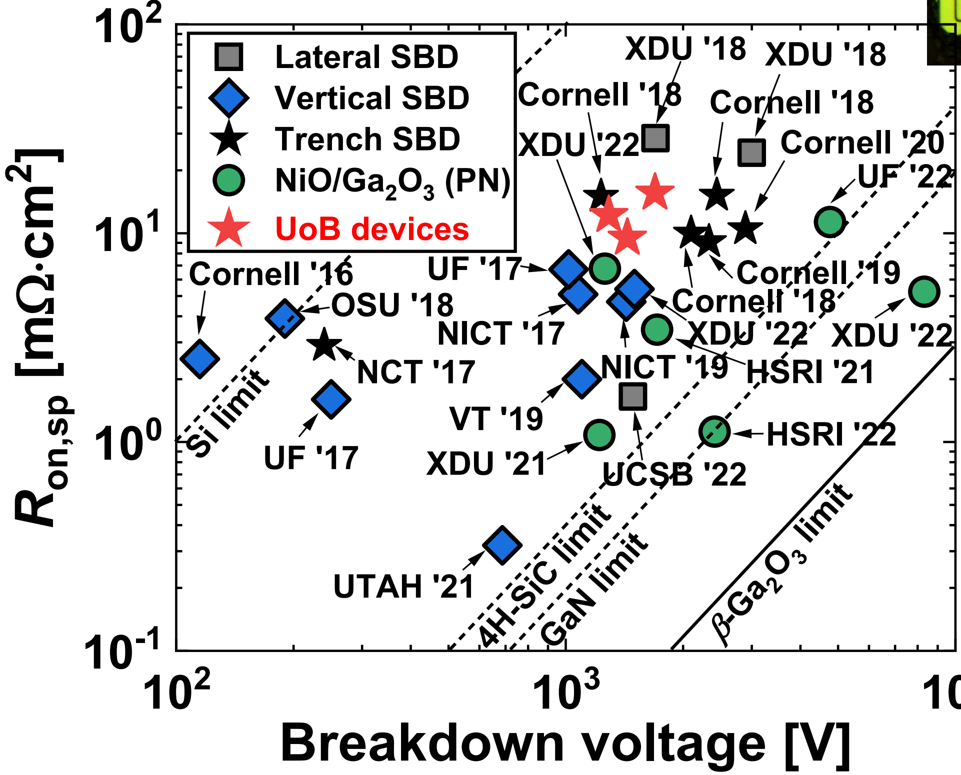
How to improve Ga_2O_3-Al_2O_3 interface?

T. Moule, M. Kuball et al., IEEE TED, Jan. 2022

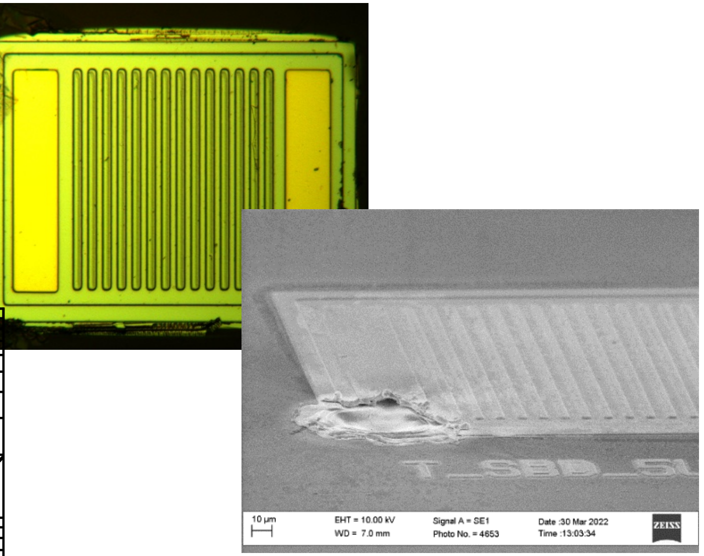
Bristol fabricated Ga_2O_3 trench SBDs



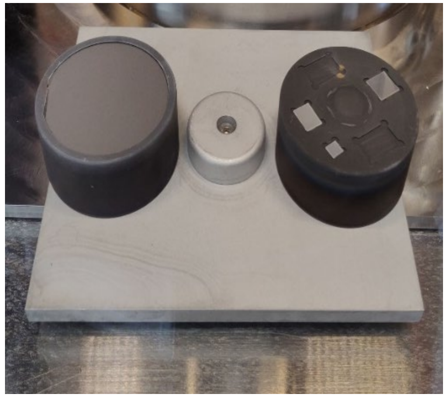
Kim et al, to be published



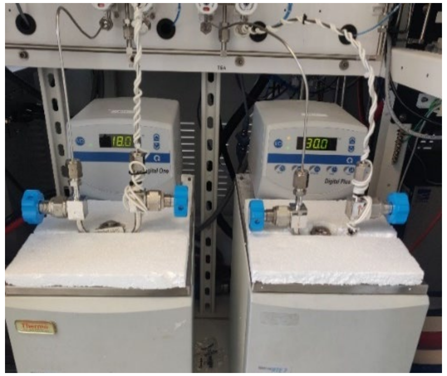
UoB devices in graph - no field plates



MOCVD growth in Bristol: Ga_2O_3



Up to 2-inch substrates

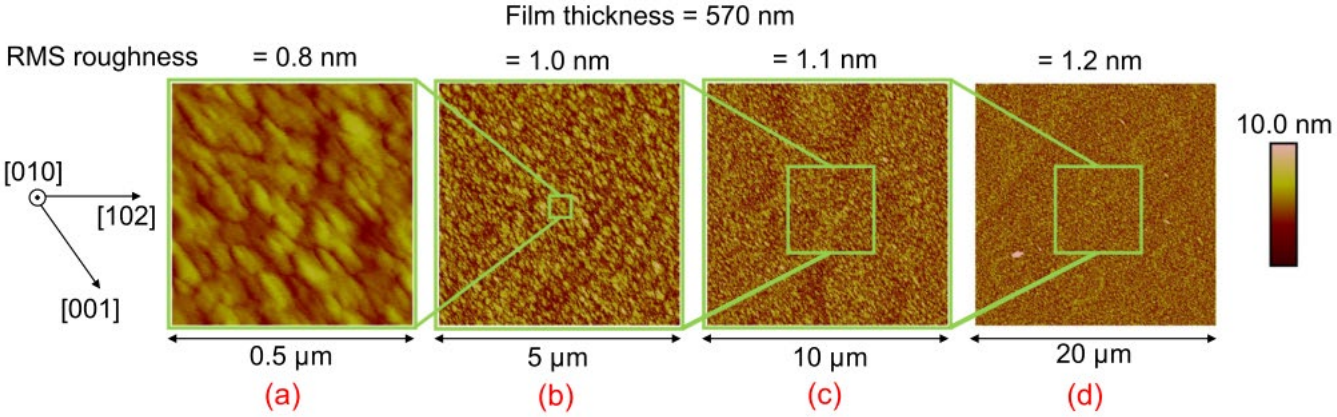


TEGa and TEAl sources

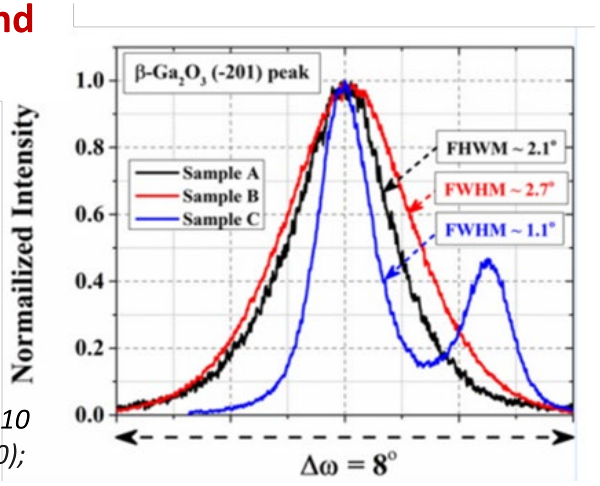
- Agnitron Agilis MOCVD System (commissioned in May 2022).
- First Ga_2O_3 commercial MOCVD reactor in the UK & Europe.
- Growth of epi-layers of Ga_2O_3 and $Al_x(Ga_2O_3)_{1-x}$ including for vertical devices.

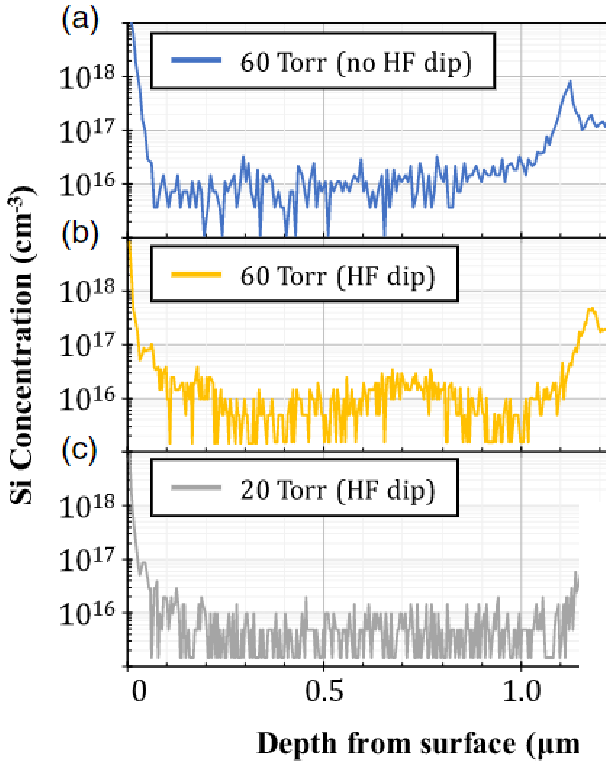
MOCVD/HVPE growth of Ga_2O_3, typically on Ga_2O_3 or sapphire

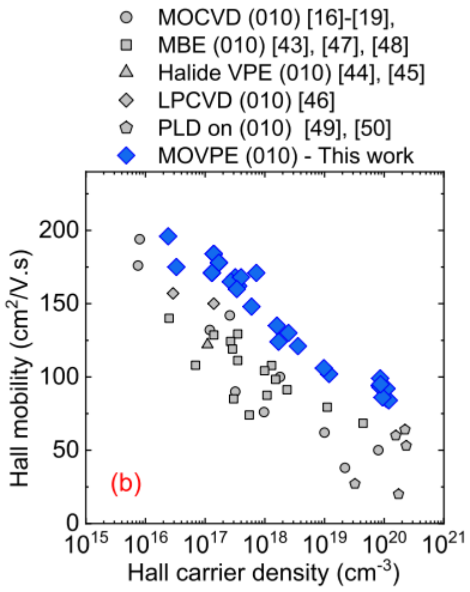
Growth on (010) Ga_2O_3



Smooth surface roughness; low background carrier density possible, decent mobility demonstrated.



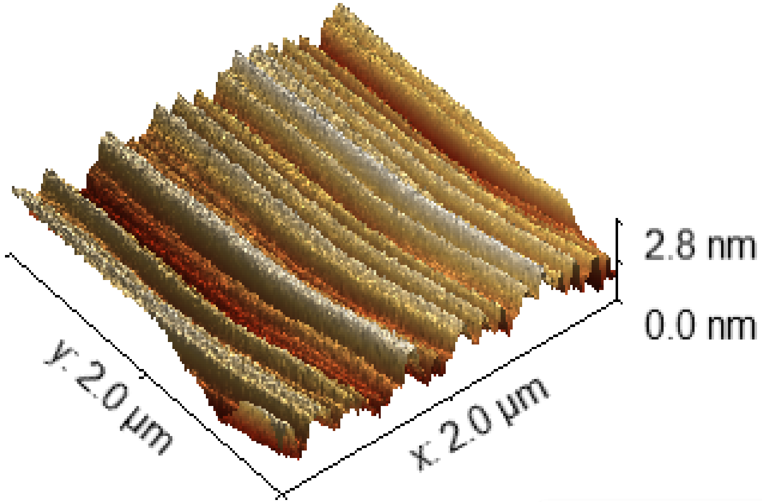


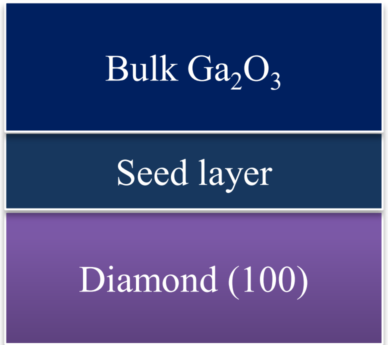


Example references: Bhattacharyya et al., APL Mater. 11, 021110 (2023); Feng et al. Physica Status Solidi RRL, 14, 2000145 (2020); Karim et al., J. Vac. Sci. Technol. A 39, 023411 (2021).

Two step growth onto diamond (100)

AFM image (diamond bare substrate)



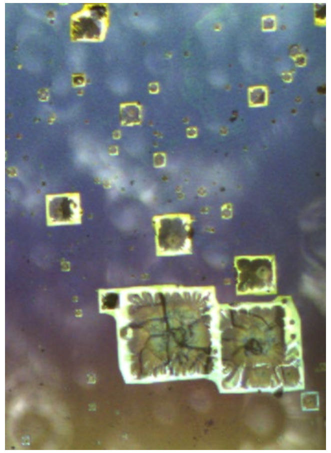


Bulk Ga_2O_3

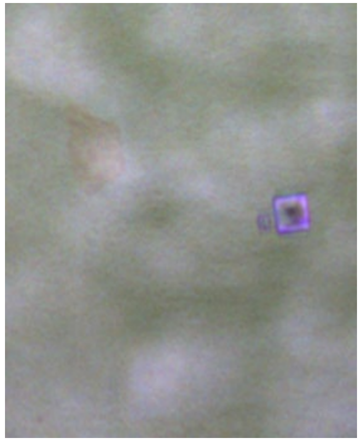
Seed layer

Diamond (100)

Nandi et al, Proceedings Photonics West 2023

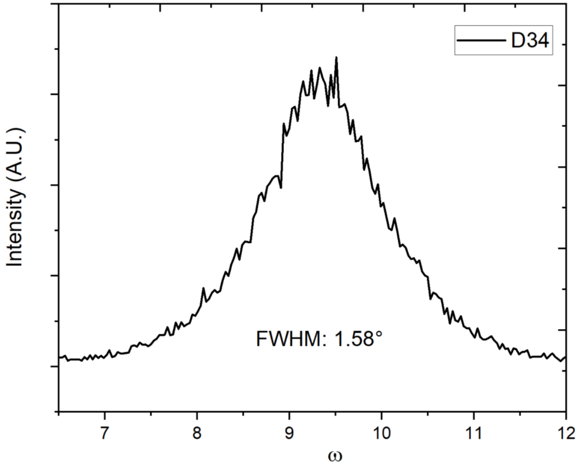


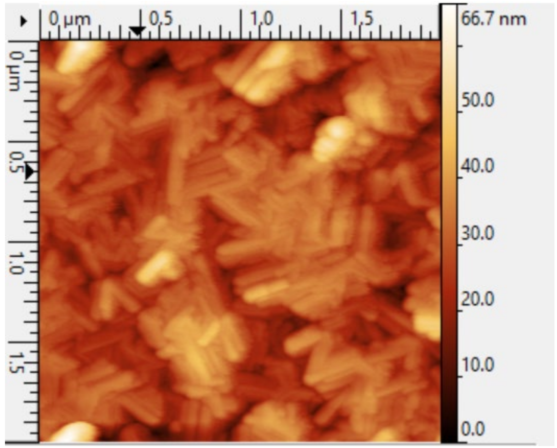
D1



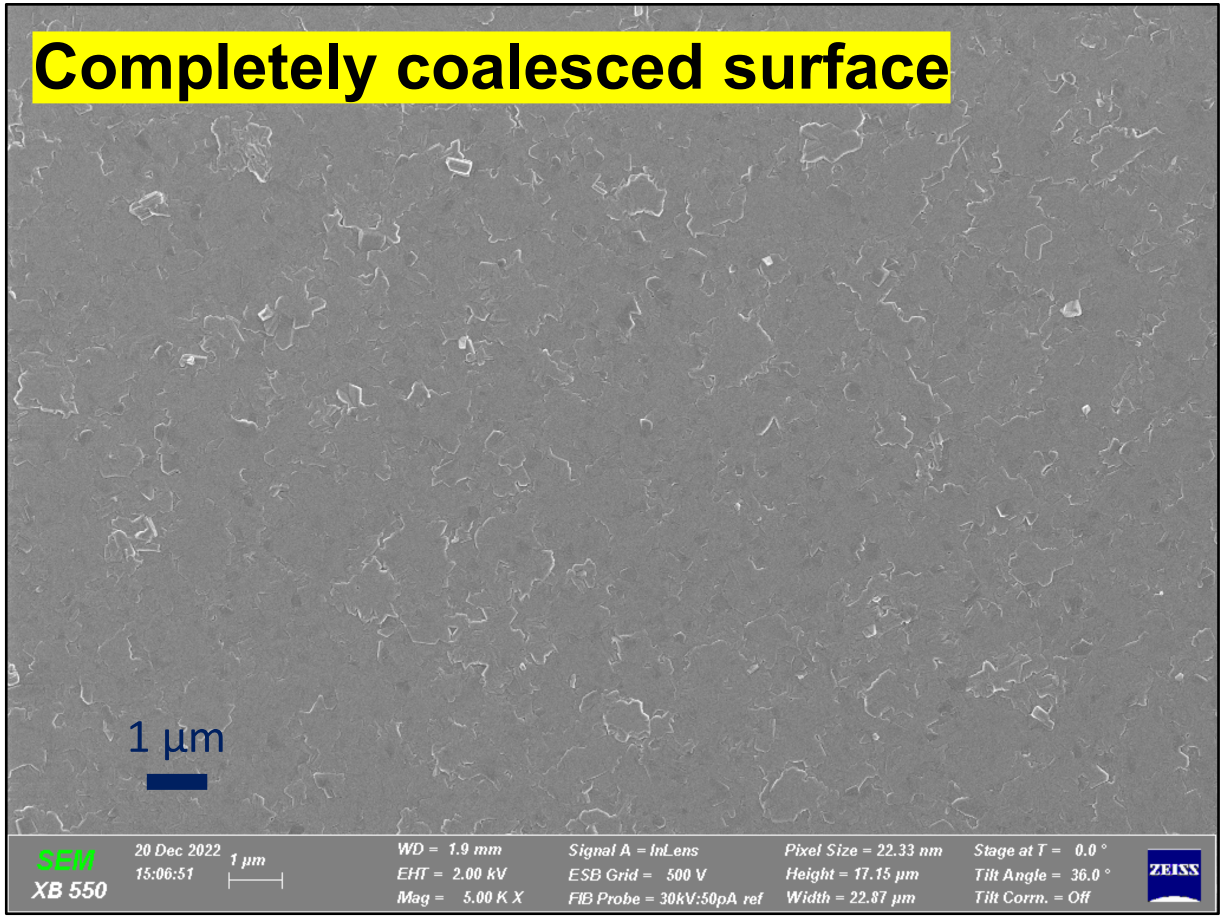
D2

D6



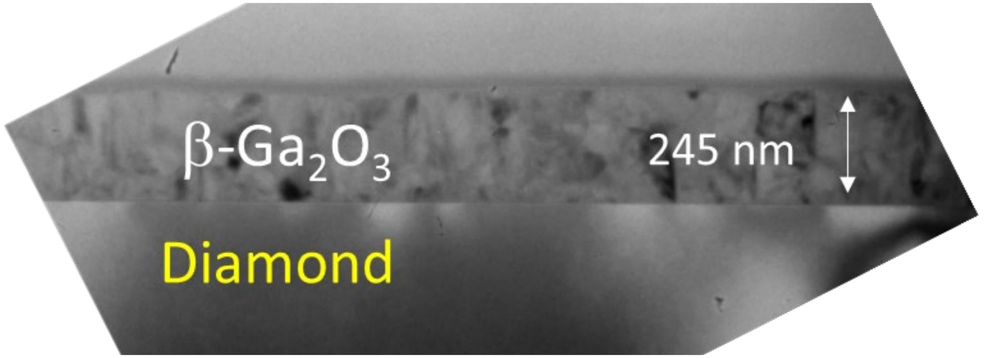


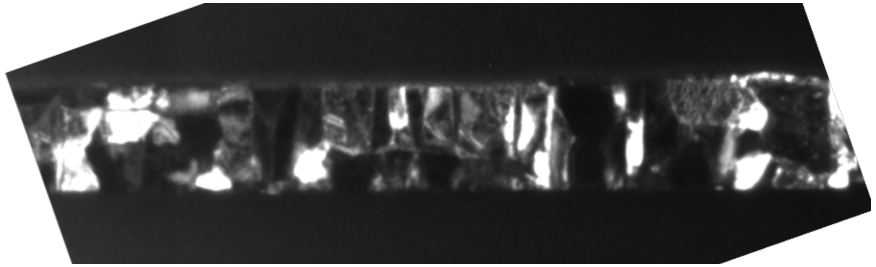
SEM / TEM of the grown (-201) Ga_2O_3 layer



Nandi et al, to be published

BF cross-sectional TEM image





DF cross-sectional TEM image (g=a)

Different competing crystallite orientations though all (-201), not that different from Ga_2O_3 on sapphire – VERY PROMISING !

Conclusions

- Ga_2O_3 power electronics has already exceeded many performance parameters of GaN and SiC power electronic devices.
- Though there are therefore huge opportunities for Ga_2O_3 power electronics, it has its challenges of low thermal conductivity and lack of workable p-type doping; also killer defects for devices are not that well understood yet.
- Integration of Ga_2O_3 with diamond can overcome some of Ga_2O_3's limitations; superjunctions, state of the art MOCVD growth on diamond.
- Good quality Ga_2O_3 Schottky Barrier Diodes (SBD) demonstrated; some failure modes of Ga_2O_3 devices discussed.

ROYAL ACADEMY OF ENGINEERING
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA