Ga_2O_3 for power electronics and its thermal properties

Takeki Itoh
Speck Group
Materials Department

Crystalline phases of Ga_2O_3

β-Ga_2O_3 is the stable phase of the Ga_2O_3 crystalline system, which is widely researched now.

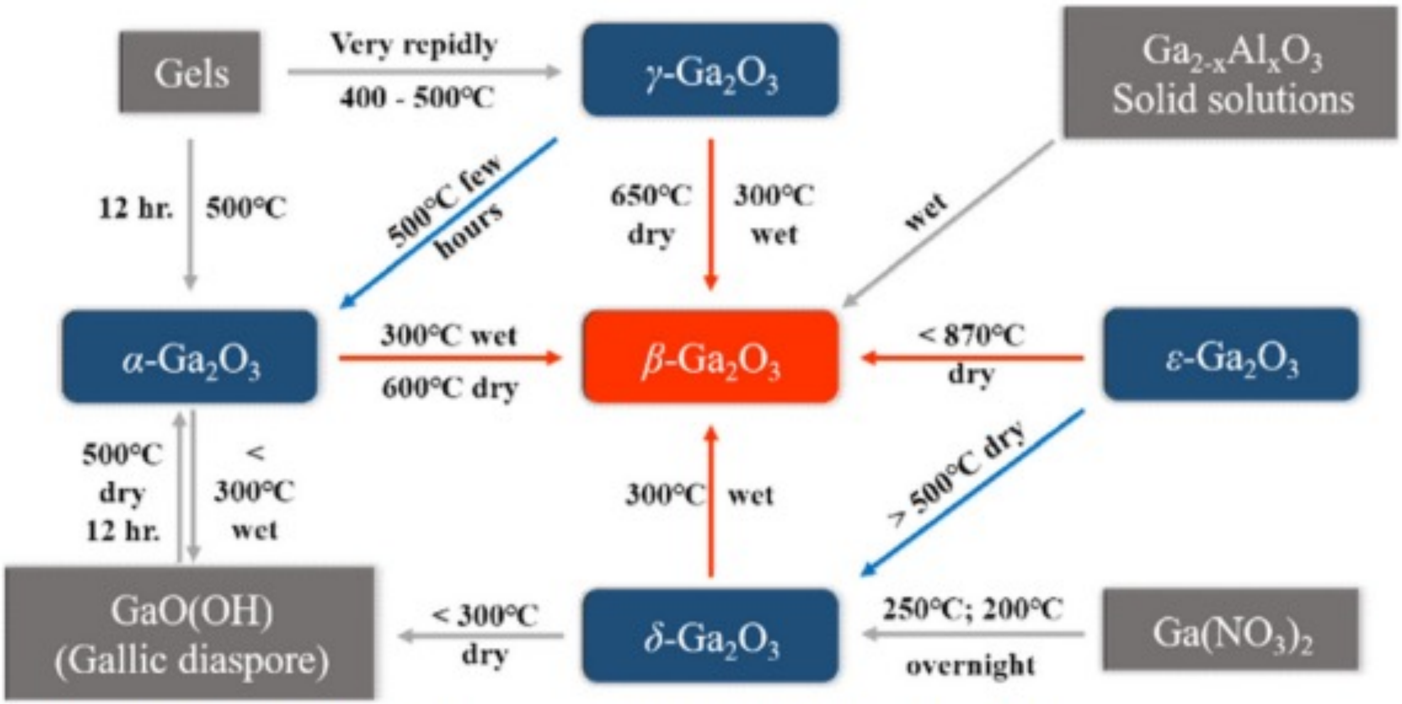
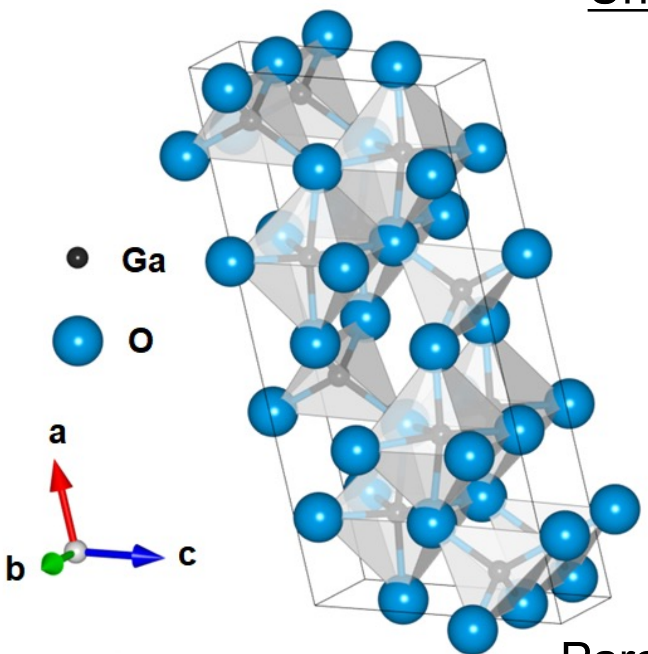


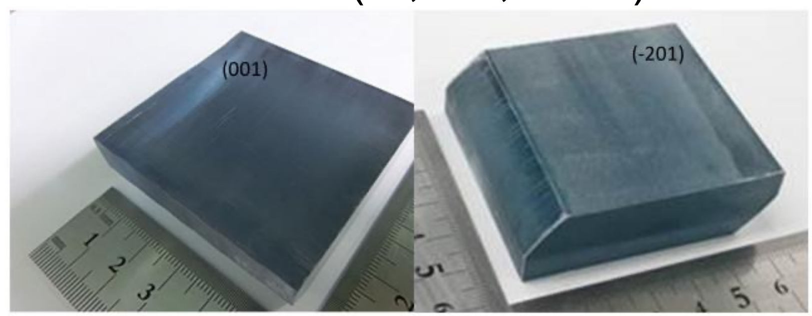
Fig. 1 Transformation relationships among the crystalline phases of Ga2O3 and their hydrates [30]

Introduction of β-Ga_2O_3

Unit cell and properties of β-Ga_2O_3



- Crystal structure: M**onoclinic**
- Energy band-gap: **4.8 eV**
- Bulk substrate**: Melt-growth method**
- n-type doping: **Shallow donors** (Si, Ge, Sn…)



Lattice constant:

a = 1.22 nm
b = 0.30 nm
c = 0.58 nm
α = 90°
β = 104°
γ = 90°

Parameters of major semiconductors

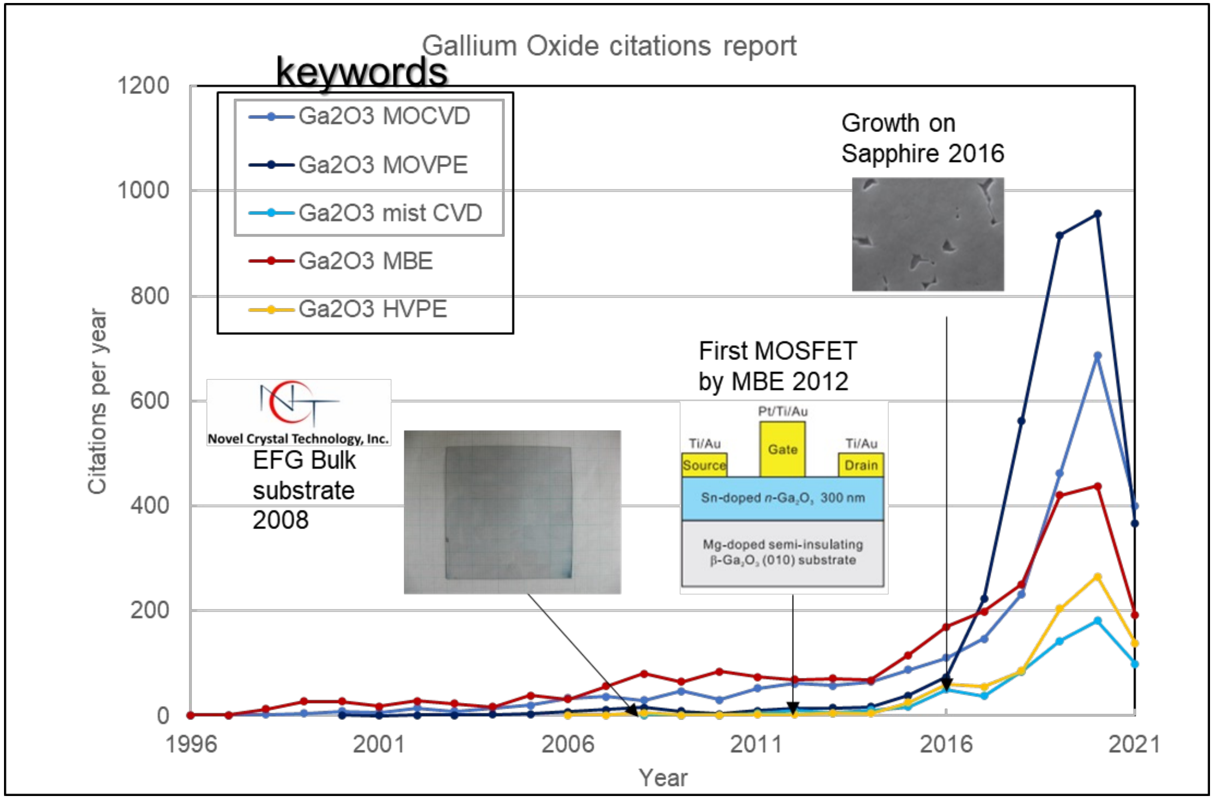
	Si	4H-SiC	GaN	Diamond	β-Ga_2O_3
Band gap (eV)	1.1	3.3	3.4	5.5	4.8
Electron mobility ($cm^2 V^{-1} s^{-1}$)	1,500	1,000	1,200	1,800	300[a)]
Breakdown field (MV/cm)	0.3	3.0	3.3	10	8[a)]
Dielectric constant	11.8	10	9.5	5.5	10
Baliga's FOM (low freq.)	1	570	860	21,000	3,200

a) Estimated.

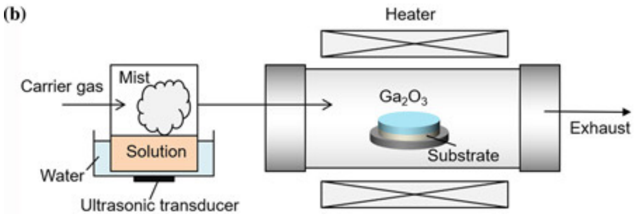
K. Sasaki *et al.,* 2012 Appl. Phys. Express **5** 035502 (2012).

Ga_2O_3 research trend

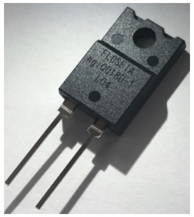
The growth of Ga_2O_3 has been promoted by the realization of high-quality bulk substrates.



- High quality single crystal substrate was available since 2008.
- First MOSFET demonstration in 2012.
- Mist CVD-grown Ga_2O_3 based diodes have reached mass-production phase.



Mist CVD schematic



Ga_2O_3 SBD

D. Shinohara *et al*., Jpn. J. Appl. Phys. **47**, 7311 (2008).
https://flosfia.com/products/

Highly-cited research

Gallium oxide (Ga_2O_3) metal-semiconductor field-effect transistors on single-crystal β-Ga_2O_3 (010) substrates

Masataka Higashiwaki,[1,2,a)] Kohei Sasaki,[3] Akito Kuramata,[3] Takekazu Masui,[4] and Shigenobu Yamakoshi[3]

NICT

1068 citations

Applied Physics Letters **100**, 013504 (2012).

Dr. Higashiwaki

Hetero-epitaxy of ε-Ga_2O_3 layers by MOCVD and ALD

F. Boschi [a,b], M. Bosi [b], T. Berzina [b], E. Buffagni [b], C. Ferrari [b], R. Fornari [a,b,*]

UNIVERSITÀ DI PARMA

111 citations

Journal of Crystal Growth **443**, 25 (2016).

Prof. Fornari

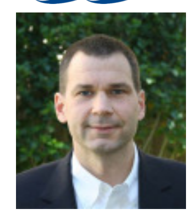
MOCVD grown epitaxial β-Ga_2O_3 thin film with an electron mobility of 176 cm^2/V s at room temperature

APL Materials **7**, 022506 (2019); https://doi.org/10.1063/1.5058059

Yuewei Zhang[1,a),b)], Fikadu Alema[2,b)], Akhil Mauze[1], Onur S. Koksaldi[3], Ross Miller[2], Andrei Osinsky[2], *and* James S. Speck[1,a)]

UCSB

agnitron technology



91 citations

APL Materials **7**, 022506 (2019).

Prof. Speck

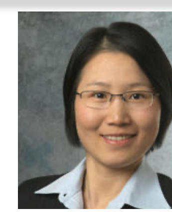
Dr. Osinski

MOCVD homoepitaxy of Si-doped (010) β-Ga_2O_3 thin films with superior transport properties

Appl. Phys. Lett. **114**, 250601 (2019); https://doi.org/10.1063/1.5109678

Zixuan Feng[1,a)], A F M Anhar Uddin Bhuiyan[1], Md Rezaul Karim[1], *and* Hongping Zhao[1,2,b)]

THE OHIO STATE UNIVERSITY



81 citations

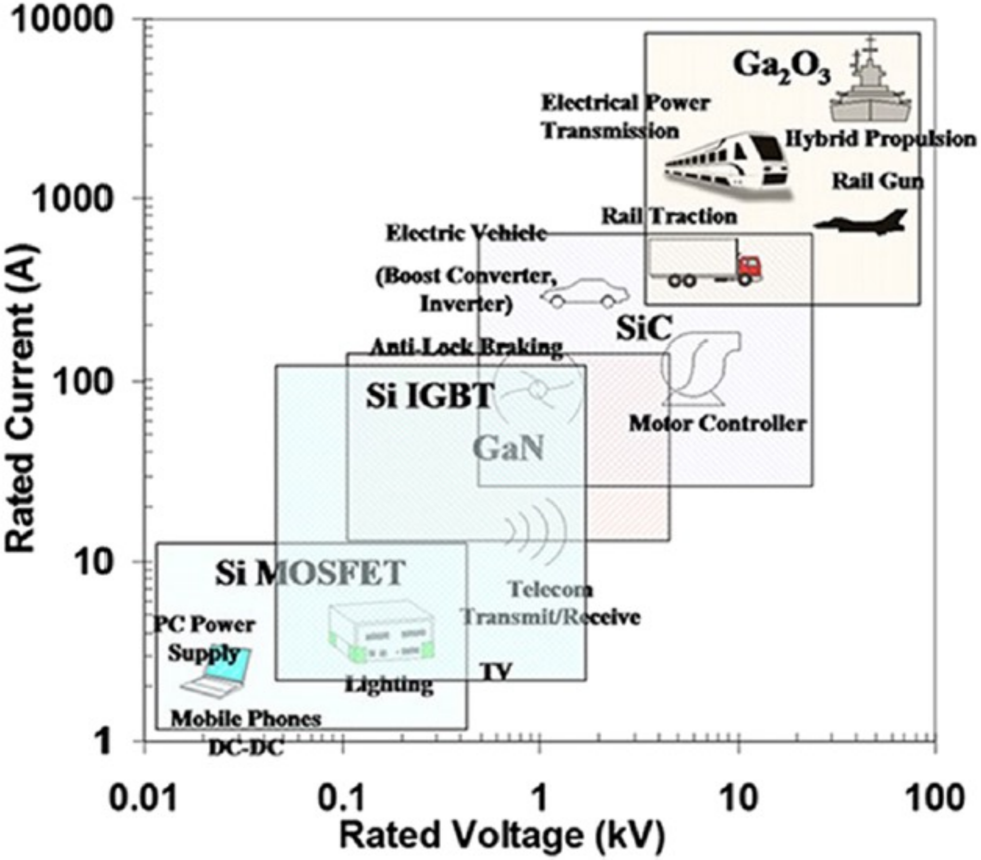
Applied Physics Letters **114**, 013504 (2019).

Prof. Zhao

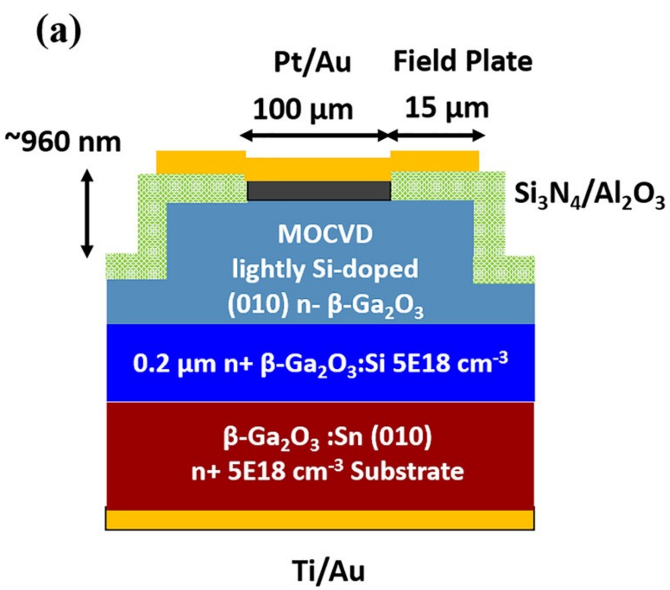
Applications of Ga_2O_3

Power electronics are applied to all over the electric ecosystem. Schottky barrier diode is one kind of power devices among thyristors, bipolar transistors and MOSFETs.

Semiconductors used as power electronics



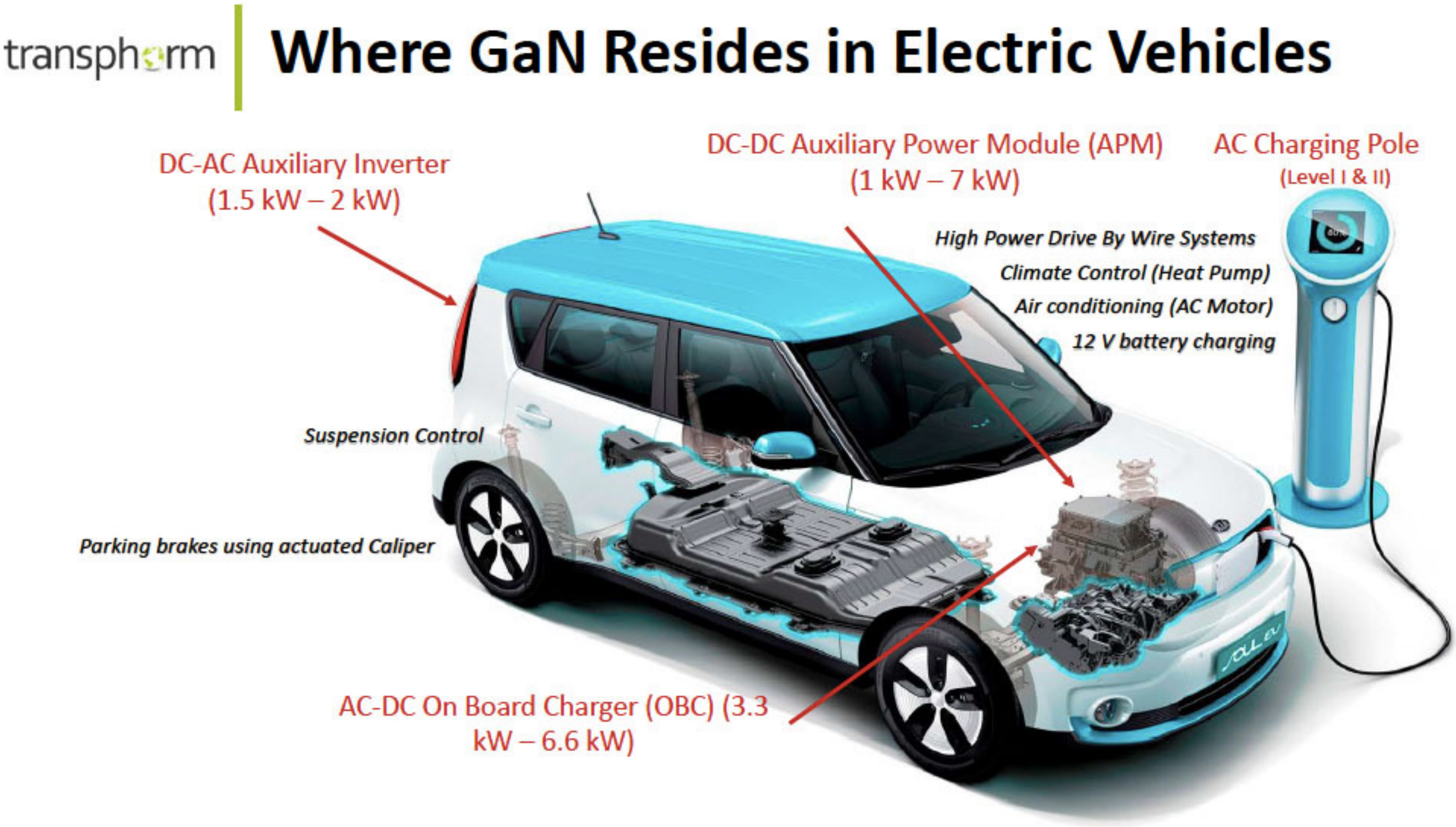
MOCVD-grown Ga_2O_3 SBD



Pros: high quality material
Cons: Thick film is unavailable (surface roughening).

J. Zhang *et al.,* APL Mater. **8**, 020906 (2020). E. Farzana *et al.,* Appl. Phys. Lett. 118, 162109 (2021).

GaN power electronics in an EV



The GaN revolution: Transphorm talks – Products to applications fueling the new power semiconductor market
www.i-micronews.com

Power electronics in EVs

Nissan Leaf S,S Plus	Tesla Model 3 Standard range, Long range
Lithium-ion battery	Lithium-ion battery
Si-based power electronics	SiC-based power electronics
	
Battery size: 40 kWh, 62 kWh	60 kWh, 82 kWh
Range: 149 miles, 226 miles	272 miles, 358 miles
kWh per mile: 0.268, 0.274	0.221, 0.229

21.2% more efficient

Specs for different inverters

Side-by-Side Comparison

MUNRO & ASSOCIATES, INC.

Battery Electric Vehicles (BEV) - Inverter

	2018 Tesla Model 3 Inverter	2019 Nissan Leaf Inverter	2019 Jaguar I-Pace Inverter
			
Cost (USD)	$522.22	$468.41	$555.29
Max. Input Voltage (V_{DC})	430	450	500
Dimensions (mm)	370 x 278 x 122	386 x 386 x 223	407 x 272 x 83
Parts / Fasteners	1275 / 44	1287 / 56	2185 / 106
Weight (kg)	4.81	11.15	8.23
Coolant Medium	Water/Glycol	Water/Glycol	Water/Glycol

Cost and weights include: Housing, PCBA, IGBT Module & Cooling Structure, DC-link Capacitor, Motor Phase Lead, Connectors, Self-contained structural and connected components.

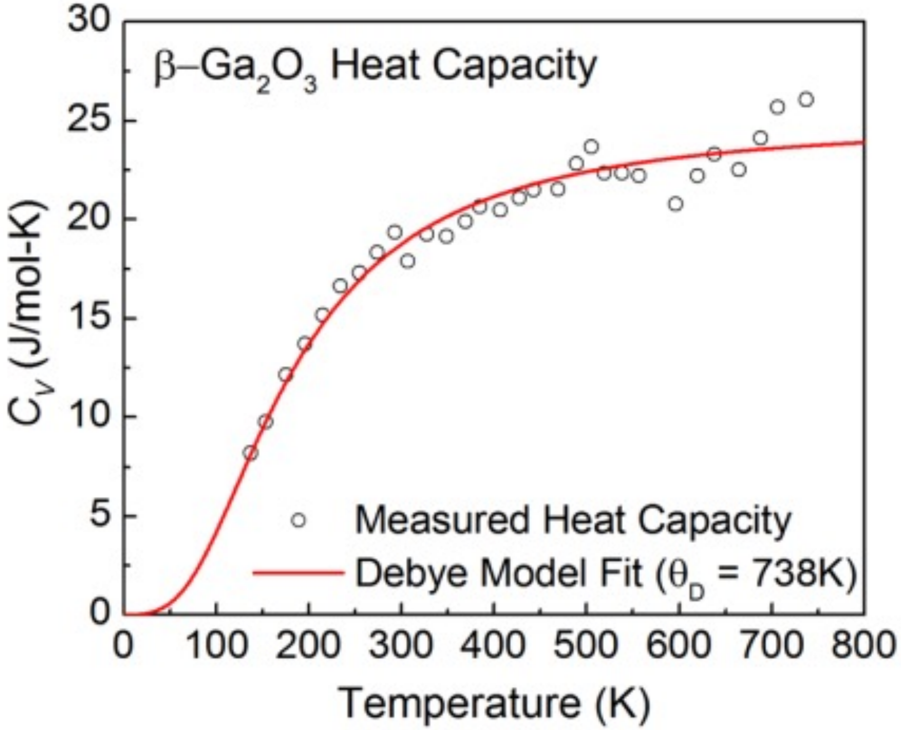
Thermal conductivity

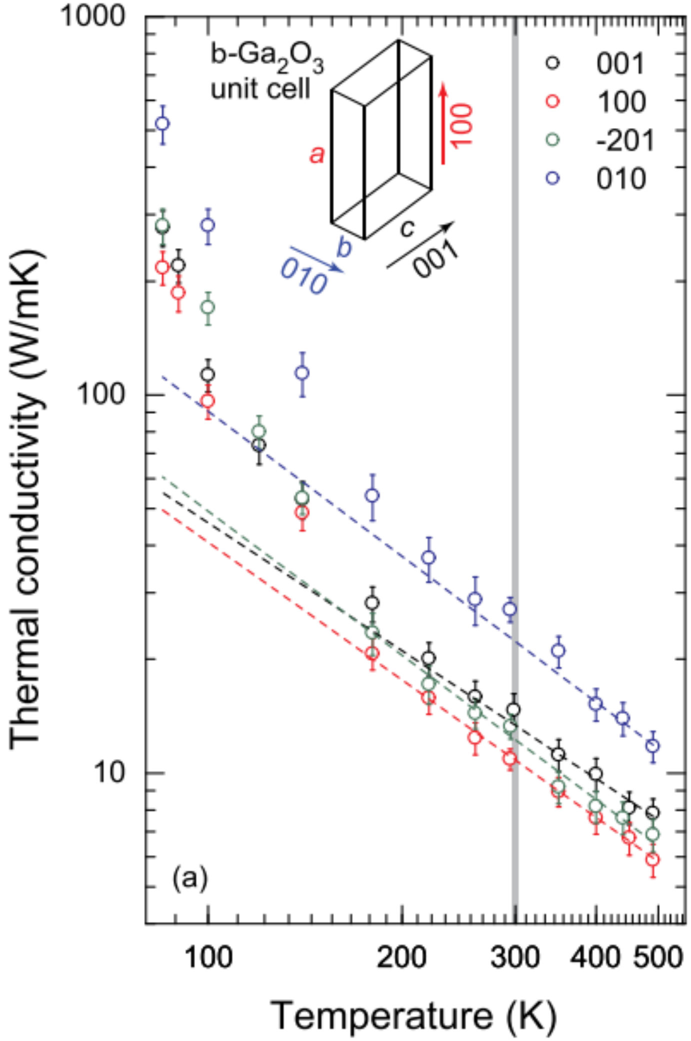
From another point of view, gallium oxide shows poor thermal conductivity compared to major semiconductor materials.

Semiconductor material	Si	GaN	4H-SiC	β-Ga_2O_3
Bandgap E_g (eV)	1.1	3.4	3.3	4.7–4.9
Electron mobility μ ($cm^2\ V^{-1}\ s^{-1}$)	1400	1200	1000	300
Breakdown electric field E_{br} (MV/cm)	0.3	3.3	2.5	8
Baliga's FOM ($\varepsilon \mu E_b^3$)	1	870	340	3444
Thermal conductivity λ ($W\ cm^{-1}\ K^{-1}$)	1.5	2.1	2.7	0.11

Debye model study

$$C(T) = 3Nk\frac{3}{x_0^3}\int_0^{x_0}\frac{x^4e^x}{(e^x-1)^2}dx,$$





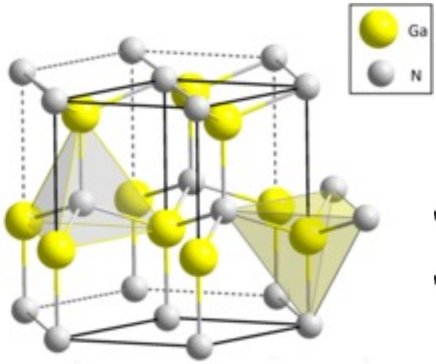
Guo *et al*., Appl. Phys. Lett. 106, 111909 (2015).

T-dependent thermal conductivity

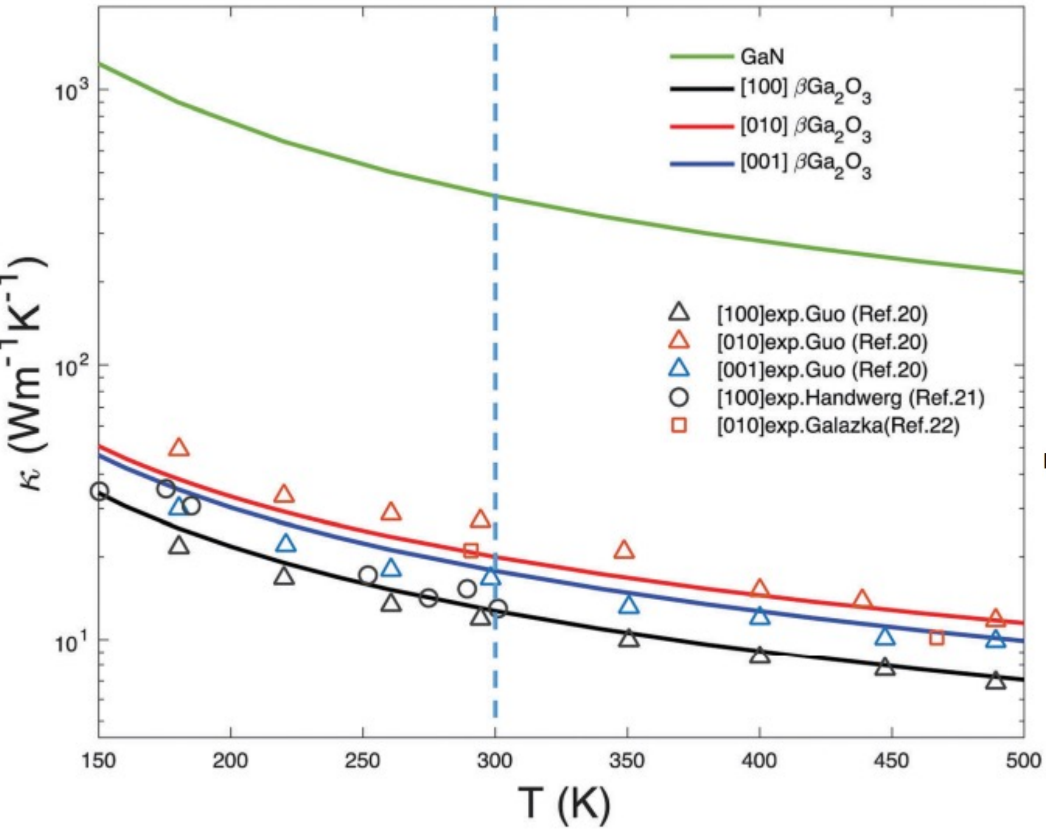
Table 1 Thermal conductivity of the bulk β-Ga_2O_3 at 300 K

Crystallographic orientation	This study	Experiment	Simulation[19]
[100]	12.73	10.9 ± 0.7,[20] 13 ± 1[21]	16.06
[010]	20.00	27.1 ± 2,[20] 21[22]	21.54
[001]	17.80	14.7 ± 1.4[20]	21.15

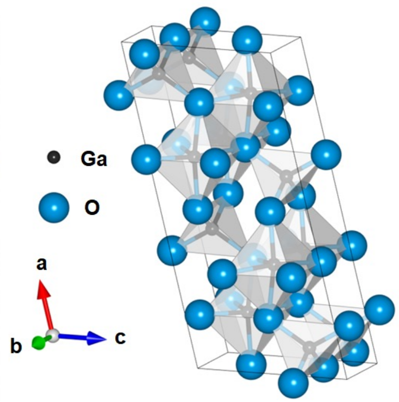
GaN



Hexagonal



β-Ga_2O_3

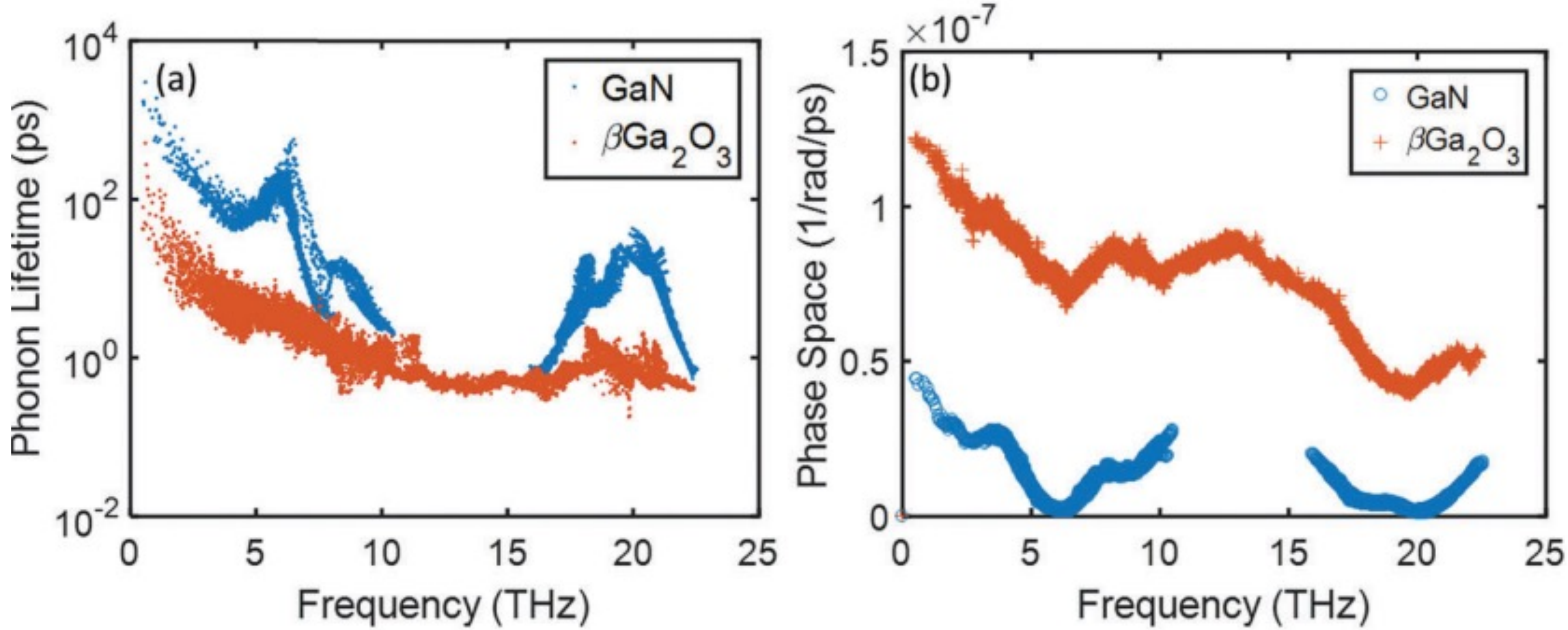


Large phonon scattering

Z. Yan and S. Kumar, Phys. Chem. Chem. Phys. 20, 29236 (2018).

Phonon lifetime of β-Ga_2O_3

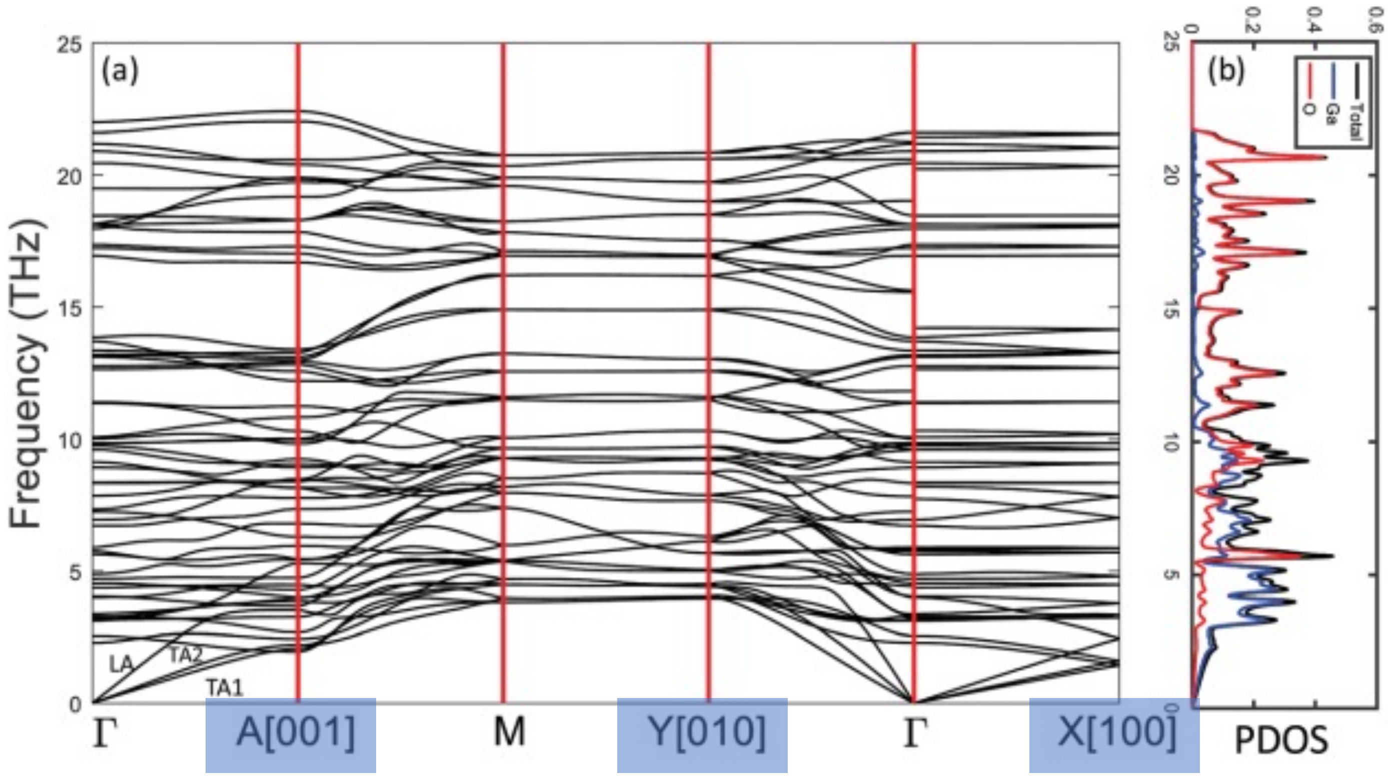
β-Ga_2O_3 has a much shorter phonon lifetime than GaN in the entire frequency domain.



Z. Yan and S. Kumar, Phys. Chem. Chem. Phys. 20, 29236 (2018).

Phonon dispersion of β-Ga_2O_3

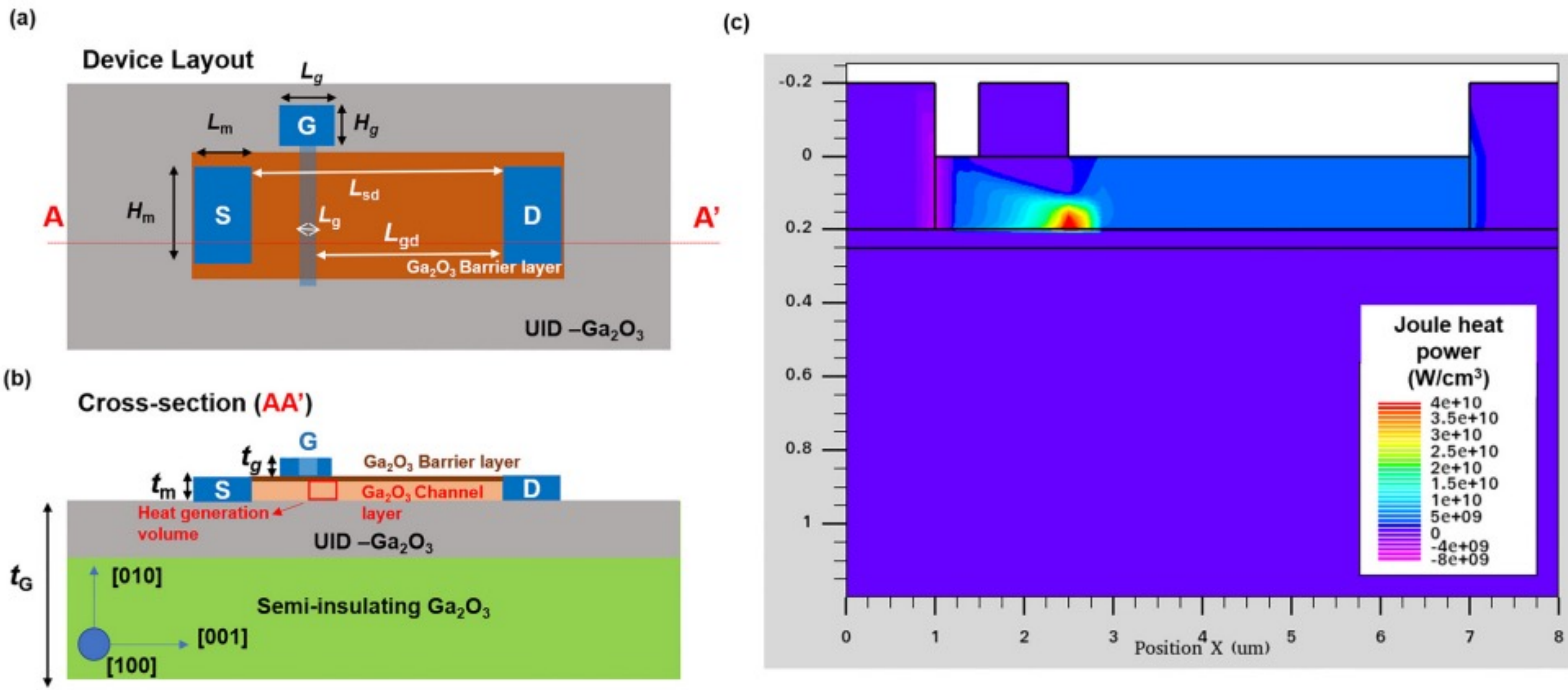
Large gap between acoustic phonon and optical phonon in β-Ga_2O_3 system.



Z. Yan and S. Kumar, Phys. Chem. Chem. Phys. 20, 29236 (2018).

Device thermal simulation

Schematic layout of the investigated β-Ga_2O_3 single finger metal–semiconductor field-effect transistor (MESFET)



C. Yuan, Y. Zhang, R. Montgomery, S. Kim, Ji. Shi, A. Mauze, **T. Itoh**, J. S Speck, S. Graham, J. App. Phys. **127**, 54502 (2020).

Device structures for simulations

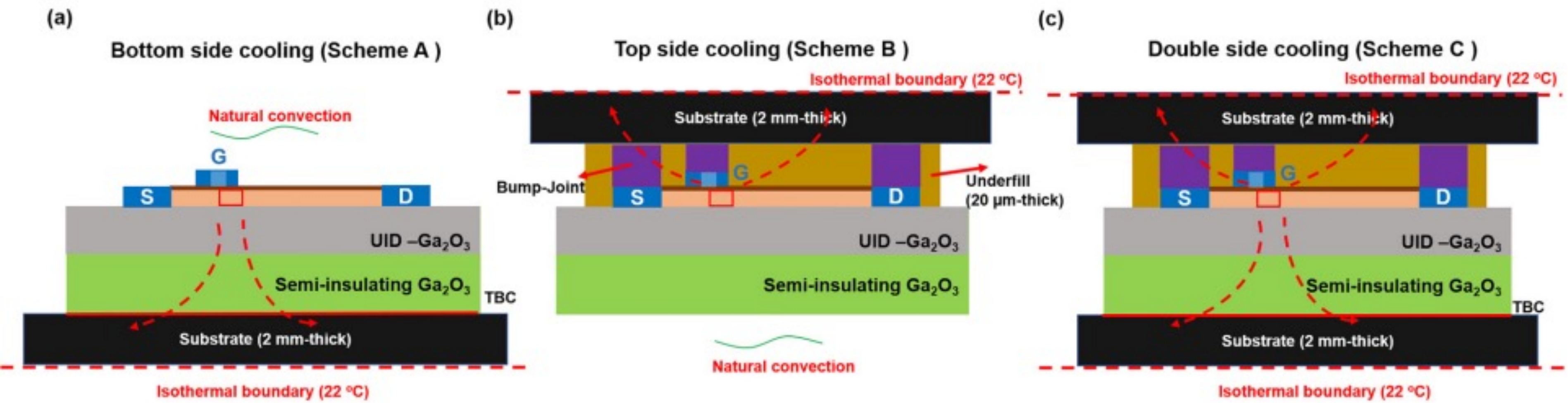
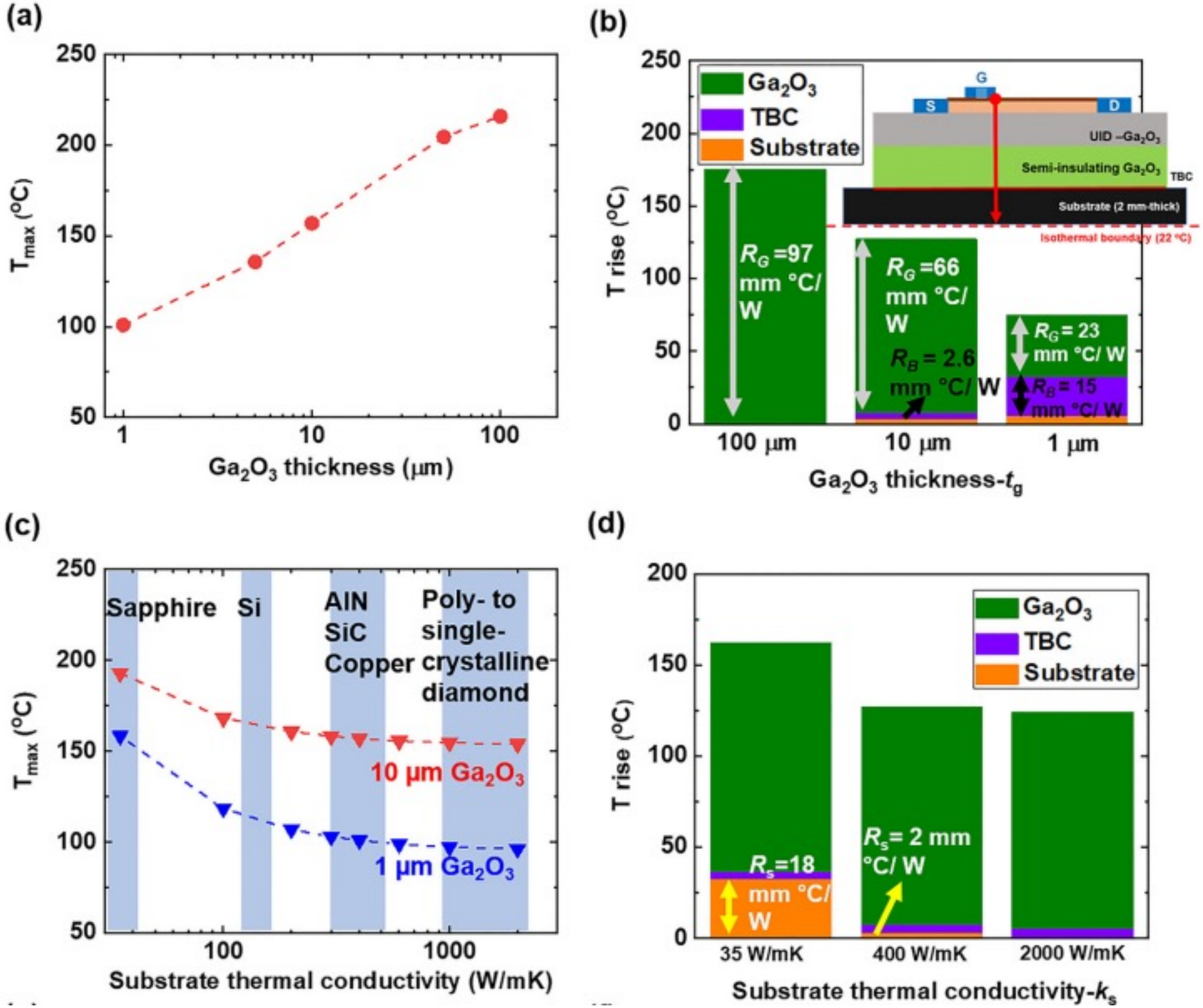


TABLE II. Variable's range, baseline, and optimal cooling values.

Variables	Range	Baseline	Optimal cooling parameter
Ga_2O_3 thickness (t_g) (μm)	1–100	10	1
Thermal boundary conductance (TBC) (MW/m^2 K)	5–200	20	200
Substrate thermal conductivity (k_s) (W/m K)	35–2000	400	2000
Underfill thermal conductivity (k_f) (W/m K)	0.2–11	2	11
Bump joint thermal conductivity (k_b) (W/m K)	10–200	50	200
Heat spreader deposited at the active region (W/m K)	10–500	300	500

C. Yuan, Y. Zhang, R. Montgomery, S. Kim, Ji. Shi, A. Mauze, **T. Itoh**, J. S Speck, S. Graham, J. App. Phys. **127**, 54502 (2020).

Results of Simulation



Thank you!