Research & Applications of Thermal Conductivity of Gallium Oxide (Ga_2O_3)

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***Abstract*—This report investigates the high-power applications of gallium oxide (Ga_2O_3) in electronic and optoelectronic devices. Due to its superior electrical properties, gallium oxide has emerged as a promising candidate as a semiconductor material for use in high-power applications. However, its low thermal conductivity presents a significant challenge, limiting the material's overall performance and reliability in recent devices. This research delves into the various innovations developed over recent years from scientific research to address the thermal management issues associated with Ga_2O_3. Surges in popularity show continuous breakthroughs in paving the way for its broader adoption in next-generation electronic devices.**

***Index Terms*—Gallium oxide, thermal conductivity, bandgap, breakdown voltage, semiconductor, high-power electronics**

I. Introduction

With the ever-increasing demand for high-power and high-frequency applications in the realm of electronics, ultra-wide bandgap semiconductors such as gallium oxide (Ga_2O_3) have emerged as the forerunners due to their superior material properties. Despite its qualities, gallium oxide's main weakness revolves around its poor thermal conductivity, as it is rated the worst of all other semiconductors under consideration for high-power applications, such as gallium nitride and silicon carbide. Due to its inability to dissipate heat efficiently, devices operating at high temperatures can quickly lead to overheating and reduced performance, eventually succumbing to device failure. To address this challenge, scientists have been exploring numerous methods, such as focusing on specific polymorphs, utilizing its anisotropic behavior, integrating with composite materials and interlayers, and creating new packaging solutions to enhance the thermal management of Ga_2O_3-based devices. These efforts aim to mitigate the material's weaknesses while preserving the superior electrical properties to pave the way for the future of electronic devices. In this report, we will explore the motivation behind this research, key scientific concepts, theoretical developments, and experimental results that have emerged in recent years. By addressing the thermal challenges of gallium oxide through research and development, we can pave the way for its widespread adoption in high-power electronic devices to ensure both efficiency and reliability in future technologies.

II. Motivations

Gallium oxide is a chemical compound consisting of two gallium atoms and three oxygen atoms, forming a white, transparent crystalline solid. This compound exhibits semiconductor properties, characterized by electrical conductivity that falls between a conductor and an insulator. Due to its superior properties, gallium oxide has emerged as a highly promising material for the future generation of electronic and optoelectronic devices.

	Si	4H-SiC	GaN	β-Ga_2O_3
Bandgap E_g(eV)	1.1	3.3	3.4	4.5
Relative dielectric constant ε	11.8	9.7	9.0	10.2–12.4
Breakdown electric field E_{br}(MV/cm)	0.3	2.5	3.3	>7
Room-temperature electron mobility μ(cm^2/Vs)	1400	1000	1200	~200
Saturation electron velocity V_{sat}(×10^7 cm/s)	1.0	2.0	2.5	1.0–1.5
Thermal conductivity (W/cmK)	1.5	2.7	2.1	0.11–0.27
Baliga's figure of merit (= $\varepsilon\mu E_{br}^3$)	1	340	870	1570–1900
Johnson's figure of merit (= $E_{br}^2 V_{sat}^2$)	1	280	760	540–1200

Figure 1. Material Properties of Silicon, 4H-Silicon Carbide, Gallium Nitride, and B-Gallium Oxide [1]

The table in Figure 1 compares key material properties of traditional semiconductors such as Si, 4H-SiC, GaN, and β-Ga_2O_3, showcasing the superior electrical properties that gallium oxide has over its competitors. One of the main properties of gallium oxide is its ultra-wide bandgap, which ranges from 4.5-4.9 eV. The bandgap of a material is the energy difference between the valence band, where electrons are bound to atoms, and the conduction band, where electrons are free to move and conduct electricity. While a traditional semiconductor typically has a bandgap of 1.1eV, the wide bandgap of gallium oxide enables it to operate at significantly higher voltages and temperatures, making it valuable for high-power applications such as power grids and radar systems. In addition to its wide bandgap, gallium oxide also boasts excellent chemical stability, which is a crucial factor for the longevity and reliability of modern electronic devices. The importance of chemical stability ensures that the material can withstand harsh environments and temperatures without degrading due to any chemical reactions, yet gallium oxide is able to maintain its integrity across a temperature range from room temperature up to its own melting point. Another critical property of gallium oxide is its exceptional breakdown voltage, which refers to the maximum voltage that a material can endure before it begins to conduct electricity uncontrollably. Gallium oxide has a breakdown electric field voltage of around 8MV/cm, which is significantly higher than that of competing semiconductor materials such as silicon or gallium nitride. Higher breakdown voltages contribute to more efficient power systems and enhances the overall performance and reliability for devices undergoing high-voltage operations. Overall, these properties would assume to position gallium oxide as the leading semiconductor material for the future of electronic devices, but what stops it from being such a powerhouse is its absurdly low thermal conductivity. Thermal conductivity (often denoted by k, λ, or κ), refers to the material's intrinsic ability to transfer and conduct heat. For design purposes, it is crucial to choose semiconductor materials with high thermal conductivity for effective heat dissipation, as well as preventing any local hotspots. From Figure 1, we can see that gallium oxide's thermal conductivity is $1/6^{th}$ of Si, $1/8^{th}$ of GaN, and $1/10^{th}$ of 4H-SiC. One of the main reasons for its low rating is the material's inability to conduct holes, due to the structure of the valence band in the material's band structure. Therefore, even if there are any potential dopants that are introduced to create acceptor states, the holes tend to become trapped before they can contribute to any meaningful conduction. Therefore, the motivation for researching the applications of gallium oxide come from finding innovative ways to enhance its thermal management.

III. Key Scientific Concepts

Before delving into the theoretical developments that have been made with gallium oxide over recent years, it is important to understand the versatile categories that it holds. Gallium oxide can exist in several different crystalline structures, which are also known as polymorphs.

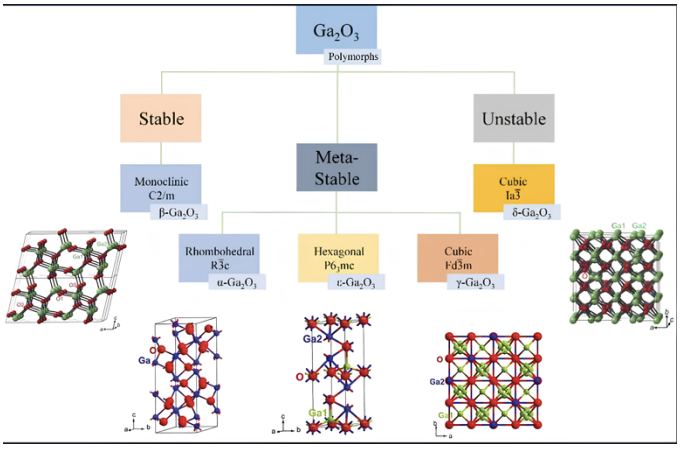

Figure 2. Five different polymorphs of Ga_2O_3 along with their crystal structures and space groups [2]

Each polymorph of gallium oxide possesses distinct structural, electronic, and thermal properties, making them significant for various material applications [3].These polymorphs are donated as α, β, γ, δ, and ϵ, each with its own unique crystal structure and material advantages. The first polymorph, α-Ga_2O_3, has a hexagonal structure and is the most stable polymorph specifically for high temperatures. Despite its stability at elevated temperatures α-Ga_2O_3 is metastable at room temperatures, which limits any mainstream practical use for semiconductor research related to high-power electronic devices. The γ-Ga_2O_3 polymorph, is characterized by a cubic structure, which has a specific configuration that is denoted as the defective spinel polymorph. γ-Ga_2O_3 is mainly used

for gas sensing applications due to its high surface area and it is also metastable, transforming into the β-Ga_2O_3 when placed in higher temperatures. The ϵ-Ga_2O_3 and δ-Ga_2O_3 polymorphs have an orthorhombic and cubic structure respectively, yet there are the least explored and studied in terms of scientific research, due to the metastability of the orthorhombic polymorph and the instability of the cubic polymorph. The β-Ga_2O_3 polymorph resembles a monoclinic structure and is the leading candidate for scientific studies exploring the future of gallium oxide due to its thermodynamic stability, synthesis, easy availability, and its anisotropic thermal conductivity. It is the most stable at room temperature and standard atmospheric pressure, and it can be easily synthesized due to its chemical stability. In terms of thermal conductivity, the anisotropic behavior means that it is direction dependent, which means that conductivity can be higher or lower depending on the crystalline direction. The crystal structure of β-Ga_2O_3 belongs to the point group C2/m, which indicates a two-fold rotation symmetry around an axis, and a mirror plane that exists perpendicular to the axis. The lattice parameters are the physical dimensions that define the geometry and symmetry of the unit cells in a unit cell structure. For β-Ga_2O_3, the lattice parameters are denoted a = 12.214 Å, b = 3.0371 Å, c = 5.7981 Å, β = 103.83°, V = 208.85 Å³, Z = 4, and ρ = 5.961 g/cm³ [3].

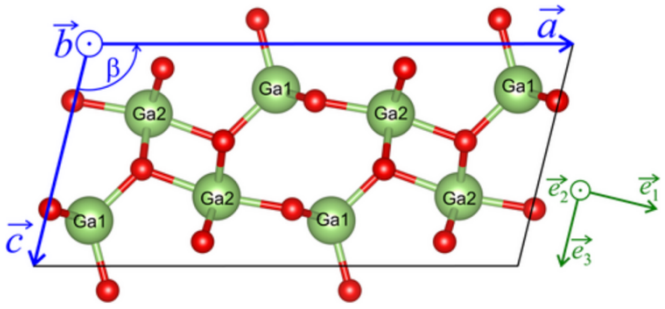

Figure 3. Atomic Unit Cell of β-Ga_2O_3 [3]

In Figure 3, we can see the visual representation of the monoclinic structure's unit cell, represented with eight whole gallium atoms and twelve whole oxygen atoms. In terms of donor dopants, n-type doping can be achieved with impurities such as silicon, germanium, and tin, while p-type doping is seldom seen in scientific research due to its poor hole conduction, but there have been potential acceptor dopants such as magnesium, zinc, and beryllium that may be used in the future.

IV. Key Theoretical Developments

There are many theoretical developments in β-Ga_2O_3 that have shown to enhance the thermal management for future high-power applications. A study by Handwerg et. al [4] investigates the temperature-dependent diffusivity and conductivity of a Mg-doped insulating β-Ga_2O_3 single crystal. Results were measured in three different crystalline directions: [100], [010], and [001] from temperatures in the range from 64-300K. The study uses a thin metal strip heater that is deposited on the surface of the crystal, with an alternating current that passes through the metal strip at a certain frequency, ω.

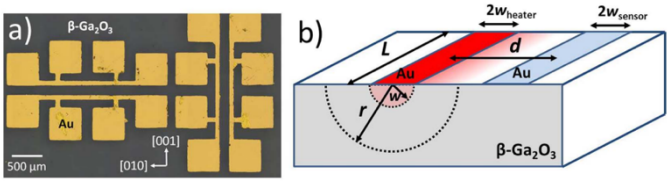

Figure 4a. Two-line heater pairs on Mg-doped β-Ga_2O_3 crystal, b) Measuring temperature flow between two Au lines through the β-Ga_2O_3 crystal [4]

In Figure 4, we can see the arrangement of the two-line heater pairs placed on top of the Mg-doped β-Ga_2O_3 crystal. This setup will cause the temperature of the material underneath the strip to oscillate at a frequency 2ω, and the amplitude and voltage can be extracted to find the thermal diffusivity and conductivity. By changing the orientation of the β-Ga_2O_3 crystal will find different values due to its anisotropy.

axis	L.P. [17]	D	λ	$\lambda_{ex,ref}$[8]	$\lambda_{theo,ref}$[9]
	Å	mm^2s^{-1}	$Wm^{-1}K^{-1}$	$Wm^{-1}K^{-1}$	$Wm^{-1}K^{-1}$
a [100]	12.2	3.7 ± 0.4	11 ± 1	10.9 ± 1.0	16
b [010]	3.0	9.6 ± 0.5	29 ± 2	27.0 ± 2.0	22
c [001]	5.8	7.1 ± 0.4	21 ± 2	15	21

Figure 5) Lattice parameters (L.P), thermal diffusivity D and thermal conductivity (λ) values for different crystalline directions at room temperature [4]

Figure 5 represents the thermal conductivity values for three different crystalline directions as previously mentioned, with additional reference values for comparison. Denoted in the symbol λ, the highest reported thermal conductivity is seen along the [010] direction, at 29 ± 2 W/mK, while the lowest is along the [100] direction, at 11 ± 1 W/mK. These results clearly demonstrate how the anisotropic behavior of the monoclinic β-Ga_2O_3 structure must be used to obtain the potential for the next generation in high-

power applications. Another study by Guo et. al [5] delved into exploring the thermal conductivity of a β-Ga_2O_3 single crystal across four different crystal directions, including [001], [100], [010], and [-201]. The temperatures in the study for the material range between 80-495K, providing a larger subset in terms of both direction and temperature. The study uses a time-domain thermo-reflectance (TDTR) method, which is a pump-probe technique that analyzes the surface temperature of the material after being heated by short pulses of energy with a pump laser. A second probe laser then monitors the changes in reflectivity of the heated area over time.

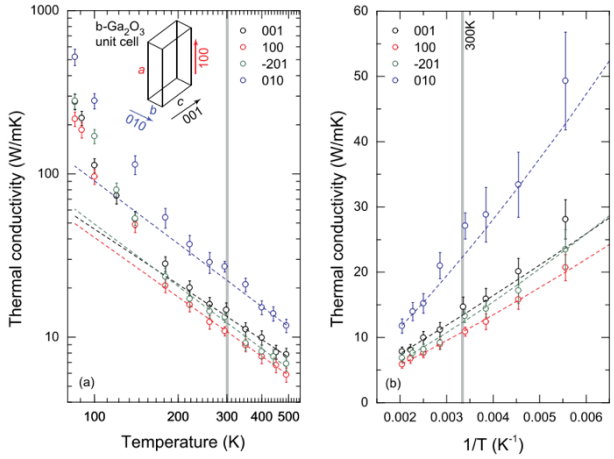

Figure 6. Temperature-dependent thermal conductivity of β-Ga_2O_3 measured along different crystal directions with the TDTR method, (a) shows the thermal conductivity and temperature in logarithmic scale, (b) shows a linear plot of thermal conductivity against 1/T [5]

Figure 6 demonstrates the results of the thermal conductivity values using the TDTR method across all four crystalline directions. The figure demonstrates a linear relationship between temperature and thermal conductivity. From the four crystalline directions, [100] exhibits the lowest thermal conductivity at 10.9 ± 1.0 W/mK, while [010] shows the highest at 27.0 ± 2.0 W/mK. These align with the results compared to the previous study, where [010] seems to be the dominant direction for the thermal conductivity of the monoclinic structure. A study by You. et al. [6] focuses on trying to overcome the heat dissipation limitations of the monoclinic polymorph by integrating Cu-filled thermal vias into a β-Ga_2O_3 Schottky diode. The method utilized was based upon UV laser drilling to form through-vias without producing any crystalline damage and is subsequently followed by Cu electroplating to fill the vias. The temperature changes of the β-Ga_2O_3 Schottky diodes were measured with the use of a high-resolution thermal imaging camera to observe the effects of low application on the diodes as seen in Figure 7.

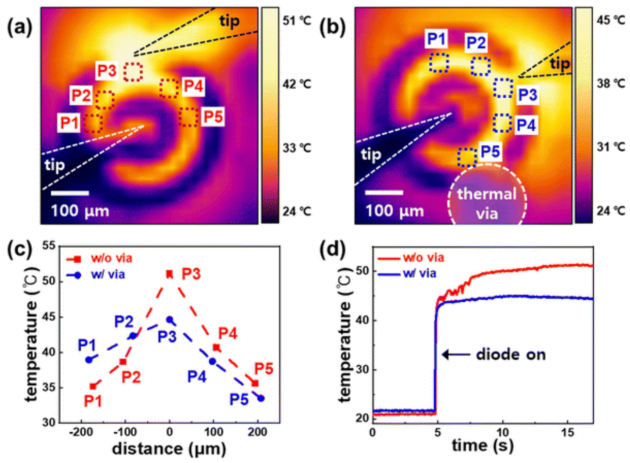

Figure 7. Infrared camera images of β-Ga_2O_3 Schottky diodes (a) without and (b) with thermal via after low power application; (c) peak temperature profiles of dotted boxes in (a) and (b); (d) Peak temperature profiles of P3 spots in (a) and (b) [6]

Based on the infrared images shown in Figure 7, the study achieved significant improvements, including a 21% reduction in temperature at a power density of 5.7 W/mm³, a 90% decrease in the time required to reach steady-state peak temperature, a 33% reduction in temperature with the implementation of thermal vias, and an over 40% improvement in heat dissipation with the use of multiple thermal vias positioned near the channel. These enhancements are crucial for improving the thermal management of β-Ga_2O_3 devices, which show the potential in enabling more reliable and efficient operation in high-power applications.

V. Key Experimental Results

Reflecting the surging interest in overcoming the thermal management challenges of β-Ga_2O_3 devices, numerous studies have demonstrated experimental results that showcase new and inventive solutions that have promising potential for future developments. To start, we first need to introduce the single crystal β-Ga_2O_3 metal semiconductor field-effect transistor, also known as the MESFET [7]. The MESFET was the first demonstration to use single-crystal β-Ga_2O_3 transistors that were based on a

300nm thick Sn-doped n-Ga_2O_3 channel layer grown on a Mg-doped β-Ga_2O_3 [010] substrate. It is also the first experimental attempt in terms of fabricating field-effect transistors with gallium oxide, which turned out to have satisfactory electrical values, including a maximum drain current of 15mA/mm, a drain voltage of 40V, and a large three-terminal off-state voltage of 250V. The success of the initial MESFET experiment is what opened the door for many future β-Ga_2O_3 based FETS for mainstream applications in the world of power electronics, with thermal managements as the core priority to overcome.

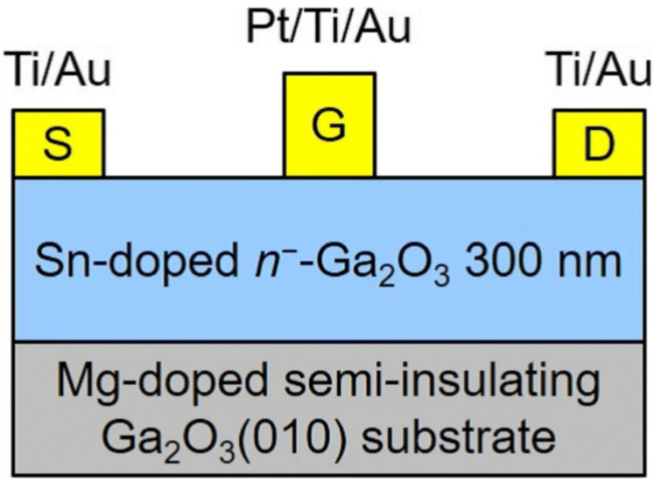

Figure 8. Schematic cross-section of β-Ga_2O_3 MESFET [7]

In Figure 8, we can also see that the source and drain contacts are composed of titanium and gold, with an additional layer of platinum as they form well for ohmic contacts with the β-Ga_2O_3 material. However, the ohmic contacts were poor in design and value and the overall transistor succumbed to small surface leakage. Despite its flaws, it was the introduction to the future of β-Ga_2O_3 devices for high-power applications.

In recent events, Wang et. al [8] discusses the development of a 15A β-Ga_2O_3 Schottky barrier diode (SBD) that can achieve low thermal resistance and enhance thermal conductivity. The main innovation in their approach lies in its double-sided packaging, which enhances the thermal management by allowing heat to be extracted directly from the junction, completely bypassing the β-Ga_2O_3 chip. In comparison, traditional bottom-side cooling typically has a thermal resistance of around 1.43 K/W. The new double-sided approach lowers the thermal conductivity significantly down to 0.5 K/W when cooled from the junction, which outperforms even silicon carbide Schottky rectifiers in comparison, as seen in Figure 9.

Device	Package	Package Size* (mm^2)	V_{ON} (V)	I_F (A) ** @ 2 V	Cooling	$R_{\theta JC}$ (K/W)
Ga_2O_3 SBD (this work)	Double-side	7.3×7.3	0.83	13	Junction Bottom	0.5 1.43
SiC SBD (C3D10060G)	TO-263-2	6.5×7.9	0.85	18	Bottom	1.2
SiC SBD (E3D08065G)	TO-263-2	6.5×7.9	0.85	14.5	Bottom	1.47
SiC SBD (C6D04065E)	TO-252-2	5.2×4.3	0.85	12	Bottom	2.89
Ga_2O_3 SBD [14]	no package		~1	~0.02	Bottom	~4.5

*Size of the die-attached thermal pad. **Forward current at 2 V.

Figure 9. Thermal Resistance comparison between β-Ga_2O_3 SBDs and commercial SiC SBDs with similar current ratings and package sizes [8]

The study suggests the importance in proper packaging solutions to enhance thermal management, as it is the forerunner against semiconductor materials with significantly higher thermal conductivities.

A study by Malakoutian et. al [9] discusses the development to improve the thermal conductivity of β-Ga_2O_3 by growing a polycrystalline diamond layer onto its surface, due to its exceptionally superior thermal conductivity values. The method was to utilize a microwave plasma chemical vapor deposition technique (CVD) to allow diamond growth onto the β-Ga_2O_3.

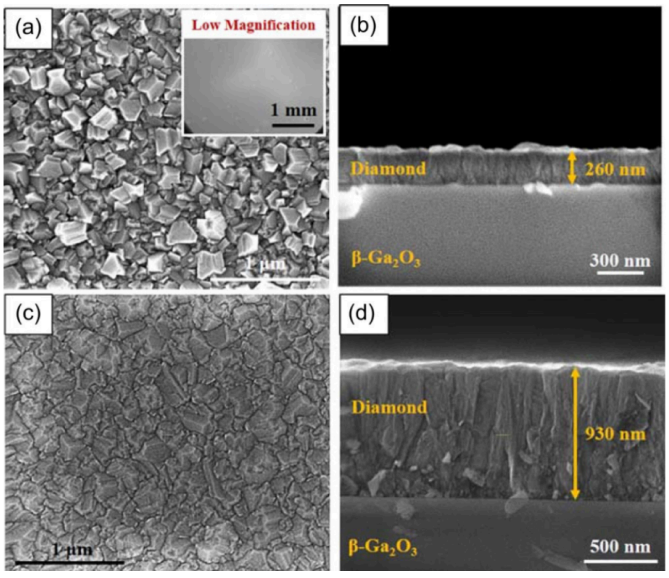

Figure 10. (a) and (b) 260nm diamond on 19nm β-Ga_2O_3 *(c) and (d) 930nm diamond on 100nm* β-Ga_2O_3 [9]

Figure 10 shows SEM images of substantial

diamond growth on the β-Ga_2O_3 surface in different lengths. In terms of quantitative results, the thermal conductivity reached a maximum of 110 ± 33 W/mK, a significant improvement over the previous studies with β-Ga_2O_3. Polycrystalline diamond is also much more affordable than using single-crystal diamond, especially for large wafer synthesis and efficient for growth onto β-Ga_2O_3.

VI. Future Prospects

Research continues to spike in popularity for β-Ga_2O_3, and there are many future goals that scientists are hoping to achieve to overcome the weakness of its properties.

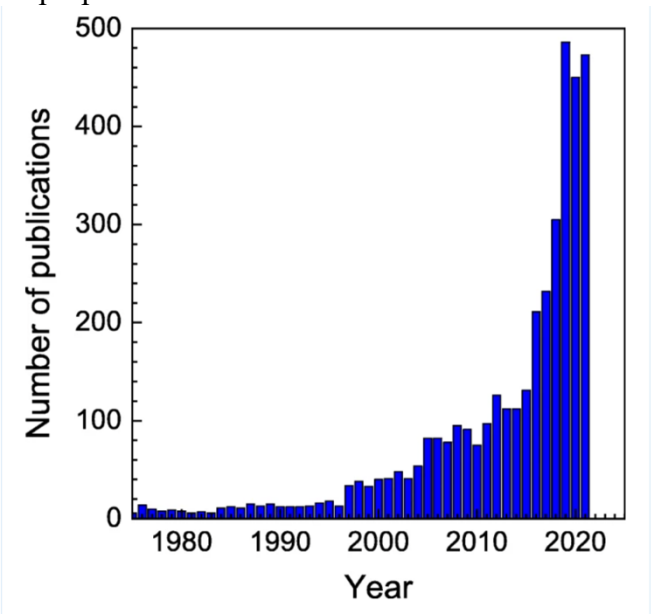

Figure 11. Number of publications on Ga_2O_3 from 1975 to 2020. The papers were searched with criterion of containing β-Ga_2O_3 [10]

However, there are several goals that future researchers should investigate. The first idea is integrating β-Ga_2O_3 with materials that have higher thermal conductivity ratings, such as polycrystalline diamond and other ultra-wide bandgap semiconductors to help dissipate heat more effectively. Also, due to the anisotropic symmetry of β-Ga_2O_3 , it is important to maximize the use of aligning crystals in the orientation where the thermal conductivity is most favorable. Although low thermal conductivity in β-Ga_2O_3 will be inevitably low, it will have to require innovative packaging solutions to manage heat dissipation efficiently with careful design considerations. Another way is to look at improving the thermal boundary conductance between β-Ga_2O_3 and the other substrate layers, particularly the use of interlayers to help enhance the heat transfer across interfaces. With the recent increase in interest, innovative developments for β-Ga_2O_3 are beginning to surface, and we will expect to see devices incorporating these advancements soon.

References

[1] Xue, HuiWen, et al. “An overview of the ultrawide bandgap Ga2O3 semiconductor based Schottky barrier diode for power electronics application.” *Nanoscale Research Letters*, vol. 13, no. 1, 19 Sept. 2018, https://doi.org/10.1186/s11671-018-2712-1.

[2] Lu, Chao, et al. “A review of metal–semiconductor contacts for β-ga2O3.” *Journal of Physics D: Applied Physics*, vol. 55, no. 46, 23 Sept. 2022, p. 463002, https://doi.org/10.1088/1361-6463/ac8818.

[3] Klimm, Detlef, et al. “The thermal conductivity tensor of β-ga2O3 from 300 to 1275 K.” *Crystal Research and Technology*, vol. 58, no. 2, 5 Dec. 2022, https://doi.org/10.1002/crat.202200204.

[4] Handwerg, M, et al. “Temperature-dependent thermal conductivity and diffusivity of a MG-doped insulatingβ-ga2O3 single crystal along [100], [010] and [001].” Semiconductor Science and Technology, vol. 31, no. 12, 8 Nov. 2016, p. 125006, https://doi.org/10.1088/0268-1242/31/12/125006.

[5] Guo, Zhi, et al. “Anisotropic thermal conductivity in single crystal β-gallium oxide.” Applied Physics Letters, vol. 106, no. 11, 16 Mar. 2015, https://doi.org/10.1063/1.4916078.

[6] You, Younghyun, et al. “Enhancement of heat dissipation in β-ga2O3 schottky diodes through Cu-filled thermal vias: Experimental and simulation investigations.” Journal of Materials Chemistry C, vol. 12, no. 29, 2024, pp. 11094–11102, https://doi.org/10.1039/d4tc01811g.

[7] Higashiwaki, Masataka, et al. “Gallium Oxide (ga2o3) metal-semiconductor field-effect transistors on single-crystal β-ga2o3 (010) substrates.” Applied Physics Letters, vol. 100, no. 1, 2 Jan. 2012, https://doi.org/10.1063/1.3674287.

[8] Wang, Boyan, et al. “Low thermal resistance (0.5 K/w) ga2o3 schottky rectifiers with double-side packaging.” IEEE Electron Device Letters, vol. 42, no. 8, Aug. 2021, pp. 1132–1135, https://doi.org/10.1109/led.2021.3089035.

[9] Malakoutian, Mohamadali, et al. “Polycrystalline diamond growth on β-ga2O3 for thermal management.” Applied Physics Express, vol. 14, no. 5, 16 Apr. 2021, p. 055502, https://doi.org/10.35848/1882-0786/abf4f1.

[10] Higashiwaki, Masataka. “B-GA2O3 material properties, growth technologies, and devices: A Review.” *AAPPS Bulletin*, vol. 32, no. 1, 17 Jan. 2022, https://doi.org/10.1007/s43673-021-00033-0.