A simplified method of measuring thermal conductivity of $\beta$-Ga$_2$O$_3$ nanomembrane

Yixiong Zheng and Jung-Hun Seo

Department of Materials Design and Innovation, University of Buffalo, the State University of New York (SUNY), Buffalo, NY 14260, United States of America

E-mail: junghuns@buffalo.edu

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Abstract

In this work, we report a simplified method to measure thermal conductivity from the typical Raman thermometry method by employing a much simpler dispersion relationship equation and the Debye function, instead of solving the heat equation. Unlike the typical Raman thermometry method, our new method only requires monitoring of the temperature-dependent Raman mode shifting without considering laser power-dependent Raman mode shifting. Thus, this new calculation method offers a simpler way to calculate the thermal conductivity of materials with great precision. As a model system, the $\beta$-Ga$_2$O$_3$ nanomembrane (NM) on a diamond substrate was prepared to measure thermal conductivity of $\beta$-Ga$_2$O$_3$ NMs at different thicknesses (100 nm, 1000 nm, and 4000 nm). Furthermore, the phonon penetration depth was investigated to understand how deep phonons can be dispersed in the sample so as to guide the dimensional design parameter of the device from the thermal management perspective.

1. Introduction

In recent years, $\beta$-Ga$_2$O$_3$ has been studied as a next-generation ultra-wide bandgap semiconductor due to several notable properties. $\beta$-Ga$_2$O$_3$ has an ultra-wide bandgap ($\sim$4.9 eV) [1–3], a high breakdown electric field (8 MV cm$^{-1}$) [4], as well as decent electron mobility (300 cm$^2$/Vs), and all of these excellent electrical and optical properties give rise to the possibility of applying $\beta$-Ga$_2$O$_3$ in high power and ultra-violet optoelectronic applications [1, 5–7]. These applications typically generate a substantial degree of heat during the operation; thus, such joule heating could lead to the active region temperature by increasing tens or even over one hundred degrees above ambient temperature. However, one critical drawback of $\beta$-Ga$_2$O$_3$ is its extremely low thermal conductivity ($10 \sim 30$ W m$^{-1}$ K$^{-1}$) compared to other wide bandgap semiconductors, for example, aluminum nitride (AlN) at $\sim$200 W m$^{-1}$ K$^{-1}$ [8], gallium nitride (GaN) at $\sim$170 W m$^{-1}$ K$^{-1}$ [9], and silicon carbide (SiC) at 387 W m$^{-1}$ K$^{-1}$ [10].

The poor thermal property can limit the performance of $\beta$-Ga$_2$O$_3$-based applications. Another and perhaps more critical issue in $\beta$-Ga$_2$O$_3$ is the lack of an efficient dopant. It is known that n-type $\beta$-Ga$_2$O$_3$ can be grown using C, Si, or Sn [11], but no efficient p-type dopants were found. Previous theoretical calculations have predicted that it is difficult to grow p-type $\beta$-Ga$_2$O$_3$ because holes have robust self-localization as a result of the ionicity of metallic oxides [12–16]. Thus, it can be estimated that the hole mobility would give an extremely small value of $10^{-6}$ cm$^2$/V $\cdot$ s indicating insignificant p-type conductivity of $\beta$-Ga$_2$O$_3$, even if it is possible to introduce holes into the material. In order to circumvent these two serious technical challenges in $\beta$-Ga$_2$O$_3$, various heterogeneous integration methods have been proposed such as [17–19].

In this paper, a sub-micron thick freestanding $\beta$-Ga$_2$O$_3$ layer, also called a $\beta$-Ga$_2$O$_3$ nanomembrane(NM), was used to create a $\beta$-Ga$_2$O$_3$/diamond heterostructure using a layer transfer printing method. As is known, the $\beta$-Ga$_2$O$_3$/diamond heterostructure offers two beneficial properties: (1) extremely high thermal conductivity ($\sim$2200 W m$^{-1}$ K$^{-1}$) and, (2) it can be used as a p-type doped semiconductor, which can possibly fulfill the aforementioned lacking properties of $\beta$-Ga$_2$O$_3$ [1, 20, 21]. Based on this heterostructure, the thermal
conductivity of $\beta$-Ga$_2$O$_3$ NM was measured using the peak shifting of the Raman spectrum. To measure the thermal conductivity of a material, three different methods have been commonly used. The first method is the electrical 3$\omega$-method, which uses a thin metal heater to apply a pulsed current to generate heat to the target sample [22]. However, the 3$\omega$-method requires a micro-fabrication process that leads to additional time for the sample preparation and is sometimes destructive to samples, especially when the sample is brittle or soft [23]. The second method is a time-domain thermoreflectance (TDTR) method that uses the reflectance of the sample surface under different temperature conditions [24]. However, it is inevitable to have a higher degree of errors that are mainly associated with the phase errors in various optical components. This method also requires a thin metal layer on top of the target material to measure thermal conductivity. Recently, a Raman thermometry method, which is based on the micro-Raman spectroscopy, was used by capturing the changes in Raman vibrational modes. It is very sensitive to the thermally-induced molecular vibrations and thus has been used to investigate the thermal properties of two-dimensional materials [25]. Also, it is a contactless method that does not require any micro-fabrication, thus the thermal property of various forms of samples can be measured. We have recently employed the Raman thermometry method to investigate the thermal property of $\beta$-Ga$_2$O$_3$ and successfully extract the thermal conductivity of $\beta$-Ga$_2$O$_3$ [26]. While it was the first thermal conductivity study of $\beta$-Ga$_2$O$_3$ NM using the Raman thermometry method, it has several technical challenges that can potentially create errors. A typical Raman thermometry measurement requires modified micro-Raman spectroscopy that includes a transmittance controller and a power meter. This method also requires multiple steps to calculate the heat distribution of the spot on which the Raman laser is shined. In general, it requires two types of objective lenses that have different magnification, for example, 50$\times$ and 100$\times$ objective lenses. These lenses are used to measure the Raman spectra of the sample under different temperatures, followed by another Raman spectroscopy measurement under different laser powers at each temperature point using these two different objective lenses. To extract thermal conductivity, it requires solving the heat equation, which involves a Gaussian profile laser source, and the estimation of the heat absorption by the laser power during the calculation can lead to inevitable errors in thermal conductivity values.

The primary objective of this paper is to provide a new calculation method for the thermal conductivity measurement from the Raman spectrum by solving a much simpler dispersion relationship equation and Debye function instead of solving the heat equation. Unlike the typical Raman thermometry method, our new method only requires temperature dependent Raman mode shifting monitoring without considering laser power dependent Raman mode shifting. Thus, this new calculation method offers a simpler way to calculate the thermal conductivity of materials.

2. Experimental part

2.1. Measurement setup
A new Raman thermometry method is based on a conventional micro-Raman spectroscopy as illustrated in figure S1(b) is available online at stacks.iop.org/NANOX/1/030010/mmedia. As described, the transmittance controller for changing the amount of Joule heating to the sample is not needed in the new method because the Raman mode shifting as a function of the laser power is not needed. Instead, temperature-dependent Raman mode shifting is needed because it represents thermally-induced lattice vibration. For a similar reason, the new Raman thermometry method does not require a set of Raman spectra measured using different objective lenses to apply different Joule heating to the sample [27]. The idea behind our new Raman thermometry was inspired by the Raman scattering mechanism as shown in figures 1(a) and (b). The Raman spectrum represents the phonon vibrational modes under specific conditions. In this method, Raman peaks will shift to a lower energy region as the temperature increases. For $\beta$-Ga$_2$O$_3$, 30 phonon vibrational modes exist, and 27 of them are optical modes. Among them, we choose the $A_g^{(3)}$ phonon mode to study the thermal property of $\beta$-Ga$_2$O$_3$ NM as shown in figure 1(c), because the $A_g^{(3)}$ phonon mode is one of the prominent Raman peaks of $\beta$-Ga$_2$O$_3$ [28, 29]. As shown in figure 1(b), only one photon out of $10^{16}$ incident photons could exist after Raman scattering, indicating the lower energy than that of initial photons due to photon-to-phonon scattering within $\beta$-Ga$_2$O$_3$ NM [30]. Therefore, combining Raman shifting with the dispersion relationship equation allows us to calculate the angular frequency of phonon vibrational mode within $\beta$-Ga$_2$O$_3$ NM, thus allowing us to extract the thermal conductivity of $\beta$-Ga$_2$O$_3$ NM. In addition, the Tempered Levy super-diffusive theory [31] enables us to calculate the phonon penetration depth by considering a phonon-phonon scattering and phonon-boundary scattering mechanisms. In this study, as shown in figure S1(b), the Raman (Renishaw InVia) measurement temperature ranged from 100 K to 500 K with a 40 K interval. We used 20$\times$ and 5$\times$ objective lenses to capture Raman spectra in addition to comparing thermal conductivity values from each objective lens (figures S3–S5). It should be noted that higher magnification in the objective lens generates a higher Joule heating in the sample, thus leading
to a wider Raman peak shifting. For each temperature point, the Raman settings were: 514 nm green laser with a grating 2400 l/mm, exposure time of 10 s with a three accumulation.

2.2. Sample preparation

In this work, the $\beta$-Ga$_2$O$_3$ thin films were prepared using a mechanical exfoliation method from a bulk phase in which $\beta$-Ga$_2$O$_3$ had a $(-201)$ crystal orientation (Sn doped with $1 \times 10^{18}$ cm$^{-3}$ donor concentration; Novel Crystal Technology). First, as shown in figures S2(a), (b), the wafer was cleaved into small pieces, followed by mechanical exfoliation using the well-known Scotch tape method [32–34]. It should be noted that the surface crystal orientation became $(100)$ after exfoliation because $\beta$-Ga$_2$O$_3$ has relatively weaker bonding toward a $(100)$ direction as compared to other directions. After this step, sub-micron thin and free-standing form of $\beta$-Ga$_2$O$_3$ fakes can be called $\beta$-Ga$_2$O$_3$ nanomembranes (NMs) (figure S2(c)). After $\beta$-Ga$_2$O$_3$ nanomembranes with the desired thickness were obtained, we carefully transfer-printed them onto a single crystalline diamond substrate (undoped $(100)$ diamond) using a kinetically controlled transfer printing method using an elastomeric stamp (PDMS, Polydimethylsiloxane) [35], which doesn’t involve any adhesive material between $\beta$-Ga$_2$O$_3$ nanomembrane and diamond substrate to form an intimate contact. (Figures S2(d)–(f)). The desired thickness and the details about how to assure the thickness value to be accurate can be found in our previous study [26]. Our $\beta$-Ga$_2$O$_3$ NM samples are shown in figures 1(d)–(f), which were accurately characterized by a three-dimensional surface profilometer (Profilm3D Filmetrics) with a spatial resolution of <5 nm. The three $\beta$-Ga$_2$O$_3$ NMs thicknesses are 100 nm, 1000 nm, and 4000 nm, with a typical width of 40 μm. Surface morphologies of both $\beta$-Ga$_2$O$_3$ NM and diamond present the roughness less than 0.5 nm as shown in the atomic force microscopy (AFM) image of figure S1(a). The diameters of the laser spot of 5× and 20× objective lenses in the micro-Raman spectroscopy were measured with the knife-edge method [36] yielding 2.5 μm and 1.5 μm, respectively, thus the laser spot sizes were much smaller than the width of $\beta$-Ga$_2$O$_3$ NM (~40 μm). Prior to $\beta$-Ga$_2$O$_3$ NM transfer-printing, the diamond substrate was thoroughly cleaned using an ammonium sulphuric acid solution for 30 min at 200 °C and then rinsed in an ammonium hydroxide/hydrogen peroxide solution, followed by a deionized water rinse to obtain a contaminant-free and native oxide-free surface. After the transfer-printing, the samples were annealed at 300 °C for 1 min in the rapid thermal annealing (RTA) system to enhance the bonding strength.

3. Results and discussion

The stable form of Ga$_2$O$_3$ under ambient conditions is monoclinic $\beta$-Ga$_2$O$_3$, which belongs to the space group C2/m in international notation. The primitive unit cell of $\beta$-Ga$_2$O$_3$ consists of 10 atoms which lead to 30

![Figure 1](image-url)
phonon modes of which 27 are optical modes and the other three modes are acoustic modes [28]. From the 27 optical modes, we chose the A\(^{(1)}\) phonon mode to study the thermal property of \(\beta\)-Ga\(_2\)O\(_3\) NM, because the A\(^{(3)}\) phonon mode is one of the prominent Raman peaks of \(\beta\)-Ga\(_2\)O\(_3\) [29]. In this work, we investigated Raman peak shifting as a function of temperature using the dispersion relationship between angular frequency and wave vector as shown in the following equation [37]:

\[
\omega^2 = \frac{2\beta}{Mm}(M + m) \left[ 1 - \frac{Mm}{(M + m)^2} \sin^2 (q\lambda)^2 \right]
\]  

\(\omega\) is the angular frequency, \(\beta\) is the force constant which measures the strength of interatomic bonds, \(M\) is the mass of the relatively heavy atom, which is the Ga atom in \(\beta\)-Ga\(_2\)O\(_3\), and \(m\) is the mass of the light atom, which is the O atom in \(\beta\)-Ga\(_2\)O\(_3\), \(a\) is the lattice constant of the crystal, and \(q\) is the wave vector of \(\beta\)-Ga\(_2\)O\(_3\) NM. The angular frequency represents the vibration modes of \(\beta\)-Ga\(_2\)O\(_3\) NM, and the wave vector can be calculated by equation (2) [38]:

\[
q = \frac{2\pi}{\lambda}
\]  

Here, we need to consider a three-dimensional (3D) \(\beta\)-Ga\(_2\)O\(_3\) NM structure, while the dispersion relationship only can be evaluated as a one-dimensional (1D) structure. Regarding this different dimensionality, a 3D atom vibration can be viewed as a 3D harmonic oscillator, thus a 3D harmonic oscillator vibration can be viewed as three independent 1D harmonic oscillator vibrations according to the solid heat capacity theory and the Born–Oppenheimer approximation [39]. Therefore, it is possible to use the 1D dispersion relationship equation to calculate thermal conductivity of \(\beta\)-Ga\(_2\)O\(_3\) NM. Thus, the thermal conductivity \((k)\) can be calculated as described below [40]:

\[
k = \frac{1}{3} c \cdot v \cdot l
\]  

where \(c\) represents the specific heat, \(v\) is the phonons’ velocity, and \(l\) is the mean free path. Then, the specific heat can be calculated by Debye model of the specific heat, under the Debye approximation, and the heat capacity per unit volume at constant volume can be given by equation (4) [41]:

\[
G_v = 3NkD_v \left( \frac{\theta}{T} \right)
\]  

where \(N\) is the Avogadro number, \(k\) is the Boltzmann constant, \(\theta\) is the Debye temperature, and \(T\) is the absolute temperature, in equation (4), the quantity \(D_v(x)\) is defined as [41]:

\[
D_v(x) = \frac{3}{\theta^3} \int_0^{x_0} \frac{x^3 e^x}{(e^x - 1)^2} dx
\]  

where \(x_0 = \frac{\theta}{k}\), which is a scale factor for obtaining the Debye specific heat. The Debye temperature is defined by equation (6) [42]:

\[
\theta = \frac{\hbar \nu_D}{k}
\]  

where \(\hbar\) is Planck’s constant, \(k\) is the Boltzmann’s constant, and \(\nu_D\) is the Debye frequency.

Figure 2 shows Raman shifting as a function of temperature from 100 K to 500 K with a 40 K interval using two different objective lenses, namely, 5× (figures 2(a)–(c)) and 20× objective lenses (figures 2(d)–(f)). From the slope of each case, the relationship of Raman peak shifting with respect to temperature can be extracted. Also, the wavelength could be converted from the wavenumber of Raman shifting based on equation (7):

\[
\lambda (m) = 0.01 / \text{wavenumber} (\text{cm}^{-1})
\]  

Afterward, using equation (1), the angular frequency which represents the vibrational or rotational modes can be calculated by plugging the value of the wave vector into the equation. Then, the frequency of the wave vector can be extracted by equation (8) [38]:

\[
f = \frac{\omega}{2\pi}
\]  

From equation (8), a velocity of the phonon can be calculated by equation (9):

\[
\nu = \lambda \cdot f
\]  

To calculate thermal conductivity from the equation (3), the mean free path of the phonon in \(\beta\)-Ga\(_2\)O\(_3\) NM needs to be calculated using the empirical relationship as described in equation (10) [43, 44]. The mean free path result is shown in figure 3.
Once the specific heat of $\beta$-Ga$_2$O$_3$ NM, the phonon velocity, and mean free path values are calculated, the thermal conductivity ($k$) can be obtained using equation (3). Figure 4 shows the thermal conductivity of $\beta$-Ga$_2$O$_3$ NM measured with both the 5x and 20x objective lenses. Both cases show similar thermal conductivity values of 38.93 W m$^{-1}$ K$^{-1}$, 81.75 W m$^{-1}$ K$^{-1}$ and 120.39 W m$^{-1}$ K$^{-1}$ for 100 nm, 1000 nm, and 4000 nm thick $\beta$-Ga$_2$O$_3$ NM, respectively at 100 K, and gradually reduced to 2.75 W m$^{-1}$ K$^{-1}$, 9.28 W m$^{-1}$ K$^{-1}$, and 17.13 W m$^{-1}$ K$^{-1}$ at 300 K for 100 nm, 1000 nm, 4000 nm thick $\beta$-Ga$_2$O$_3$ NM. The different thermal conductivity ($k$) of 100 nm-, 1000 nm-, and 4000 nm- thick $\beta$-Ga$_2$O$_3$ NMs can be explained by a kinetic theory-based model which describes the phonon-boundary scattering of thin-films with different thicknesses [45,46].

\[ l = 0.8 \cdot T^{-3.3} \text{ (nm} \cdot \text{K}^{3.3}) \]  

(10)

Figure 2. Raman shifts as a function of temperature taken from three different $\beta$-Ga$_2$O$_3$ NM thicknesses using two different objective lenses. Raman shifts were measured using ((a), (b), and (c)) a 5x objective lens and ((d), (e), and (f)) a 20x objective lens for 100 nm-, 1000 nm-, and 4000 nm-thick $\beta$-Ga$_2$O$_3$ NM, respectively. The dashed lines were drawn to aid the trend of data points.

Figure 3. Calculated mean free path of phonons in $\beta$-Ga$_2$O$_3$ NM with respect to temperature. The dashed lines were drawn to aid the trend of data points.
$k = \frac{1}{3} \sum_{j=1}^{3} \int_{0}^{\omega_{\text{max}}} \hbar \omega D_j(\omega) \frac{\partial f_{\text{BE}}}{\partial T} \phi_j(\omega) \times \left( \frac{1}{\tau_{\gamma}} + \frac{1}{\tau_{U}} + \frac{\nu_j(\omega)}{d} \right)^{-1} d\omega$ 

where $D$ is the phonon density of states (DOS), $\partial f_{\text{BE}} / \partial T$ is the temperature derivative of the Bose–Einstein distribution function, and the subscript $j$ denotes the branch in the phonon dispersion spectrum. Other parameters, $1/\tau_{\gamma}$, $1/\tau_{U}$, $d$, are the phonon–impurity scattering rate, the Umklapp scattering rate, the film thickness, respectively. Among these last three parameters, the phonon-boundary scattering rate is dominant over the phonon–impurity scattering rate and the Umklapp scattering rate, which suggests that the thickness dependence of through-plane thermal conductivity values of three $\beta$-$\text{Ga}_2\text{O}_3$ NMs (i.e., 100 nm-, 1000 nm-, and 4000 nm-thick $\beta$-$\text{Ga}_2\text{O}_3$ NMs) is attributed to the phonon-boundary scattering which is sensitive to the thickness of the thin-film. Therefore, more boundary scatters occurred as the thickness of $\beta$-$\text{Ga}_2\text{O}_3$ NM gets thinner and as a result, the phonon mean free paths become relatively smaller, thus thermal conductivity of $\beta$-$\text{Ga}_2\text{O}_3$ NMs are reduced. This result also agrees well with our previous study in addition to results from other groups [23, 26, 47]. The specific heat calculated by the Debye model is shown in figure 5(a). The specific heat of $\beta$-$\text{Ga}_2\text{O}_3$ NM was calculated using equation (4), which agrees well with results from the literature [40]. In addition, the depth of phonon energy was investigated by the Tempered Levy super-diffusive theory [31]. This value represents how far or how deep the phonon energy can be transmitted or penetrate into $\beta$-$\text{Ga}_2\text{O}_3$ NM. In order to obtain the penetration depth of phonons, a phonon should have a ‘quasi-particle’ characteristic with a
quasi-ballistic thermal transport property as shown in equation (11):

\[ L = \frac{k}{g} \]  

(11)

where \( g \) represents the thermal boundary conductance (TBC) which between \( \beta\text{-Ga}_2\text{O}_3 \) NM and diamond substrate. In this calculation, we obtained the TBC value from our previous study [26] and another reference [47], because both results have a \( \beta\text{-Ga}_2\text{O}_3 \) NM/diamond heterostructure that was prepared by the mechanical exfoliation method. The penetration depth of the phonon is shown in figure 5(b). As seen in this figure, the quasi-ballistic penetration depth of phonon at 300 K for 100 nm, 1000 nm and 4000 nm thick \( \beta\text{-Ga}_2\text{O}_3 \) NM were measured to be 300 nm, 755 nm, and 1400 nm, respectively.

To investigate more about the photon transport across the \( \beta\text{-Ga}_2\text{O}_3 \) NM/diamond interface, namely thermal boundary conductance (TBC, \( g \)) between \( \beta\text{-Ga}_2\text{O}_3 \) NM and diamond, a Landauer approach was employed with transmission function from the diffuse mismatch model [47]:

\[
 g = \sum_p \frac{1}{2} \int_0^{\infty} D_1(\omega) \frac{df_{BE}}{d\omega} \omega \tau_2(\omega) \tau_2(\theta, \omega) \times \cos \theta \sin \theta d\omega
\]

where, D is the phonon density of states (DOS), \( f_{BE} \) is the Bose–Einstein distribution function, \( \omega \) is the phonon angular frequency, \( \nu \) is the phonon group velocity of material 1 (\( \beta\text{-Ga}_2\text{O}_3 \) NM in our case), \( \tau_2 \) is the transmission coefficient from material 1 (\( \beta\text{-Ga}_2\text{O}_3 \) NM) to 2 (diamond substrate). From this relationship as predicted in [47], when the TBC is smaller than \( \sim 70 \text{ MW m}^{-2} \text{ K} \), it becomes a dominant factor limiting heat dissipation. On the other hand, when the TBC is higher than \( \sim 70 \text{ MW m}^{-2} \text{ K} \), substrate thermal conductivity becomes a dominant factor that limits device heat dissipation. Considering that poor thermal conductivity and thermal boundary conductance of most of wide bandgap semiconductors (e.g., \( \text{GaN-on-SiC} \) (3.3 MW/(m²·K)), \( \text{GaN-on-sapphire} \) (12 MW/(m²·K)) [48], it is always better to have a substrate that has a higher thermal conductivity. In this sense, the diamond substrate in our study can act as a heat sink, thus it is possible to enhance the overall thermal property of \( \beta\text{-Ga}_2\text{O}_3 \) when it is formed on a diamond substrate. More accurately, the phonon penetration depth gives us guidance on the choice of a dimensional design parameter of the device from the thermal management perspective. For example, as shown for the 100 nm thick \( \beta\text{-Ga}_2\text{O}_3 \) NM case, the phonon penetration depth (300 nm) is much larger than the thickness of \( \beta\text{-Ga}_2\text{O}_3 \) NM itself, which indicates that heat generated in \( \beta\text{-Ga}_2\text{O}_3 \) NM can be dispersed to the diamond substrate. As a result, the diamond substrate can act as an effective heat dissipation layer. On the other hand, if the thickness of \( \beta\text{-Ga}_2\text{O}_3 \) NM is thicker than the phonon penetration depth, as shown in 1000 nm and 4000 nm \( \beta\text{-Ga}_2\text{O}_3 \) NMs, heat cannot be dissipated to the diamond efficiently and \( \beta\text{-Ga}_2\text{O}_3 \) NM will be heated faster. Thus, thermal conductivity of \( \beta\text{-Ga}_2\text{O}_3 \) NM will decrease significantly as shown in figure 4.

4. Conclusion

In this work, we report a simplified method to measure thermal conductivity from the typical Raman thermometry method by employing a much simpler dispersion relationship equation and the Debye function, instead of solving the heat equation. Unlike the typical Raman thermometry method, our new method only requires monitoring of the temperature-dependent Raman mode shifting without considering laser power-dependent Raman mode shifting. Thus, this new calculation method offers a simpler way to calculate the thermal conductivity of materials. As a model system, the \( \text{b-Ga}_2\text{O}_3 \) nanomembrane (NM) on a diamond substrate was prepared to measure thermal conductivity of \( \text{b-Ga}_2\text{O}_3 \) NMs at different thicknesses (100 nm, 1000 nm, and 4000 nm). The result shows thermal conductivity of 38.93 W m⁻¹ K⁻¹, 81.75 W m⁻¹ K⁻¹, and 120.39 W m⁻¹ K⁻¹ for 100 nm, 1000 nm, and 4000 nm thick \( \text{b-Ga}_2\text{O}_3 \) NM, respectively at 100 K, and gradually reduced to 2.75 W m⁻¹ K⁻¹, 9.28 W m⁻¹ K⁻¹ and 17.13 W m⁻¹ K⁻¹ at 300 K for 100 nm, 1000 nm, 4000 nm thick \( \text{b-Ga}_2\text{O}_3 \) NM, respectively. Furthermore, the phonon penetration depth was investigated to understand how deep phonons can be dispersed in the sample so as to guide the dimensional design parameter of the device from the thermal management perspective.

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