MODIFIED NUMERICAL METHOD FOR THIN FILM THERMAL CONDUCTIVITY CALCULATION WITH MICRO-RAMAN SPECTROSCOPY

by

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DEDICATION

To Faezeh, Mom, Dad, and Mahdi.

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ABSTRACT

MODIFIED NUMERICAL METHOD FOR THIN FILM THERMAL CONDUCTIVITY CALCULATION WITH MICRO-RAMAN SPECTROSCOPY

Thin film materials have recently drawn a great attention for their wide range of applications in nano- and micro-scale devices. To overcome thermal issues associated with these devices, thin film materials must be thermally characterized since they do not have the same thermal properties as their bulk counterparts. Various analytical and experimental techniques are used to find thin film thermal conductivities. Micro-Raman spectroscopy is a preferred technique among other optical thermal conductivity measurement techniques due to its non-destructive and non-contact nature. However, the thermal size effects originating from both localized heat generation from Raman laser and phonon scattering at boundaries cause erroneous estimation of the thermal conductivities with the current methods. In this study, the gray phonon Boltzmann transport equation (BTE) is used to simulate the real conditions during the Raman experiment. Thermal conductivities from the developed virtual Raman experiment are then compared with a simple slab model in which the deduction of thermal conductivity in sub-micron thicknesses is calculated using the reduced BTE heat flux through the slab, resulting from phonon directional energy densities. Due to the frequency independence of single phonon mode in the gray BTE model, our method stays ahead of most theoretical methods in calculation time while giving adequate agreement with the literature data. The results show that the results from the developed model are in a good agreement with the slab model results as well as literature values.

ÖZET

MİKRO-RAMAN SPEKTROSKOPİSİ İLE İNCE FİLM TERMAL İLETKENLİK HESAPLAMASI İÇİN MODİFİYE SAYISAL YÖNTEM

İnce film malzemeleri son zamanlarda nano ve mikro ölçekli cihazlarda geniş uygulama yelpazesi nedeniyle büyük ilgi görmüştür. Bu cihazlarla ilgili termal sorunların üstesinden gelmek için, ince film malzemeleri, toplu muadilleriyle aynı termal özelliklere sahip olmadıklarından termal olarak karakterize edilmelidir. İnce film termal iletkenliklerini bulmak için çeşitli analitik ve deneysel teknikler kullanılır. Mikro-Raman spektroskopisi, tahribatsız ve temassız yapısı nedeniyle diğer optik termal iletkenlik ölçüm teknikleri arasında tercih edilen bir tekniktir. Ancak hem Raman lazerden lokalize ısı oluşumundan hem de sınırlarda fonon saçılmasından kaynaklanan termal boyut etkileri, mevcut yöntemlerle termal iletkenliklerin hatalı tahmin edilmesine neden olmaktadır. Bu çalışmada, Raman deneyi sırasındaki gerçek koşulları simüle etmek için gri fonon Boltzmann taşıma denklemi (BTE) kullanılmıştır. Geliştirilen sanal Raman deneyinden elde edilen ısıl iletkenlikler, daha sonra, mikron altı kalınlıklarda ısıl iletkenliğin çıkarılmasının, fonon yönlü enerji yoğunluklarından kaynaklanan levha boyunca azaltılmış BTE ısı akısı kullanılarak hesaplandığı basit bir levha modeli ile karşılaştırılır. Gri BTE modelinde tek fonon modunun frekans bağımsızlığı nedeniyle, yöntemimiz literatür verileriyle yeterli uyum sağlarken hesaplama süresinde çoğu teorik yöntemin önünde kalmaktadır. Sonuçlar, geliştirilen modelden elde edilen sonuçların, slab model sonuçları ve literatür değerleri ile uyumlu olduğunu göstermektedir.

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LIST OF SYMBOLS

C	Specific heat
D	Density of states
e	Phonon energy density
e_0	Equilibrium energy density
$e_{i,e}$	Directional phonon energy density at east face
e_i^E	Directional phonon energy density at east centroid
f	Phonon distribution function
$\hbar$	Reduced Planck's constant
k_{bulk}	Bulk thermal conductivity
k_{tf}	Thin film thermal conductivity derived from slab model
k_{tf}^*	Thin film thermal conductivity derived from virtual Raman
l_x	Length of model in x-direction
l_y	Length of model in y-direction
l_z	Length of model in z-direction
q'''	Volumetric heat generation
$\vec{s}_i$	Phonon propagation direction unit vector
$\vec{S}_i$	Direction cosine
t	Time
T	Temperature
T_{ref}	Reference temperature
$\overrightarrow{v_g}$	Phonon group velocity
α	Absorption coefficient
$\Delta\Omega_i$	Directional solid angle
ΔV	Volume of control volume
Δx	Cell spacing in the x-direction

Δy	Cell spacing in the y-direction
Δz	Cell spacing in the z-direction
θ_i	Directional polar angle
Λ	Phonon mean free path
ρ	Reflectance
τ	Phonon relaxation time
ϕ_i	Directional azimuthal angle
ω	Phonon frequency

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AlGaN	Aluminum Gallium Nitride
BTE	Boltzmann Transport Equation
CDS	Central Differencing Scheme
FVDOM	Finite Volume Discrete Ordinates Method
GaAs	Gallium Arsenide
GaN	Gallium Nitride
HEMT	High Electron Mobility Transistor
IC	Integrated Circuits
InGaN	Indium Gallium Nitiride
LED	Light Emitting Diode
LUS	Linear Upwinding Scheme
MD	Molecular Dynamics
MFP	Mean Free Path
MgO	Magnesium Oxide
MLG	Multi-layer Graphene
OLED	Organic Light Emitting Diode
Si	Silicon
TC	Thermal Conductivity
TDTR	Time Domain Thermoreflectance
TEM	Transverse Electromagnetic
TFT	Thin Film Transistor

1. INTRODUCTION

1.1. Thin Films in Microelectronic Applications

Recent advancements in microfabrication technology have made it possible to produce thin films with submicron thicknesses [1]. Fabricated thin films are used in the production of various microelectronic devices such as transistors [2], diodes [3], microprocessors [4], and solar cells [5]. Thin films are the promising parts of transistors which are the most basic components of integrated electronic circuits (ICs) in modern semiconductor electronics [6]. For instance, Figure 1.1 shows the structure of a thin-film transistor cross section which is composed of various thin films with thicknesses ranging from 5 nm to 50 µm. These devices are generally used to switch electrical power or signal. On the other hand, light Emitting Diodes (LEDs) are another most common applications of thin films that are used as visible and infrared light source. An InGaN/GaN LED is shown in Figure 1.2 which also consists of several thin film materials. Therefore, due to wide range of their applications in nano and microstructures, thin films should be thermally characterized in an accurate way.

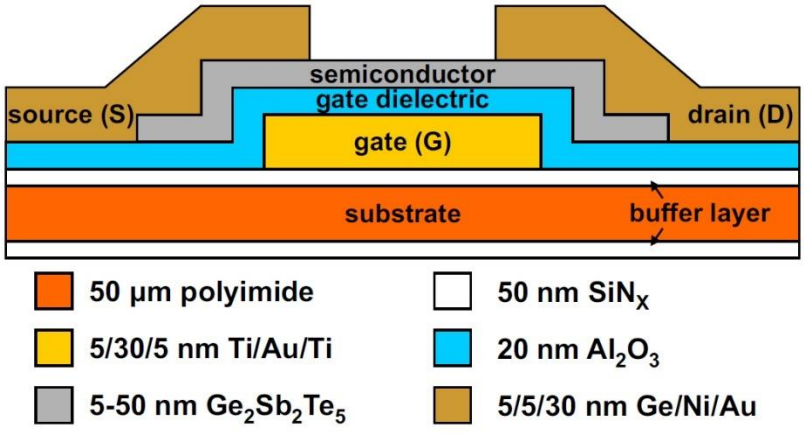

Figure 1.1. Thin-film transistor cross section on flexible plastic substrate [7].

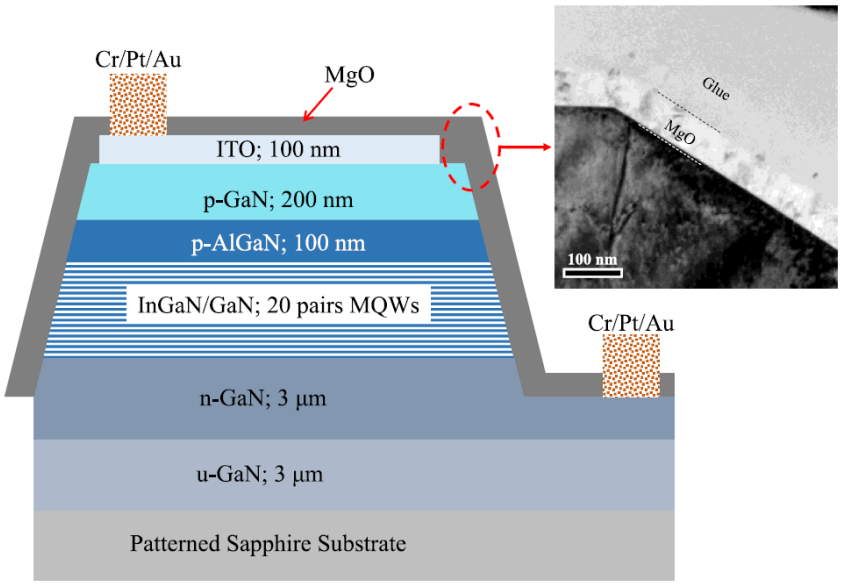

Figure 1.2. Device structure of InGaN/GaN LED epitaxial and transmission electron microscopy image of 70 nm MgO film in the inset [8].

1.2. Thermal Problems of Microelectronics

High temperatures during operation of thin film transistors and high-power LEDs as well as other nano and micro-scale electronic devices may cause degradation in devices. For instance, the hot spot region formed in Figure 1.3 due to accumulation of electrons in the drain side of the gate negatively affects the performance of an AlGaN/GaN HEMT. Therefore, the Joule heating effect causes significant problems in the process of thermal management to maintain maximum temperature under the allowed value [9]. Also there may be nonuniform luminance problems caused by inaccurate characterization of thin film transistors (TFTs) as well as image sticking problems because of organic light emitting diodes (OLEDs) degradation [10]. Therefore, to overcome thermal problems related to thin film devices and to extend their lifetime, their thickness dependent thermal conductivities should be obtained via theoretical or experimental techniques.

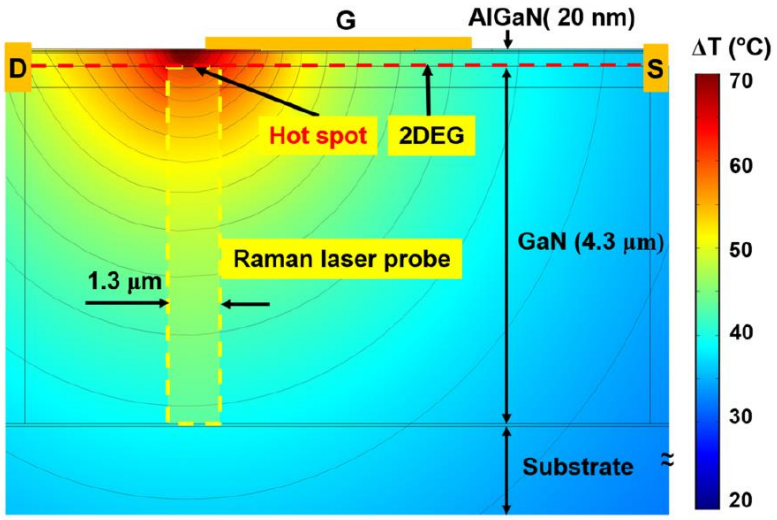

Figure 1.3. Cross sectional view of formed thermal hotspot in operating AlGaN/GaN HEMT. Reprinted by permission from AIP Publishing [11]. License number: 5237020572679.

1.3. Thin Film Thermal Conductivity

Understanding the heat transport phenomena across thin films with thicknesses comparable to or smaller than their mean free path (MFP) which is the distance that phonons can travel before exchanging their energy with other phonons, is a crucial step to calculate their thermal properties. To recognize the appropriate regime for heat transfer in thin films, the Knudsen number is defined as the ratio of phonon mean free path (MFP) to the characteristic length of the problem [12]. Figure 1.4 shows different heat transport regimes for a specified material (same MFP) according to the thickness of the film. Figure 1.4 (a) shows a fully diffusive regime in which almost all phonons are able to complete their MFP before colliding with each other or colliding with boundaries. However, as shown in Figure 1.4 (b), excited phonons at the bottom boundary, become unable to travel a distance equal to their MFP before reaching the top boundary. Therefore, the contribution of phonons to carry the energy from bottom to top, that is said to be the heat flux, reduces significantly [13]. In other words, spatial confinement of heat carriers in thin films results in a notable reduction in the value of layer thermal conductivity which is the relation between the hat flux and temperature gradient through the Fourier law of heat conduction [14]. Finally, Figure 1.4 (c) shows a quasi-ballistic

heat transport regime which happens when the layer thickness is nearly equal to the phonon MFP which includes both of diffusive and ballistic regimes.

Therefore, due to boundary scattering effects associated with ballistic thermal transport in thin films with thicknesses in the range of their mean free path (MFP) and lower, their thermal conductivity is not equal to their bulk counterparts' [15]. For that reason, quantifying the reduced thin film thermal conductivity plays an important role in thermal management and predicting junction temperature of nano and micro-devices consisting of thin films for maintenance purposes. There are various theoretical and experimental techniques for thin film thermal characterization. In this section, some of these methods and their advantages and disadvantages are discussed.

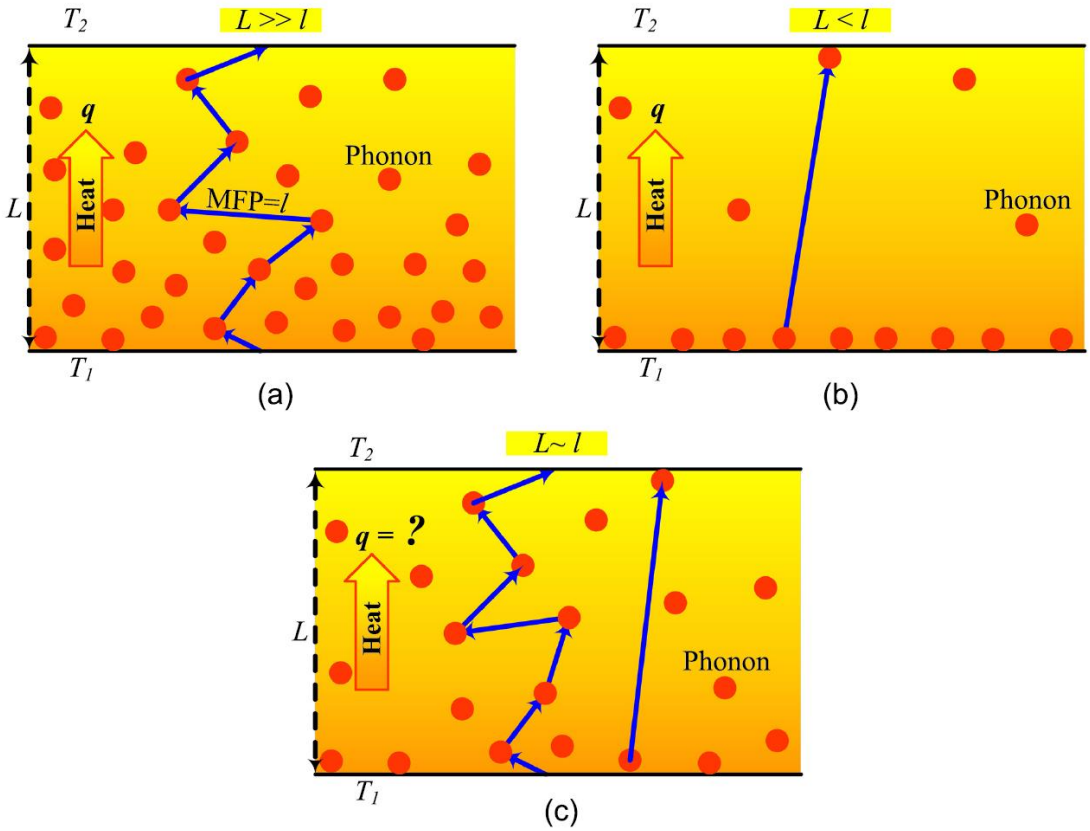

Figure 1.4. (a) Diffusive, (b) ballistic, and (c) quasi-ballistic heat transport regimes across thin films with different MFP to characteristic length ratios. Reprinted by permission from AIP Publishing [16]. License number: 5237020398417.

1.3.1. Theoretical Methods

Theoretical studies are mainly classified into two main categories, atomic-scale and meso-scale methods. Atomic-scale methods include molecular dynamics (MD) simulations [17], ab-initio calculations [18], or non-equilibrium Green's function solutions [19], where meso-scale methods include Boltzmann transport equation [20] and Monte Carlo simulations [21]. Figure 1.5 represents a nonhomogeneous nonequilibrium approach of molecular dynamics. In this approach, a constant heat flux is applied to the system in the x-direction, the resulting temperature gradient is extracted, and thermal conductivity is calculated by the Fourier law in which it is equal to the ratio of heat flux to the temperature gradient [22].

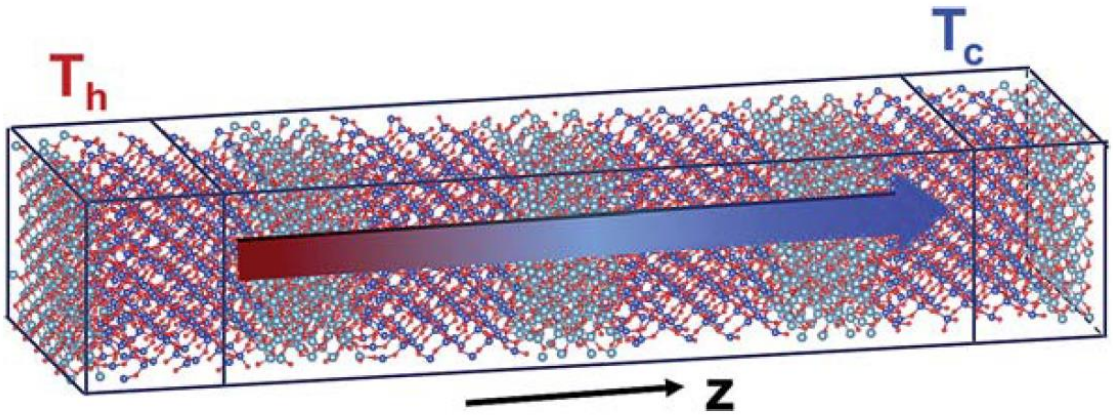

Figure 1.5. Schematic of the simulation cell for thermal conductivity calculation with molecular dynamics study. Reprinted by permission from RSC Publishing [23]. License number: 1182888-1.

1.3.2. Experimental Methods

On the other hand, there are experimental methods to measure thin film thermal conductivity. Among the most prevalent ones, are 3ω, time domain thermoreflectance, frequency domain thermoreflectance, and micro-Raman spectroscopy methods to name a few. A hot strip is put on the specimen which acts as a heater as well as a thermometer in the 3ω

method. The magnitude and phase of the produced harmonic signal as a result of oscillating surface temperature is then used to characterize thermal properties of the underlying thin film sample [24]. A similar trend is followed in time domain thermoreflectance but the difference is that instead of measuring temperature, surface reflectance is measured. In fact, after shining a laser beam onto the surface of specimen, the intensity of reflected light is measured to detect reflectivity that is a function of temperature. Measured reflectivity is matched with a theoretical method to find thermal conductivity [25]. Frequency domain thermoreflectance method is similar to TDTR method with the difference that the excitation laser is pumped with variable frequencies to overcome the problems related to mechanical motion of the probe [26].

1.4. Micro-Raman Thermal Conductivity Measurement

Due to its non-contact and non-destructive nature and no need for microfabrication of the thin film, Raman thermometry method is highly preferred among other experimental methods [27]. Additionally, being able to measure not only cross-plane thermal conductivity but also in-plane thermal conductivity, Raman technique stays ahead of other optical methods [28]. Raman thermometry method includes two main parts including the experiment and complementary thermal modelling sections.

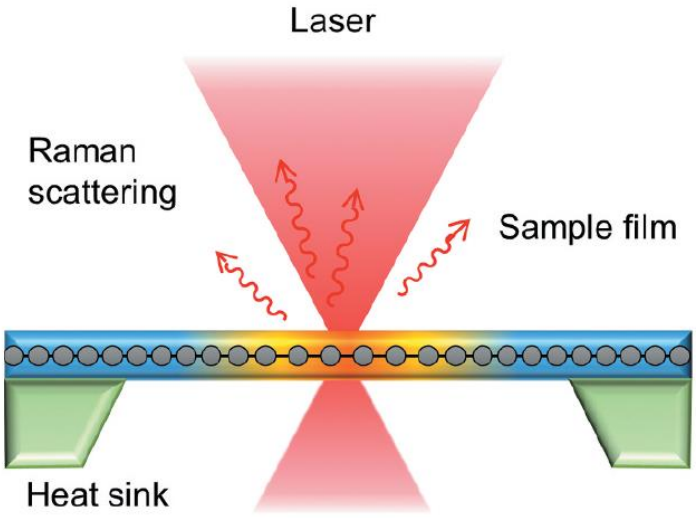

Figure 1.6. Micro-Raman thermometry experiment schematic [29].

In thermal conductivity measurement via micro-Raman experiment, an excitation laser beam is shined onto the sample and the scattered photons are collected as shown in Figure 1.6. In addition to its heating purpose, the laser acts as a probe for the analysis of the scattered light [30]. After absorption of a portion of light source energy, the rest is reflected. The reflected light contains Stokes, anti-Stokes and Rayleigh scattered signals which are all affected by the intensity of interatomic interactions inside the specimen as shown in Figure 1.7. Since Rayleigh scattering is an elastic one and does not carry the information about the molecular vibrations in the sample, the local temperature is measured using Stokes and anti-Stokes Raman scattering signals [31].

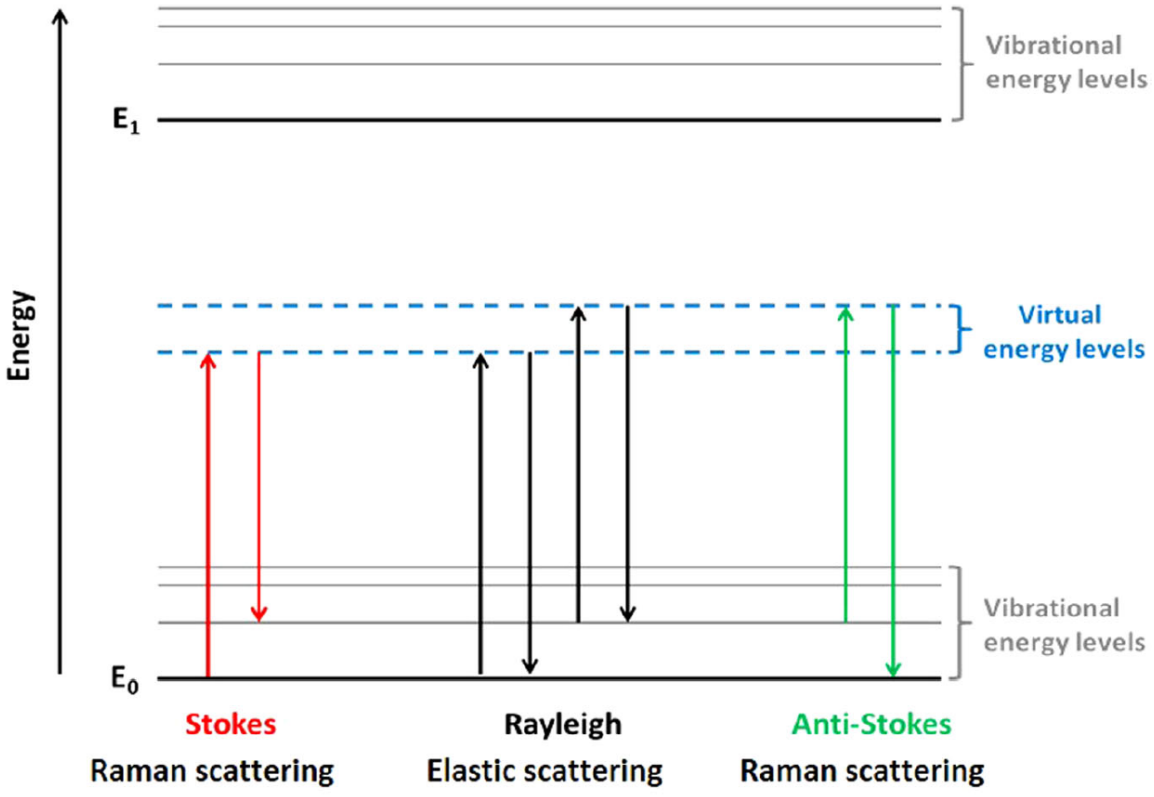

Figure 1.7. Types of scattered light during a Raman thermometry experiment and energy level of each scattered light [31].

After the detection of the scattered light, it is converted to the Raman fingerprint of the material which quantifies the intensity of Raman as a function of Raman shift as shown in Figure 1.8 (a). This test is done for different laser beam powers inducing different Raman fingerprints. The peak position of the Raman spectra differs for any temperature. The relation between the Raman shift peak position and temperature is deduced as shown in Figure 1.8 (b). Therefore, the local temperature can directly be obtained for any Raman spectrum.

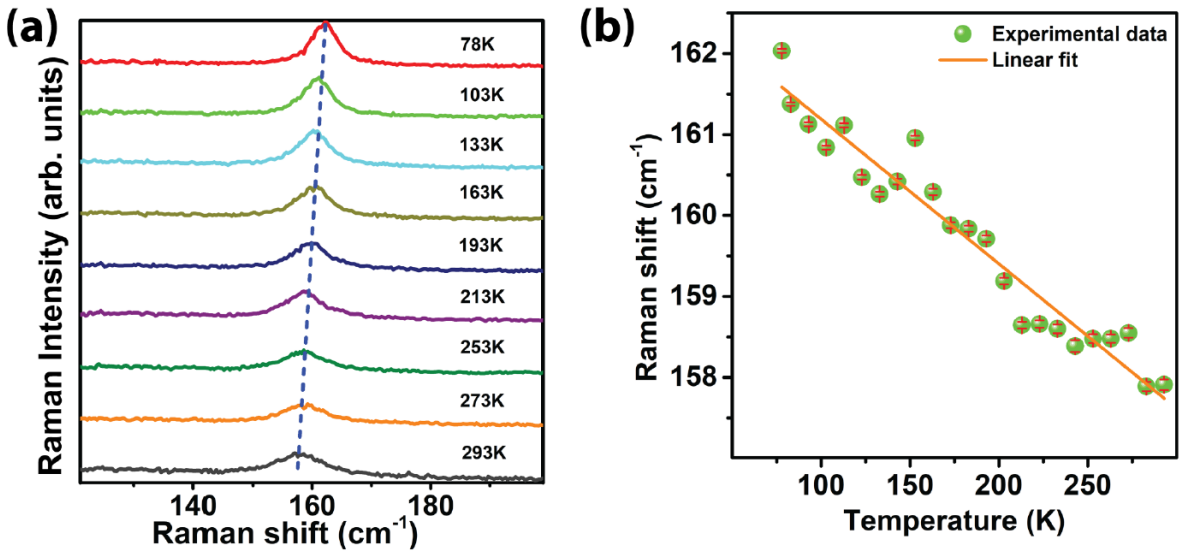

Figure 1.8. (a) Raman spectra for different temperatures and (b) Raman shift value in terms of measured temperature. Reprinted by permission from AIP Publishing [32]. License number: 5237030605177.

In Raman-based thermal conductivity measurement, it is not possible to directly measure thermal conductivity. Instead, local temperature is measured. After finding the hot spot temperature of the sample using the above-mentioned process, a complementary thermal transport model with the same boundary conditions as well as the same heat source according to laser power, probing wavelength, and material optical properties is used to predict the temperature distribution matching the measured temperature [33]. Thermal conductivity giving the best prediction is chosen as the measured thermal conductivity.

1.5. Size Effects in Micro-Raman Thermal Conductivity Measurements

Thermal size effects appear when the heat carriers become unable to transfer energy in their maximum performance. This happens during spatial confinement in thin film materials or when the heat generation region becomes as small as their mean free path. In Rama based thin film thermal conductivity measurement, not only there exists a spatial confinement due to small thin film thickness scales as shown in Figure 1.4, but also a heat generation happening in a very small region due to excitation lasers small diameter. In the conventional thin film thermal conductivity measurement via micro-Raman thermometry, the complementary thermal model is usually a Fourier based one which is not able to take size effects into account.

In order to include localized heating size effects caused by laser beam as well as boundary scattering effects during the Raman thermometry TC measurement, phonon BTE can be used to predict specimen temperature. The initial form of the phonon BTE in terms of phonon statistical distribution function (f) is given as

$$\frac{\partial f}{\partial t} + \overrightarrow{v_g}.\nabla f = \left(\frac{\partial f}{\partial t}\right)_{scatt} + q''' \tag{1.1}$$

where $\overrightarrow{v_g}$ is the phonon group velocity and q''' is the volumetric energy generation if any [34]. The scattering term on the right-hand side of this equation represents the variation of the phonon distribution function due to collisions with other phonons. This term is the main feature of the non-Fourier heat transfer and includes ballistic behavior of phonon transport in small scales. The numerical solution for this equation is introduced in chapter 3.

2. MOTIVATION

The conventional Raman-based thermal conductivity measurement techniques use Fourier-based modeling to predict temperature and therefore thermal conductivity. This research aims to remove the errors in thin thermal conductivity measurement by previous micro-Raman numerical models because of their fully diffusive nature. For this purpose, a modified micro-Raman spectroscopy model is developed which includes size effects associated with boundaries and localized heating by employing a phonon Boltzmann Transport Equation (BTE) to simulate the non-Fourier heat transport in thin films that has not been used previously. In this study Si, GaN, GaAs, and MLG materials are examined since they are promising candidates for thermal characterization due to their wide applications in semiconductor microdevices.

3. NUMERICAL SOLUTION OF THE PHONON BOLTZMANN TRANSPORT EQUATION

Various numerical techniques like Monte Carlo study [35] has been employed to solve Equation (1.1) in the literature. However, this method is not preferred in relatively large domains due to its high computational costs. Therefore, in this study we use a finite volume discrete ordinates method (FVDOM) [36] to solve the gray BTE in which it should be discretized in both spatial and angular coordinates since the phonon energy density is a function of position as well as direction.

To simply apply the phonon BTE to a domain and find the temperature distribution, phonon distribution function is replaced with its energy density function as represented in

$$e(T) = f\hbar\omega D(\omega) \tag{3.1}$$

where e, $\hbar$, ω, and $D(\omega)$ are phonon energy density, reduced Planck's constant, phonon frequency and density of states, respectively. Afterwards, the final steady state phonon BTE under gray relaxation time approximation can be written in terms of phonon energy density in

$$\overrightarrow{v_g}.\nabla f = \frac{e - e_0}{\tau} + q''' \tag{3.2}$$

where τ is the phonon relaxation time which defines the time that phonons travel before they collide with other energy carriers. According to the gray approximation phonons travel in a single group velocity as well as single relaxation time and therefore assumes that phonon properties are frequency-independent [37].

The equilibrium energy density e_0 can be related to lattice temperature using equation

$$e_0 = CT = \sum e_i w_i \tag{3.3}$$

where specific heat C is assumed to be constant and directional weights, w_i are given in Table 3.1.

The kinetic theory is given as

$$k_{bulk} = \frac{1}{3} C v_g^2 \tau = \frac{1}{3} C v_g \Lambda \tag{3.4}$$

which is used to specify phonon properties like group velocity, $\overrightarrow{v_g}$ and relaxation time, τ to be employed in Equation (3.2) where phonon mean free path, Λ is equal to group velocity times relaxation time, $v_g \tau$. This theory relates the material bulk thermal conductivity to its phonon properties.

3.1. Angular Discretization

Unlike Fourier law of heat conduction, phonon BTE needs to be discretized angularly in addition to spatial discretization. At any centroid of control volume, the angular space is discretized into several solid angles so that phonons can propagate in these directions. The number of solid angles is defined by the type of S_N quadrature chosen for discretization. Angularly discretized form of the steady state gray phonon BTE (Equation (3.2)) is rewritten in the form of

$$\vec{s}_i \cdot \nabla v_{gi} e_i = \frac{e_i^0 - e_i}{\tau} + q''' \tag{3.5}$$

where subscript i and $\vec{s}_i$ represent direction and the unit vector along phonon propagation direction. In this equation v_{gi} and e_i are directional phonon group velocity and energy density, respectively. The directional unit vector, $\vec{s}_i$ shown in Figure 3.1 can be written in terms of polar and azimuthal angles as shown in

$$\vec{s}_i = sin(\theta_i) sin(\phi_i) i + sin(\theta_i) cos(\phi_i) j + cos(\theta_i) k \tag{3.6}$$

where i, j, and k are unit vectors along x, y, and z directions, respectively.

Components of directional unit vector (shown in Figure 3.1) for any S_N quadrature can be found in Table 3.1. The number of possible directions for any S_N quadrature can be found by the following formula $N(N+2)$. For instance, in a 3D problem there are 24 possible directions for the S_4 quadrature. However, for a 2D problem there will be 12 possible directions inside half of the sphere. It should be noted that in this case weights (in Table 3.1 must be doubled for the corresponding directions.

Table 3.1. Direction cosines and weights of S_4, S_6, and S_8 quadratures [38].

Quadrature	Direction cosines			Weight
	μ	η	ξ	w
S_4	0.2958759	0.2958759	0.9082483	0.5235987
	0.2958759	0.9082483	0.2958759	0.5235987
	0.9082483	0.2958759	0.2958759	0.5235987
S_6	0.1838670	0.1838670	0.9656013	0.1609517
	0.1838670	0.6950514	0.6950514	0.3626469
	0.1838670	0.9656013	0.1838670	0.1609517
	0.6950514	0.1838670	0.6950514	0.3626469
	0.6950514	0.6950514	0.1838670	0.3626469
	0.9656013	0.1838670	0.1838670	0.1609517
S_8	0.1422555	0.1422555	0.9795543	0.1712359
	0.1422555	0.5773503	0.8040087	0.0992284
	0.1422555	0.8040087	0.5773503	0.0992284
	0.1422555	0.9795543	0.1422555	0.1712359
	0.5773503	0.1422555	0.8040087	0.0992284
	0.5773503	0.5773503	0.5773503	0.4617179
	0.5773503	0.8040087	0.1422555	0.0992284
	0.8040087	0.1422555	0.5773503	0.0992284
	0.8040087	0.5773503	0.1422555	0.0992284
	0.9795543	0.1422555	0.1422555	0.1712359

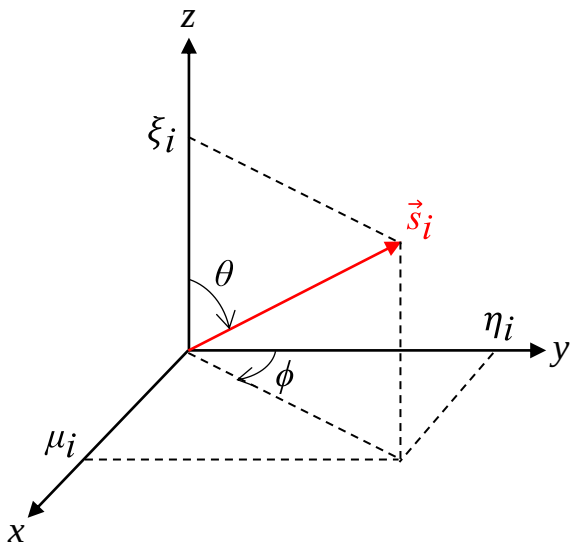

Figure 3.1. Angular discretization of phonon BTE with discrete ordinates method.

Integrating Equation (3.5) over the discrete angular control volume, angularly discretized phonon BTE is rewritten in the form of

$$\vec{S}_i \cdot \nabla v_g e_i = \frac{e_i^0 - e_i}{\tau} \Delta\Omega_i + q''' \Delta\Omega_i \tag{3.7}$$

where the direction cosine $\vec{S}_i$ and directional solid angle $\Delta\Omega_i$ are given in

$$\vec{S}_i = \int_{(\phi_i - \Delta\phi/2)}^{(\phi_i + \Delta\phi/2)} \int_{(\theta_i - \Delta\theta/2)}^{(\theta_i + \Delta\theta/2)} \vec{s}_i \, sin(\theta) d\theta d\phi \tag{3.8}$$

and

$$\Delta\Omega_i = \int_{(\phi_i - \Delta\phi/2)}^{(\phi_i + \Delta\phi/2)} \int_{(\theta_i - \Delta\theta/2)}^{(\theta_i + \Delta\theta/2)} sin(\theta) d\theta d\phi \tag{3.9}$$

where θ and ϕ are polar and azimuthal angles.

The equilibrium energy density and control volume centroid temperature can be calculated through equation

$$4\pi e^0 = C\left(T - T_{ref}\right) = \sum_{i=1}^{N(N+2)} e_i \Delta\Omega_i \tag{3.10}$$

using directional energies and corresponding solid angle. The angular discretization is the same for the 2D and 3D models where it differs in spatial discretization.

3.2. Spatial Discretization

For the spatial discretization of the 2D and 3D phonon BTE, domains are divided into rectangular control volumes as shown in Figures 3.2 and 3.3. Integrating Equation (3.7) over the spatial control volume, that has been integrated over the angular control volume in the previous section, the final form of discretized phonon BTE comes in Equations (3.11) and (3.12) for 2D and 3D problems, respectively.

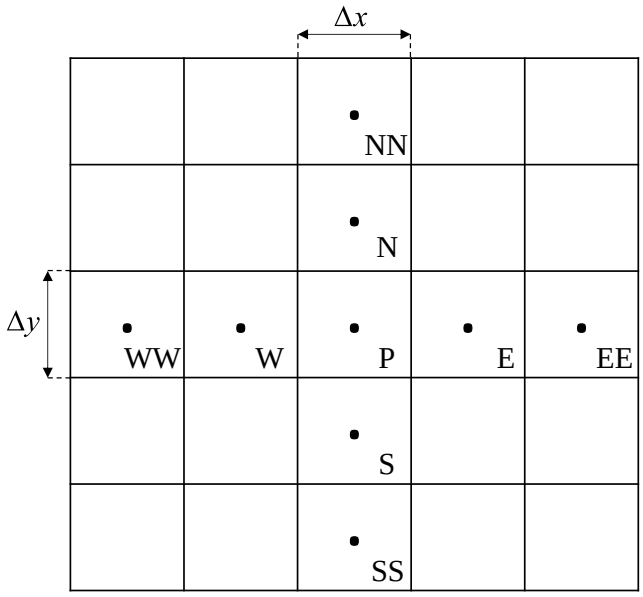

Figure 3.2. Spatial discretization of phonon BTE 2D domain with finite volume method.

The discretized phonon BTE in 2D is given as

$$v_g e_{i,e} \Delta y S_{i,x} - v_g e_{i,w} \Delta y S_{i,x} + v_g e_{i,n} \Delta x S_{i,y} - v_g e_{i,s} \Delta x S_{i,y} = \frac{e^0 - e_i}{\tau} \Delta V \Delta \Omega_i + q''' \tag{3.11}$$

where ΔV is equal to $\Delta x \Delta y$.

On the other hand, the 3D version of fully discretized phonon BTE is given as

$$\begin{aligned} & v_g e_{i,e} \Delta y \Delta z S_{i,x} - v_g e_{i,w} \Delta y \Delta z S_{i,x} + v_g e_{i,n} \Delta x \Delta z S_{i,y} \\ & - v_g e_{i,s} \Delta x \Delta z S_{i,y} + v_g e_{i,f} \Delta x \Delta y S_{i,z} \\ & - v_g e_{i,b} \Delta x \Delta y S_{i,z} = \frac{e^0 - e_i}{\tau} \Delta V \Delta \Omega_i + q''' \end{aligned} \tag{3.12}$$

where ΔV is equal to $\Delta x \Delta y \Delta z$ and $e_{i,e}$, $e_{i,w}$, $e_{i,n}$, $e_{i,s}$, $e_{i,f}$, and $e_{i,b}$ are directional phonon energy densities at east, west, north, south, front, and back faces of the control volume.

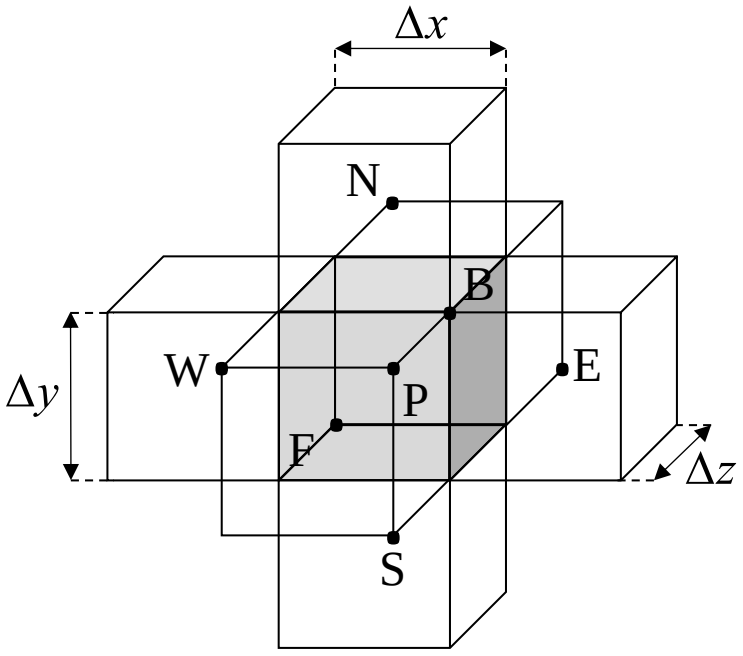

Figure 3.3. Spatial discretization of phonon BTE 3D domain with finite volume method.

To relate facial energy densities to nodal values in 2D version, a Linear Upwind Scheme (LUS) is used in which the direction matters, and they carry the information from where they come. For instance, the directional energy density at east face in the $+x$ direction is

$$e_{i,e}^{+} = e_i^P + \frac{e_i^P + e_i^W}{2} \tag{3.13}$$

while the directional energy density at east face in the $-x$ direction is

$$e_{i,e}^{-} = e_i^E + \frac{e_i^E + e_i^{EE}}{2} \tag{3.14}$$

where the capital superscripts represent cell centroid values as shown in Figure 3.2. The rest of the facial values can be derived accordingly.

For the 3D modeling, a Central Differencing Scheme (CDS) is used to define energy densities on the control volume faces as a function of their value in the control volume centroids. For instance, the east face directional energy density can be found by

$$e_{i,e} = \frac{e_i^P + e_i^E}{2} \tag{3.15}$$

where the capital superscripts represent cell centroid values as shown in Figure 3.3.

4. MODELING THE SIZE EFFECTS - PHONON BTE MODEL

One of the novelties of this study is to use phonon BTE to understand actual thermal behavior of thin films that are examined under micro-Raman thermography. For this purpose, first a slab model is developed to find the correct phonon properties. This model gives accurate phonon characteristics of any material by validating deduced thin film thermal conductivity with literature values. Therefore, a thermal conductivity spectrum is obtained that will be later used to calculate the error in the virtual Raman experiment. A schematic workflow of the current study is given in Figure 4.1. In this chapter, phonon properties of the materials which are not directly available in the literature are defined by validating the deduced thin film thermal conductivity. Therefore, there will be a better understanding from the actual conditions happening during the Raman experiment by resolving the phonon BTE.

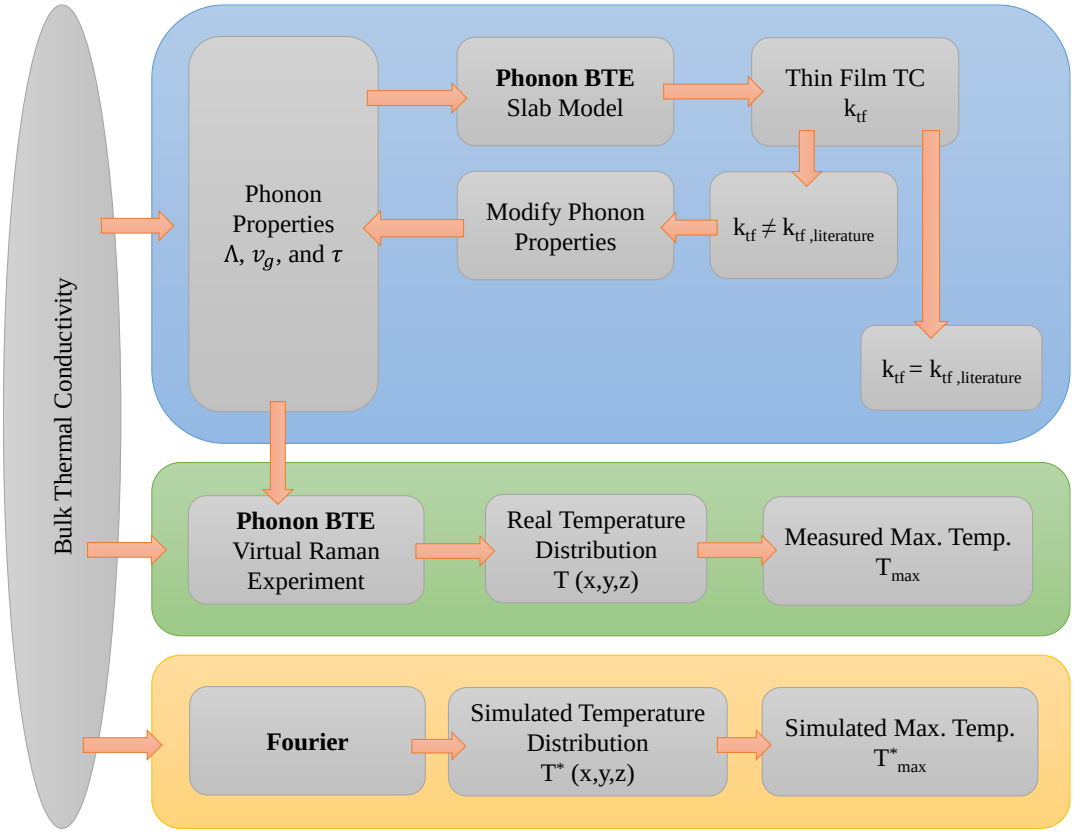

Figure 4.1. The workflow of simulations in this study.

4.1. Slab Model

In order to find the correct phonon properties of the material of interest, a 2D model is developed as shown in Figure 4.2. In this model, to eliminate size effects in y-direction and therefore purely having size effects originating from boundaries in one direction, l_y is long enough to consider infinite length along y-axis as well as infinite length in the direction perpendicular to the x-y plane. Applying zero heat flux boundary condition at top and bottom boundaries as well as different temperatures at left and right boundaries, a uniform heat flux at x-direction is established.

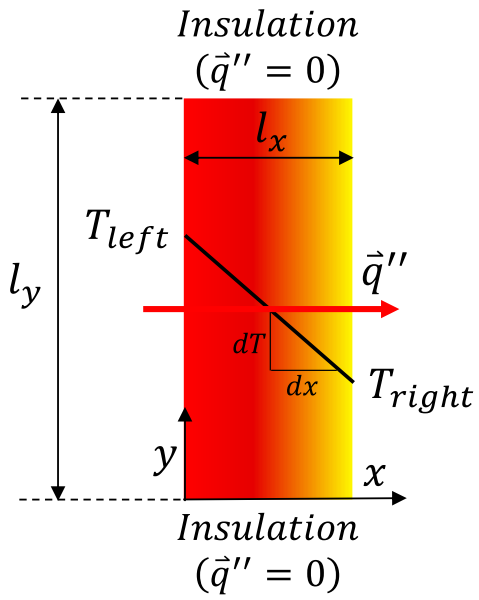

Figure 4.2. Schematic of the 2D slab model, applied boundary conditions and model parameters.

To implement the Fourier law of heat conduction to calculate thin film thermal conductivity as well as phonon BTE initialization, first the problem is solved with the 2D Fourier solvers to obtain the temperature distribution in the slab model as shown in Figure 4.3.

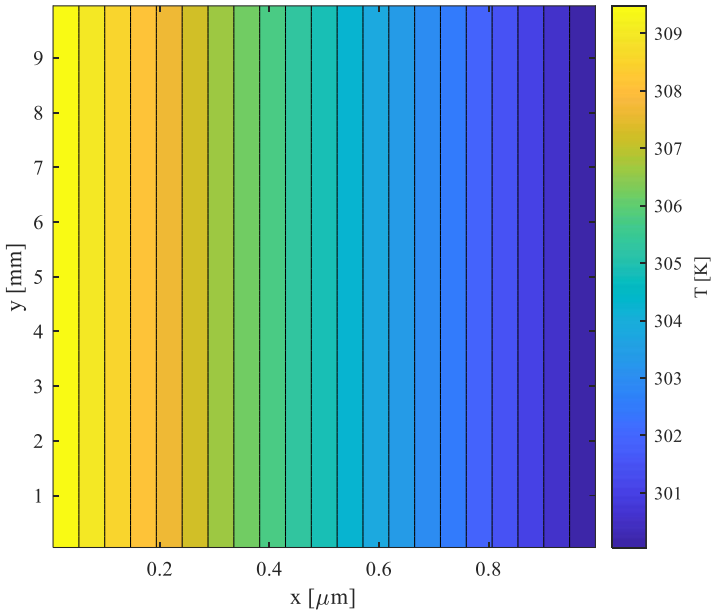

Figure 4.3. Fourier temperature contour of a 1µm Si thin film with 10mm height

On the other hand, phonon properties are guessed to be employed in the BTE solution for the same problem which is free of localized heating size effects (zero heat generation). Phonon properties are co-related to each other by the kinetic theory mentioned in Equation (3.4). Afterwards, BTE temperature distribution is obtained as shown in Figure 4.4.

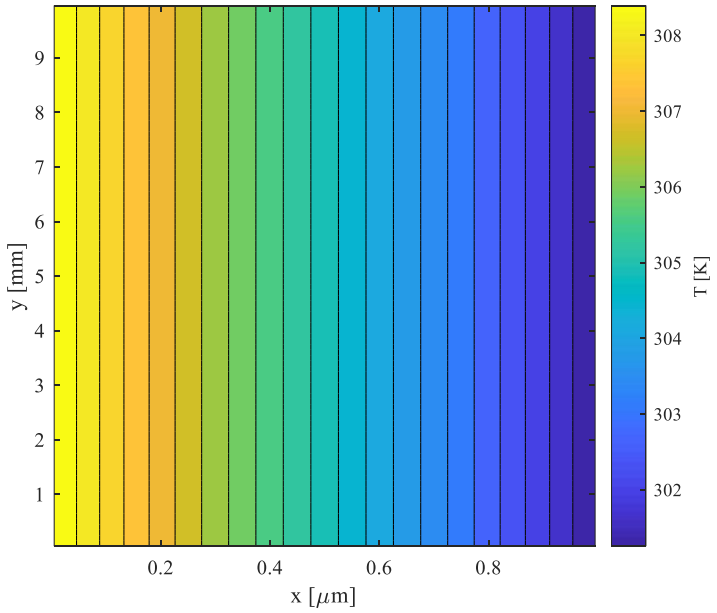

Figure 4.4. BTE *t*emperature distribution in a 1µm Si thin film with 10mm height.

As stated before, temperature profiles of both solutions are extracted at $y=l_y/2$. As shown in Figure 4.7, the slope of BTE temperature profile is lower than the Fourier profile. For any film thickness l_x, the Fourier profile stays the same while due to size effects originating from boundary scattering, temperatures at boundaries tend to tilt towards the average of left and right temperatures. This is because of present size effects originating from boundaries meaning that a set of phonons are incapable of a successful energy exchange along the x-axis inside the thin film.

The slope of the temperature profile shown in Figure 4.7 simply represent the horizontal heat flux. The cumulative reduced heat flux can be calculated from equation

$$\vec{q}'' = q_x''\vec{\imath} + q_y''\vec{j} + q_z''\vec{k} = \sum \vec{v}_i e_i \tag{4.1}$$

using directional energy densities through the BTE solution.

To calculate the reduced thermal conductivity there must be a pure heat transport in the x-direction. According to the 2D nature of the problem, q_z'' is zero. However, due to boundary scattering effects at top and bottom borders for relatively short l_y, q_y'' is not equal to zero. Therefore, to find the suitable length of the model fitting the desired conditions mentioned above, heat flux in the x-direction must be identical at any y distance. For this purpose, a one micrometer thick silicon film is modeled using different heights ranging from 1μm up to 10mm. The temperature profile of BTE solution is shown in Figure 4.5 for a 1μm high sample.

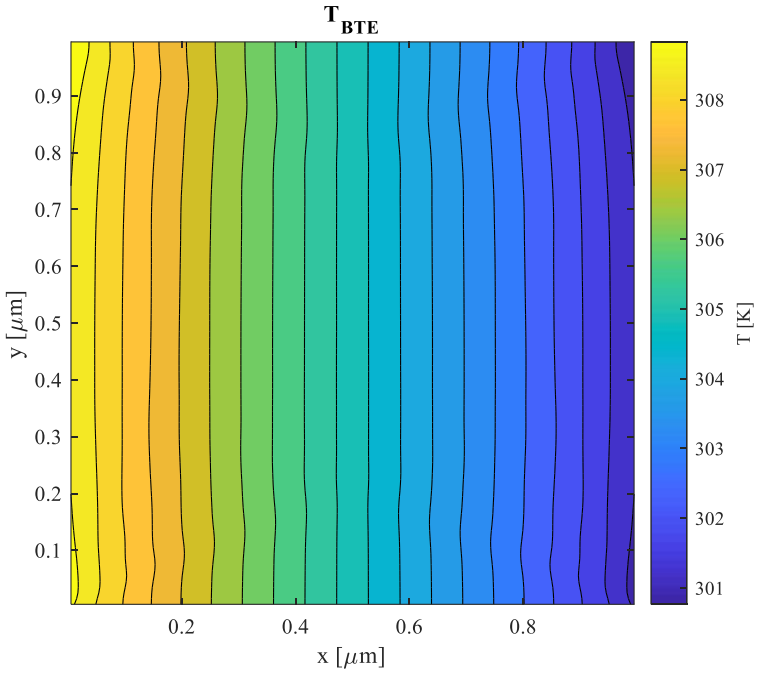

Figure 4.5. Temperature contour of a 1µm Si thin film with 1µm height.

At each step, the difference between maximum Fourier and BTE temperatures are recorded, and it is observed that it is almost the same as the previous step at 10mm height. For each l_y, the reduced BTE heat flux is measured at the center ($y=l_y/2$) and bottom ($y=0$). Reduced thermal conductivities are then calculated according to these heat fluxes that will be explained later. According to this method the difference between calculated thermal conductivities by bottom and central heat fluxes drop down to 0.06% for a height of 10mm as shown in Figure 4.6.

It is understood that slightly curved BTE temperature contour lines in Figure 4.5 for a 1µm×1µm domain become completely vertical for a 1µm×10mm domain shown in Figure 4.4. This inspires us to use a height of at least 10000 times of thickness if we are interested in a semi 1D heat transport. However, it is sufficient to use height of ten times thickness to calculate thermal conductivity employing central ($y=l_y/2$) heat flux in order to avoid longer computational time.

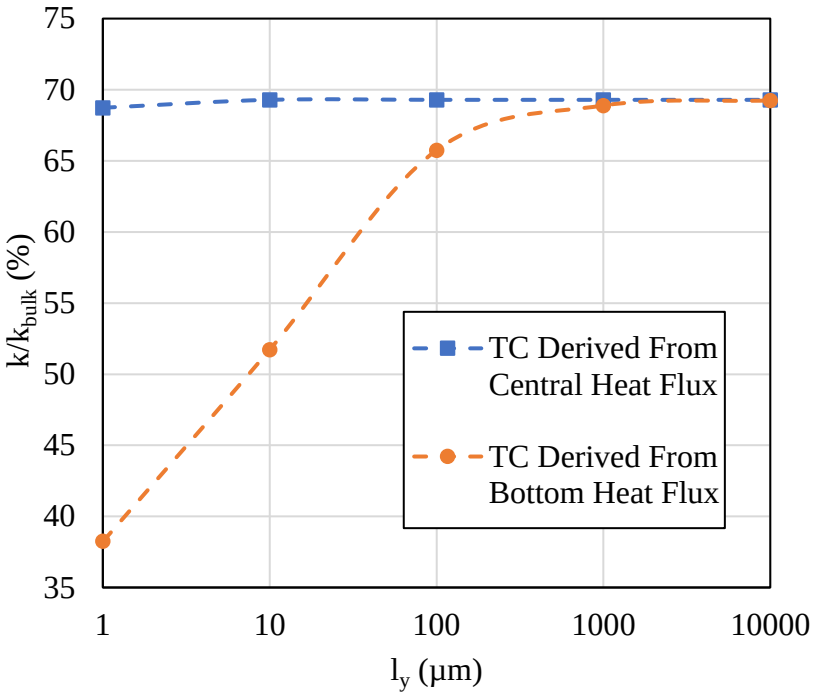

Figure 4.6. Non-dimensional thermal conductivity of 1µm Si thin film derived from central and bottom heat fluxes in terms of height.

After finding the suitable length in y-direction for the slab model the reduced thermal conductivity of thin film with any specified thickness can be calculated using Fourier law of heat conduction as

$$k_{tf} = -\vec{q}'' \frac{l_x}{\Delta T} \tag{4.2}$$

where ΔT and l_x are the initially applied temperature contrast in the x-direction and thin film thickness, respectively. Also, $\vec{q}''$ is the reduced heat flux calculated from Equation (4.1). Finally, the deduced thermal conductivity is compared with literature values. If an acceptable quantity is resulted, other thicknesses are also studied. If not, phonon properties are varied until reaching the same thermal conductivity values with the literature.

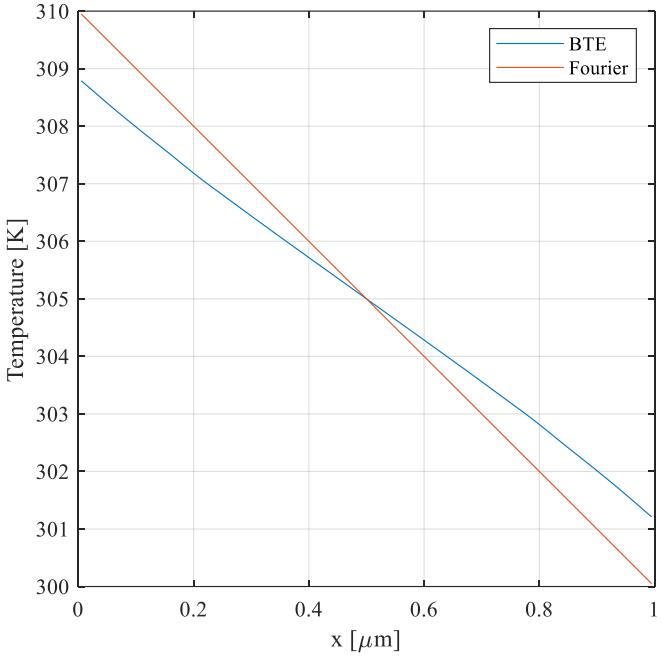

Figure 4.7. BTE and Fourier temperature profiles of the 1µm Si thin film at $y=l_y/2$.

For instance, a 1µm Si thin film is simulated applying a $\Delta T = 10\,K$ temperature difference to the boundaries while top and bottom boundaries are adiabatic. It is only important to have a temperature gradient in the x-direction for the heat to be transferred and the amount of gradient is not important. Therefore, one can apply a contrast as small as 0.1 K or as high as 100 K. Fourier temperature distribution is shown in Figure 4.3. After a number of trials, assigning 300 nm mean free path for Si as a guess, group velocity and relaxation time of Si phonons can be calculated through the kinetic theory (Equation (3.4)) being 907.4 m/s and 0.33 ns, respectively. To implement kinetic theory for these calculations, rather than using heat capacity in its mass form, isochoric form must be used which is in units of joule per kelvin per cubic meters. For this purpose, specific heats (C), are divided by material densities (ρ_d) to obtain isochoric forms (C_v) all provided in Table 1. After that Equation (3.11) is solved and BTE temperature distribution is obtained using assigned phonon properties as shown in Figure 4.4. Finally, temperature profiles are plotted for both solutions at $y=l_y/2$. It is understood from Figure 4.7 that Fourier and BTE profiles are not identical due to thermal size effects. Fourier heat flux is calculated to be $1.48 \times 10^9\, W/m^2$ while the reduced heat flux

calculated via Equation (4.1), drops down to $1.02 \times 10^9\, W/m^2$. Then the thin film thermal conductivity for a thickness of t_f is calculated through Equation (4.2) which reduces to 102 $W/m \cdot K$ where the bulk value is 148 $W/m \cdot K$. Using the same phonon properties, different thicknesses are examined and the thickness dependent nondimensional thermal conductivity is derived as shown in Figure 4.8.

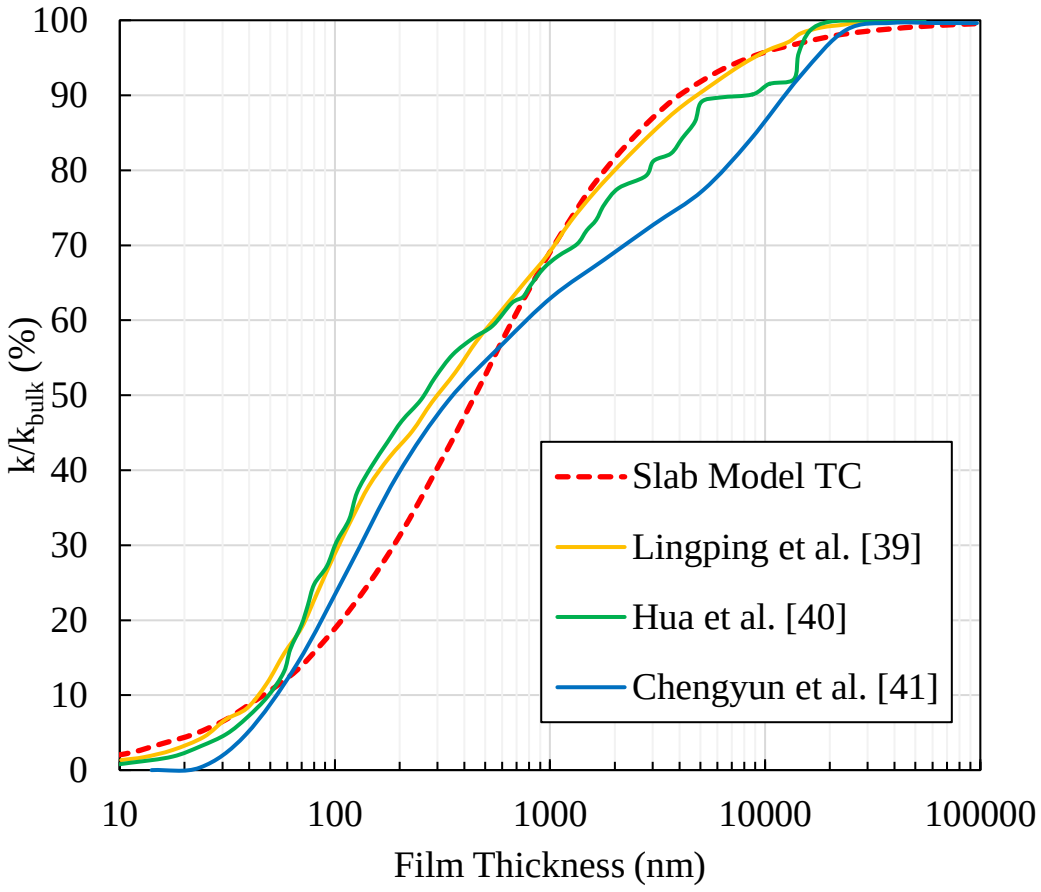

Figure 4.8. Thickness dependent thermal conductivity of Si derived from the slab model validated by results of Lingping *et al.* [39], Hua *et al.* [40], and Chengyun *et al.* [41].

In the same way, nondimensional thin film thermal conductivity spectrums are derived using validated phonon properties provided in Table 4.1. This method is used to derive thickness dependent thermal conductivities for other candidate materials with different phonon mean free paths.

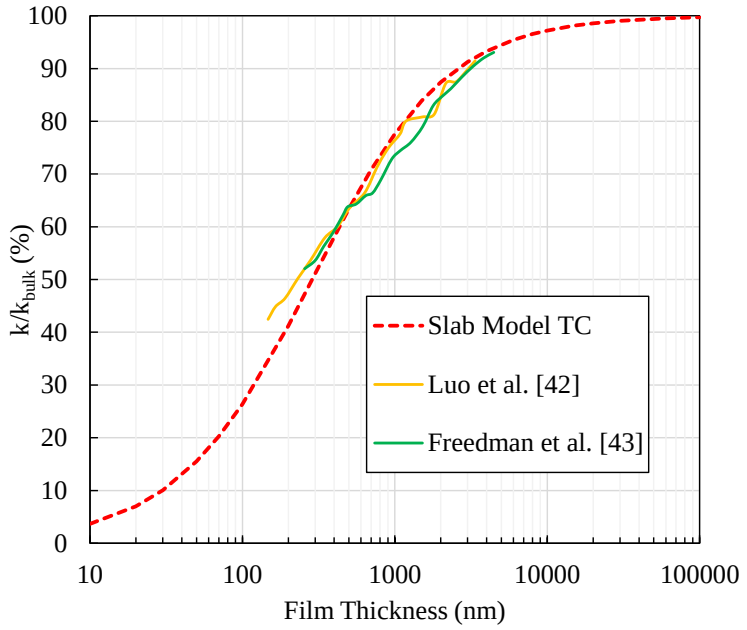

Figure 4.9. Thickness dependent thermal conductivity of GaAs derived from the slab model validated by results of Luo *et al.* [42] and Freedman *et al.* [43].

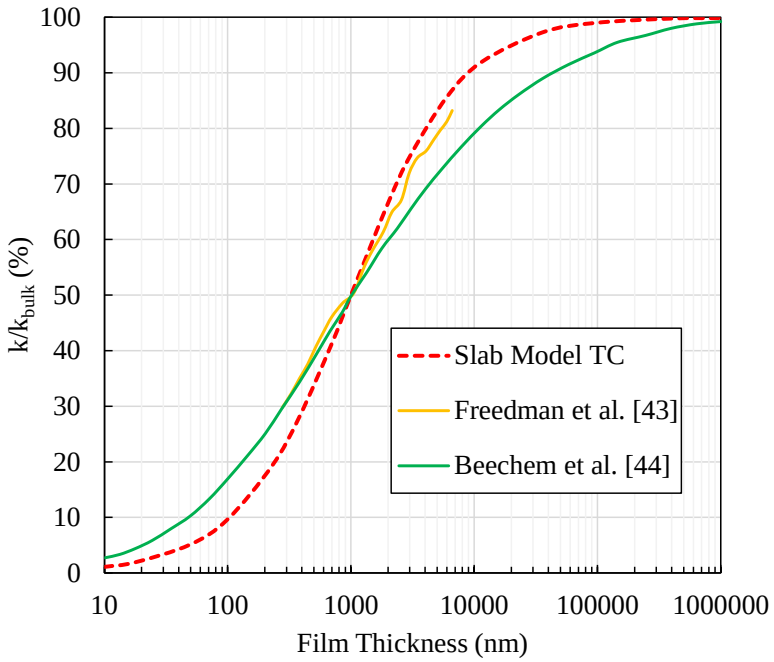

Figure 4.10. Thickness dependent thermal conductivity of GaN derived from the slab model validated by results Freedman *et al.* [43] and Beechem *et al.* [44].

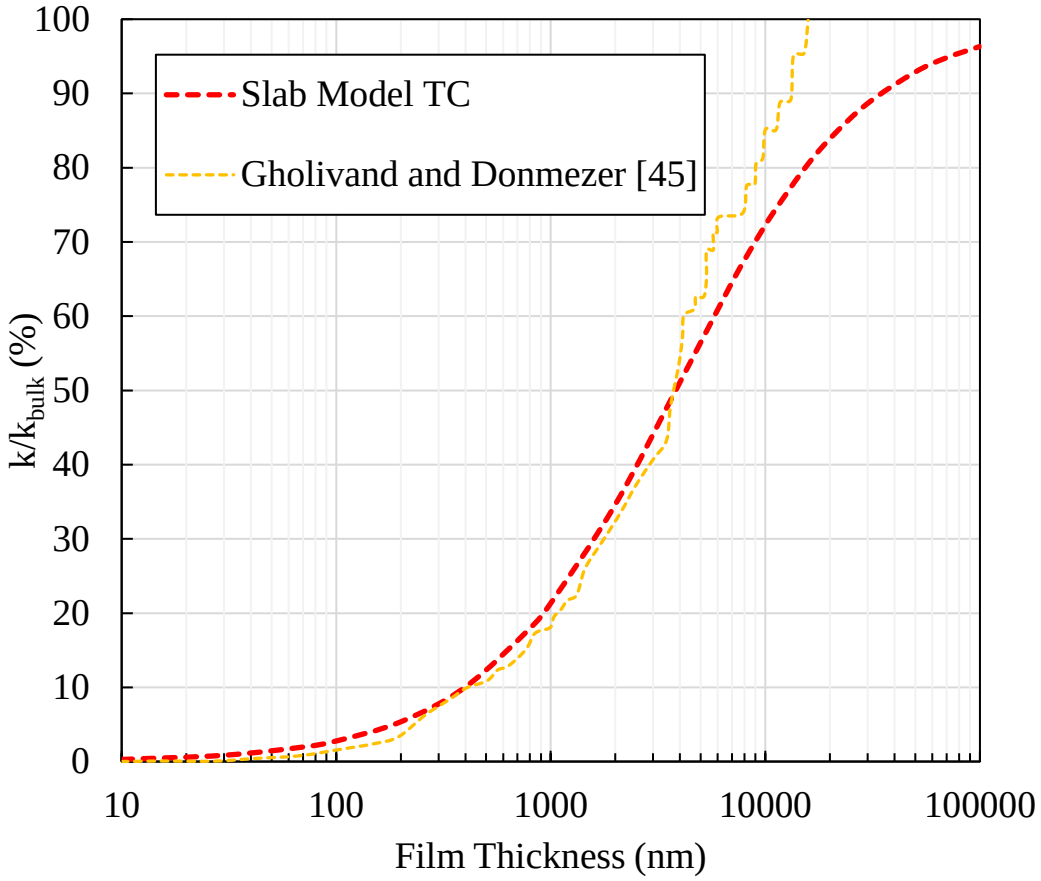

Figure 4.11. Thickness dependent thermal conductivity of MLG derived from the slab model validated by results of Gholivand and Donmezer [45].

After finding the best phonon properties matching the resulted thermal conductivity to the literature, thickness dependent values are recorded as shown in Figures 4.8 to 4.11. These properties are the main input values for the BTE solver. Therefore, using the simple slab model the correct inputs for the BTE model are derived, but also TC spectrums are derived which will be used to analyze the virtual Raman experiment model in next section.

Table 4.1. Thermal and phonon properties of GaAs, Si, GaN, and MLG materials.

Material / Property	GaAs	Si	GaN	MLG
$k\ (W/m\cdot K)$	46 [46]	148 [47]	260 [48]	3000 [49]
C (J/Kg·K)	330 [50]	700 [51]	478 [52]	100 [53]
ρ_d (Kg/m^3)	5316	2330	6150	2260
$C_v(J/m^3\cdot K)$	1754280	1631000	2939700	226000
$\overrightarrow{v_g}$ (m/s)	403.4	907.4	390.2	15316.5
τ (ns)	0.48	0.33	1.74	0.17
Λ (nm)	195	300	680	2600

To understand the amount of size effects present in different materials, it is important to know the mean free path value of dominant heat carriers inside it. According to the Knudsen number defined as the ratio of mean free path to the characteristic length, a problem with a higher Knudsen number, deals with more size effects. For example, the temperature profiles for a 1μm thick sample for different materials are plotted in Figure 4.12. As shown in this figure, materials with higher MFP values undergo size effects in larger amounts. That is why the profile of GaN stays more distant from the Fourier profile than the profile of GaAs which has a shorter MFP. It Is worth mentioning that for any material with any bulk thermal conductivity, the Fourier temperature profile is the same.

Additionally, the derived thickness-dependent thermal conductivity of GaAs, Si, GaN, an MLG are given in Figure 4.12.

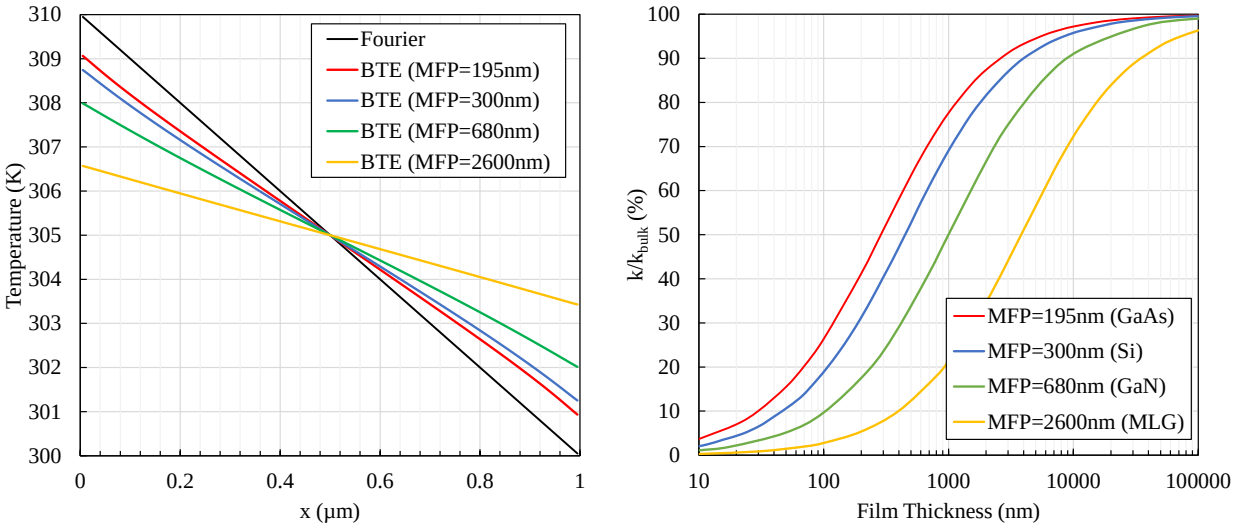

Figure 4.12. (left) BTE and Fourier temperature profiles of 1μm sample of GaAs, Si, GaN, and MLG and (right) derived thickness-dependent thermal conductivities.

4.2. Model of the Experiment (Virtual Experiment)

In this section a virtual Raman-based thermal conductivity measurement technique is developed. As stated in section 1.4, Raman spectroscopy method includes an experiment part as well as an analytical part. In a word, thermal properties for the analytical part giving the best fit to the experimental results are said to be measured values. Here, a phonon BTE solver is employed to represent the conditions during the experiment and to include thermal size effects due to ballistic-diffusive heat transport. It is worth mentioning that although our phonon BTE represents the real temperature distribution in a more accurate way than the Fourier based solutions, it does not cover the temperature variation due to mechanical stresses generated inside the specimen as a result of temperature rise in the Raman experiment. The mechanical stresses during the Raman measurements affect the Raman spectra and therefore detected temperature. As shown in the workflow in Figure 4.1, the input phonon properties for the virtual experiment are derived from the slab model.

On the other hand, the same problem is solved with a Fourier-based solve. Then the input thin film thermal conductivity is differed for each thickness to match the Fourier maximum temperature to the BTE maximum temperature. The one giving the best maximum temperature prediction is deduced as the thin film thermal conductivity of thin film.

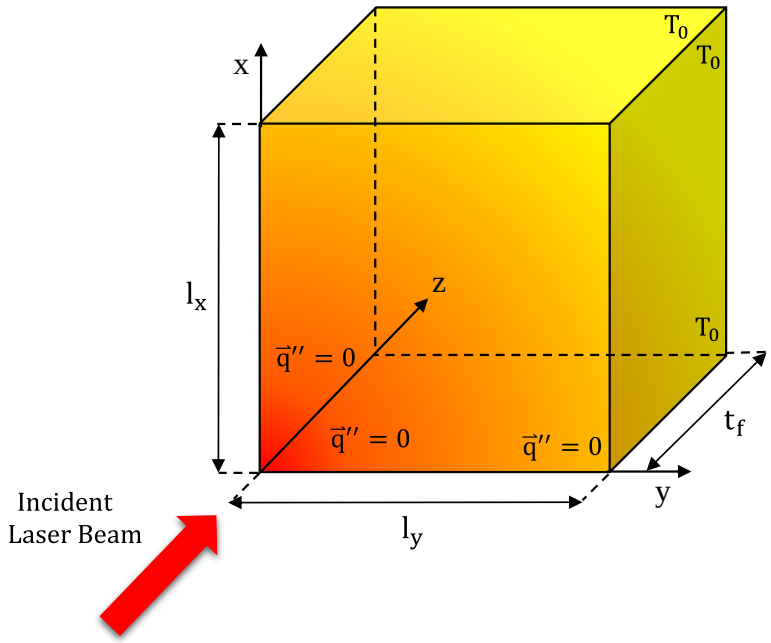

Figure 4.13. Schematic of the 3D virtual Raman experiment model with applied boundary conditions and model parameters.

To simulate the Micro-Raman experiment real conditions, a volumetric heat generation is added to the initial Fourier and phonon BTE solvers. This heat generation is appeared as q''' in Equations (3.11) and (3.12). This term is a function of position (x, y, and z) which includes laser beam properties as well as material of interest's optical properties. When an incident light is shined onto a surface of a thin film, a portion of this is reflected and the other portion is absorbed by the sample. Assuming that all the absorbed energy from the incident light is converted into heat generation inside the specimen, the intensity of light that is not reflected ($I_{non-refl.}$) is calculated by

$$I_{non-refl.} = (1 - \rho)\, I_0 \tag{4.3}$$

where ρ is the reflectance of the material at the probing wavelength (λ) of laser beam and I_0 is the intensity of incident light [54]. The probing wavelength is assumed to be 532nm in all our simulations.

After subtracting the reflected amount of incident light, according to Beer-Lambert's law the remaining intensity is absorbed through the thickness of the sample as given in

$$I(z) = I_{non-refl.} e^{-\alpha z} \tag{4.4}$$

which is a function of depth (distance from z-axis origin) and absorption coefficient α.

The rate of volumetric heat generation is

$$q'''(z) = \alpha I(z) = \alpha(1 - \rho) e^{-\alpha z} I_0 \tag{4.5}$$

which is proportional to absorbed intensity $I(z)$ where the proportionality constant is the absorption coefficient α, that is also a material-dependent optical property at the probing wavelength. Therefore, z-dependent heat generation rate is calculated by Equation (4.5). This function presents a relation between the intensity of incident light and volumetric heat generation as a function of depth. To correctly model the Gaussian laser beam profile, TEM_{00} mode [55] is used in equation

$$I_0 = \frac{2P}{\pi \omega(z)^2} e^{\frac{-2r^2}{\omega(z)^2}} \tag{4.6}$$

to modify the intensity of the incident light in order for it to be a fuction of total laser operating power P, radial distance r, and $\omega(z)$ which is the radius of the laser beam at distance z that the intensity drops down to $1/e^2 \approx 13.53\%$.

Finally, by changing the radial distance r to $\sqrt{x^2 + y^2}$, the volumetric heat source for our simulations can be written as

$$q'''(x,y,z) = (1-\rho)\alpha e^{-\alpha z}\frac{2P}{\pi\omega(z)^2}e^{\frac{-2(x^2+y^2)}{\omega(z)^2}} \tag{4.7}$$

where $\omega(z)$ can be found from equation

$$\omega(z) = \omega_0\sqrt{1+\frac{z^2}{z_R^2}} \tag{4.8}$$

which includes laser beam waist radius ω_0, and the Rayleigh range z_R. The waist radius is considered to be $362\ nm$ in all the simulations.

Furthermore, the Rayleigh range is calculated by

$$z_R = \frac{\pi\omega_0^2 n}{\lambda} \tag{4.9}$$

which is a function of material refractive index n at the excitation wavelength of the Raman laser beam λ.

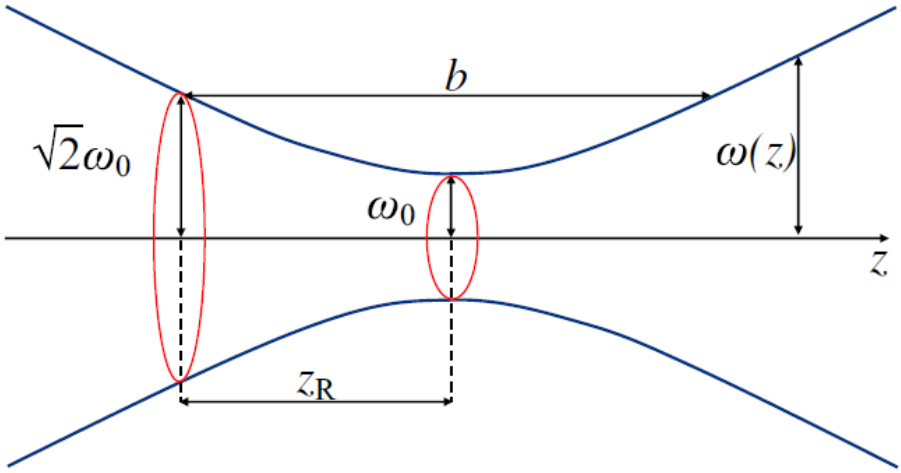

Figure 4.14. Gaussian laser beam where ω_0, z_R and $\omega(z)$ are waist radius, Rayleigh range and laser beam radius at distance z Reprinted by permission from Elsevier [56]. License number: 5237030873237.

Laser beam radius in the focal plane ($z = 0$) is considered to be equal to ω_0 where the light intensity reaches its maximum and decays by propagating in the z-direction and spreads a small amount in the radial direction as shown in Figure 4.14.

Table 4.2. Optical properties of materials at the probing wavelength of 532nm and room temperature (300 K).

Material / Property	GaAs	Si	GaN	MLG
α (cm^{-1})	70154 [57]	12233 [58]	16527 [59]	5836.8 [60]
ρ	0.37446 [57]	0.37437 [58]	0.16111 [59]	0.19179 [60]
n	4.0668 [61]	4.1432 [62]	2.4236 [63]	2.6793 [64]

4.2.1. Grid Study

To find the optimal grid size for 3D simulations, a mesh study is performed. For this purpose, a standard 1μm×1μm×1μm Silicon model is developed as shown in Figure 4.13. A Raman beam with a power of 10 mW, probing wavelength of 532 nm, and waist radius of 362 nm is shined onto the model. The localized heating process starts from the surface that is exposed to the Raman laser that is the x-y plane in z=0. Gradient of the most important variable that is temperature, occurs at x=y=z=0 position. In other words, the maximum temperature reached in the numerical simulation that will be used for thermal conductivity determination, is the most important result of the study. Therefore, the highest temperature is chosen as the case of grid study. At each step the number of rectangular meshes are increased

and maximum temperature is recorded. Figure 4.15 shows the maximum temperature variation versus the number of elements along any edge of the model.

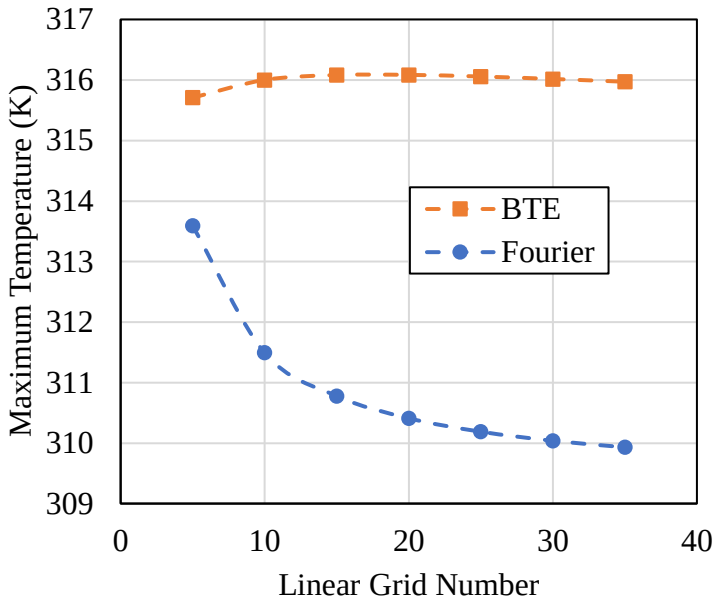

Figure 4.15. Grid independence study for the 3D model.

The difference between the Fourier maximum temperature of 25×25×25 and 20×20×20 drops down to 0.07% where the BTE maximum temperature stays almost the same. Therefore, the 20×20×20 system is considered to be sufficient for a 1µm×1µm×1µm domain for the results not to depend on grid structure. Since the geometry will be changed in our simulations for different thicknesses, the suitable mesh sizes are chosen in a way that an element's size does not exceed 50 nm. For example, in a 2µm×2µm×2µm domain, for elemental rectangular control volume not to exceed 50 nm, a 40×40×40 grid system must be developed.

4.2.2. Domain Size Study (Boundary effects)

Additional to grid independency study, a domain size independency examination is performed. As shown in the problem schematic in Figure 4.13, three sides are given kept at constant temperatures (T_0 = 300 K) and they affect the maximum temperature values reached during the virtual experiment. Therefore, they should be kept as distant as they do not affect

maximum temperature. For this purpose, a 1 µm thin film is exposed to a Raman laser beam the same as the one in the grid study section. However, this time the length of the model in x and y directions is increased in the same boundary conditions as well as the same heat generation. At each step, the most critical variable, maximum temperature is recorded as shown in Figure 4.16. Changes in the maximum temperature is plotted versus the ratio of length to thickness. The difference between the maximum temperature drops below 0.1% from l_x/l_y=2 to l_x/l_y=2.5 as shown in Figure 4.16.

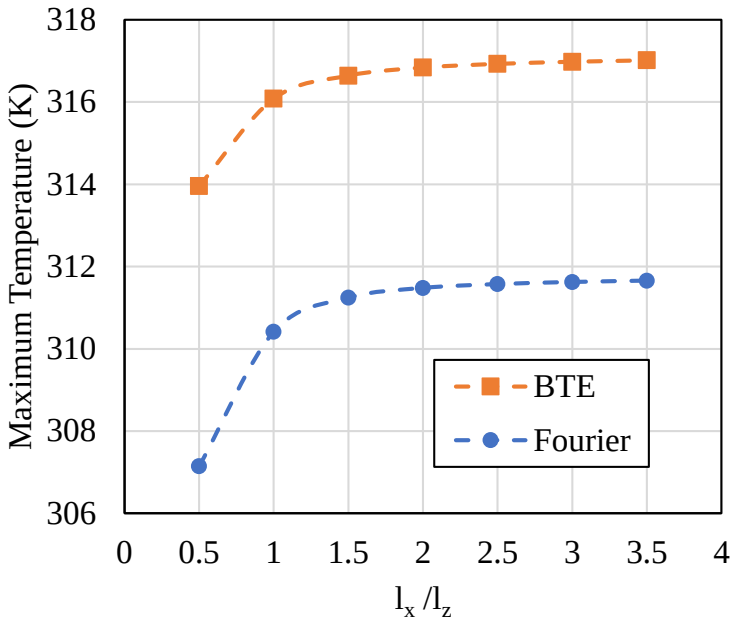

Figure 4.16. Length independency study for temperature measurement.

Therefore, it is required for l_x to be at least two times the thickness of the film to be able to neglect boundary effects on temperature measurement which means if we use two symmetry conditions in x and y directions, the length of the specimen should be at least four times its thickness. In fact, sub-micron thin film specimens in real life are provided in relatively higher ratios but simulating the whole sample requires high computational time and cost and is not efficient.

4.2.3. Results

After finding the suitable mesh structure, the problem dimensions are defined according to section 4.2.2. Then the temperature distribution is derived using both BTE and Fourier solutions. Figure 4.17 shows the 3D temperature distribution of Fourier and BTE solution of 1µm Si thin film under a laser power of 10mW and 532 nm probing wavelength with a waist radius of 362 nm.

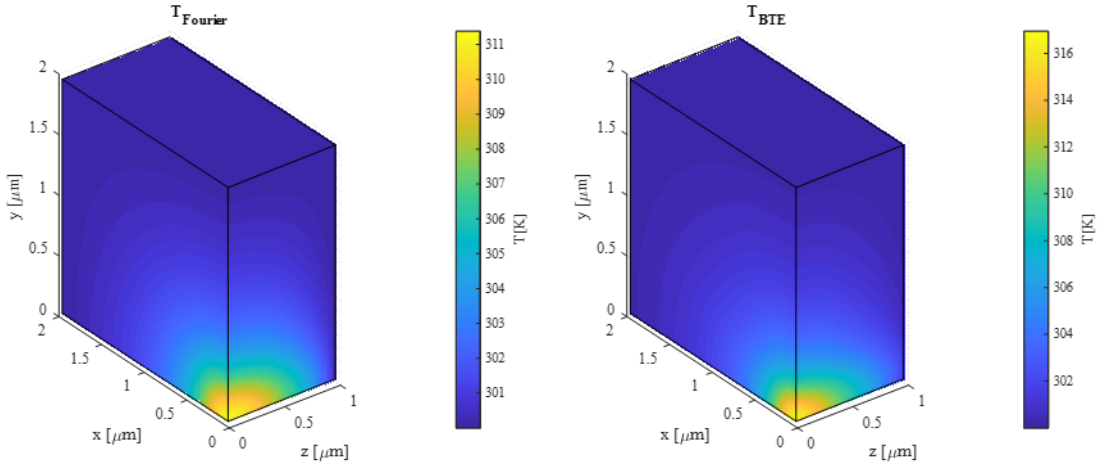

Figure 4.17. 3D temperature distribution of (left) Fourier and (right) BTE solutions for a 1µm Si thin film.

The temperature distribution on the most critical faces for the Fourier and BTE solutions are also shown in Figure 4.18 and 4.19.

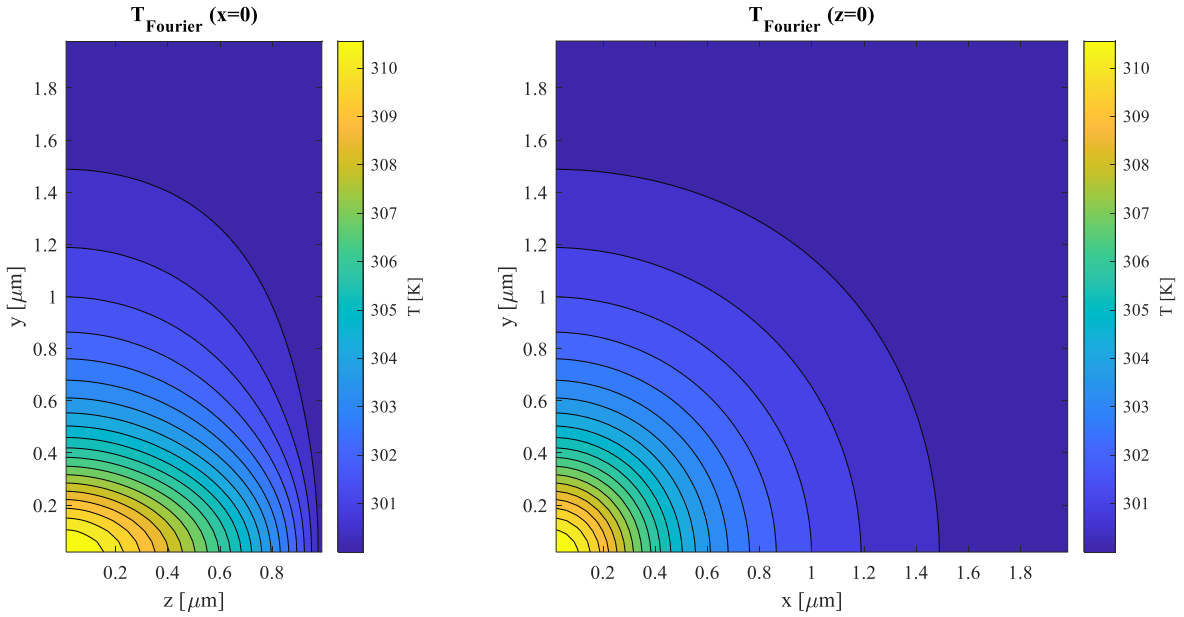

Figure 4.18. Temperature contour of the Fourier solution on the (left) z-y and (right) x-y plane.

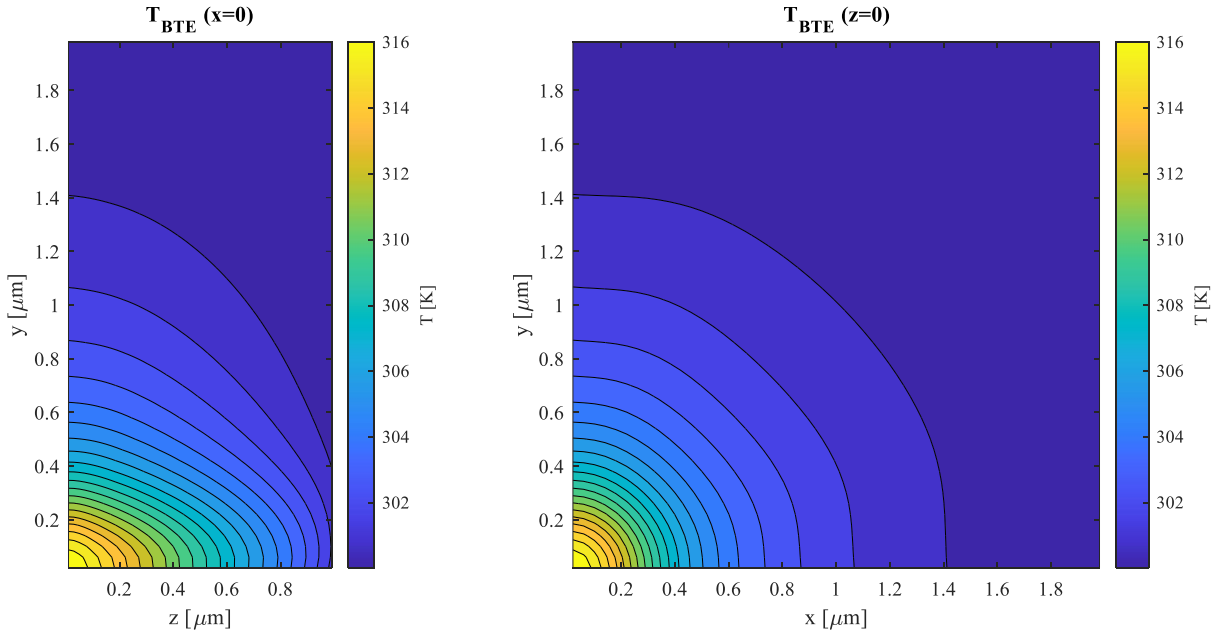

Figure 4.19. Temperature contour of the BTE solution on the (left) z-y and (right) x-y plane.

Furthermore, temperature profiles along the x and z axis are plotted in Figure 4.20. As shown in this figure maximum temperature occurs right in the center of the sample on the face exposed to the laser beam.

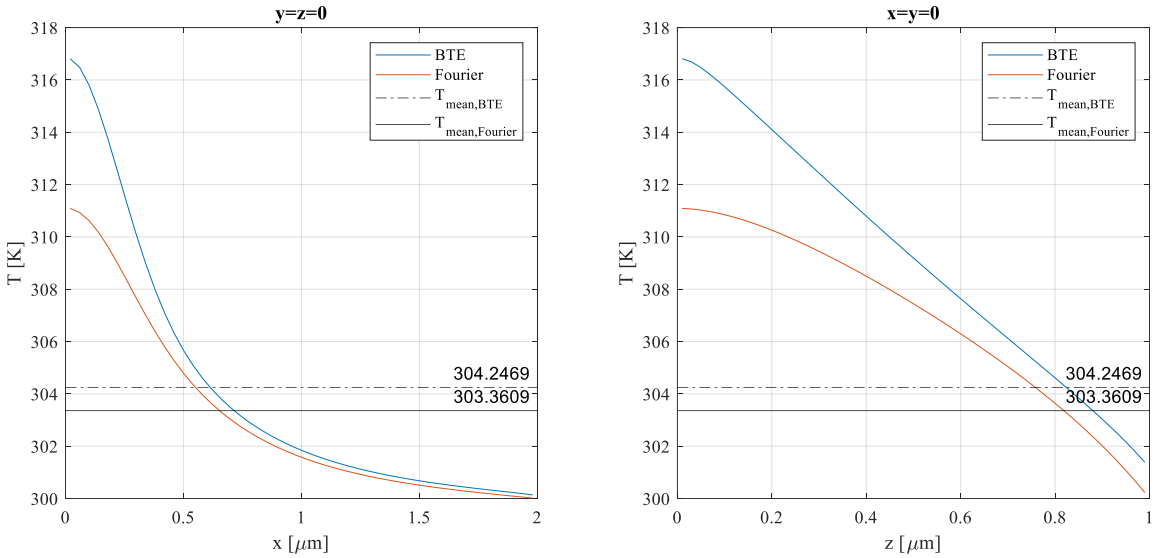

Figure 4.20. BTE and Fourier temperature profiles along the (left) radial (x or y) and (right) axial (z) directions of 1μm Si thin film with 10mW laser power.

In the conventional Raman thermometry, the local temperature is measured during the experiment which is in fact an average of temperature inside the probing region. Because of the localized heating, an infinitesimal region is heated up in which the temperature should be detected. Therefore, the smaller the averaging region, the more accurate temperature measurement. Mean temperature values shown in Figure 4.20 represent an average temperature in a cubic region with a length of waist radius and depth of $1/\alpha$ which is considered to be the penetration depth for each material. However, to match the Fourier results with the BTE results to find thin film thermal conductivity, the maximum temperature values are examined in next chapter which is more accurate than the average temperature approach.

Finally, to understand thermal size effects due to ballistic-diffusive heat transport during the Raman experiment, the difference between the maximum BTE temperature and maximum Fourier temperature is recorded. To have a better insight, the data is extracted for each material, at two different thicknesses 100 nm and 200 nm and three different laser operating powers 10 mW, 50 mW, and 100 mW. Figures 4.21 to 4.24 show the results for Si, GaN, GaAs, and MLG, respectively.

For the laser power of 10 mW in the 100 nm Si thin film there is a 3.8 K difference between maximum temperatures while it increases to 5.3 K for the 200 nm thin film in the same power. The initial maximum difference 3.8 K increases to 19.2 K and 38.4 K for 50 mW and 100 mW powers, respectively. It is deduced from Figure 4.21 that the slope of 200 nm thin film is sharper than the 100 nm one.

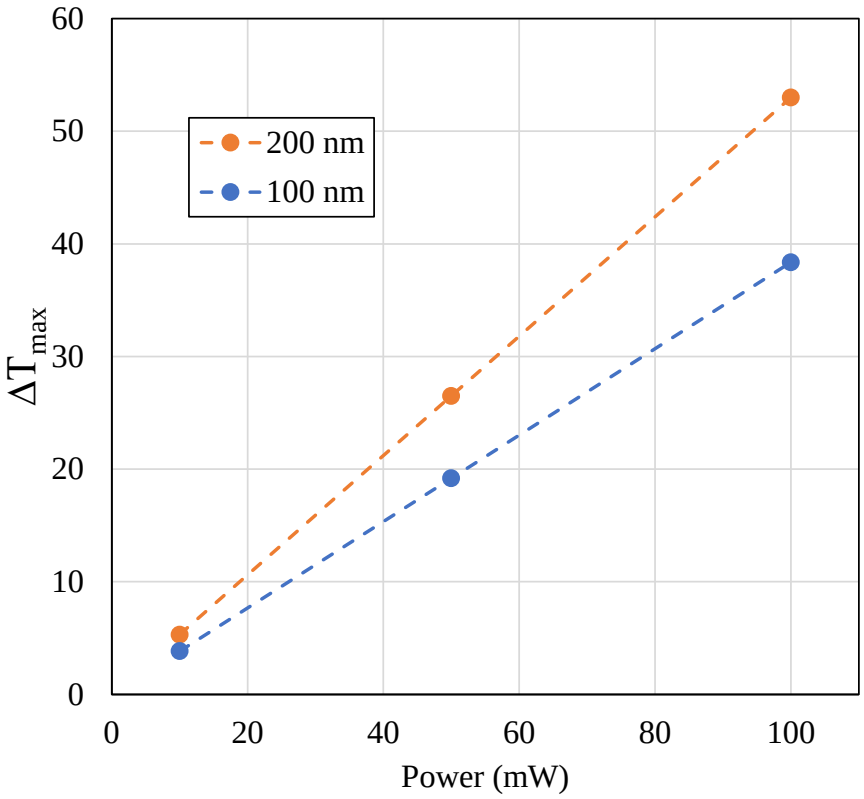

Figure 4.21. Variation of maximum temperature difference between BTE and Fourier for 100 nm and 500 nm Si thin films for laser powers of 10 mW, 50 mW, and 100 mW in the same probing wavelength of 532 nm and waist radius of 362 nm.

For the laser power of 10 mW in the 100 nm GaN thin film there is a 9.2 K difference between maximum temperatures while it increases to 13.1 K for the 200 nm thin film in the same power. The initial maximum difference 9.2 K increases to 45.8 K and 91.6 K for 50 mW and 100 mW powers, respectively. It is also deduced from Figure 4.22 that the slope of 200 nm thin film is sharper than the 100 nm one.

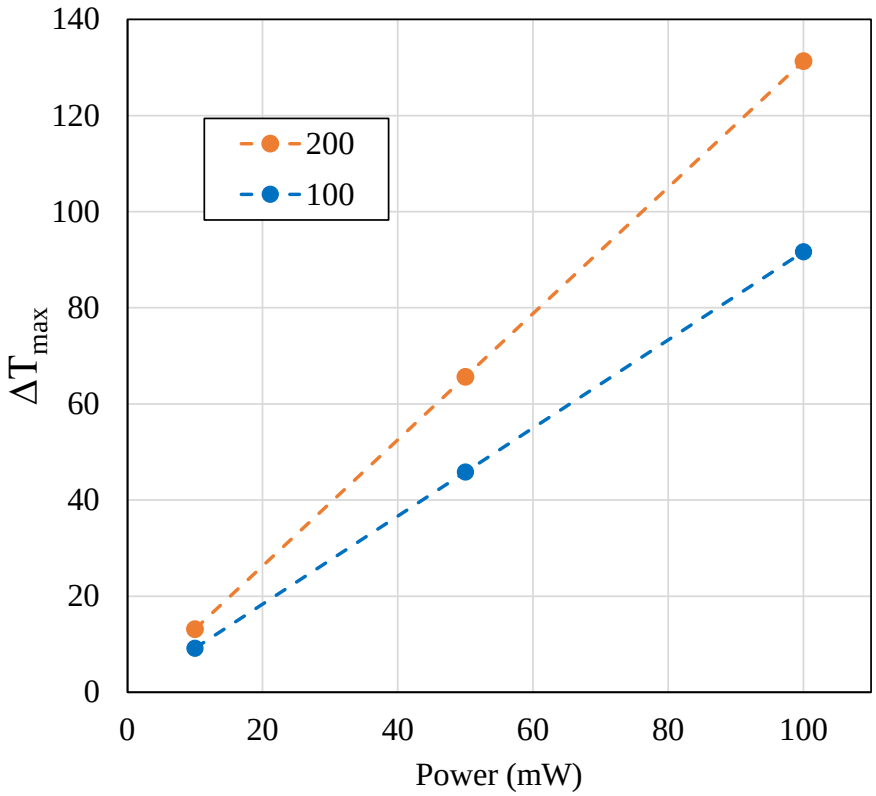

Figure 4.22. Variation of maximum temperature difference between BTE and Fourier for 100 nm and 500 nm GaN thin films for laser powers of 10 mW, 50 mW, and 100 mW in the same probing wavelength of 532 nm and waist radius of 362 nm.

For the laser power of 10 mW in the 100 nm GaAs thin film there is a 35.1 K difference between maximum temperatures while it increases to 38.1 K for the 200 nm thin film in the same power. The initial maximum difference 35.1 K increases to 175.6 K and 351.2 K for 50 mW and 100 mW powers, respectively. It is deduced from Figure 4.23 that the slope of 200 nm thin film is sharper than the 100 nm one.

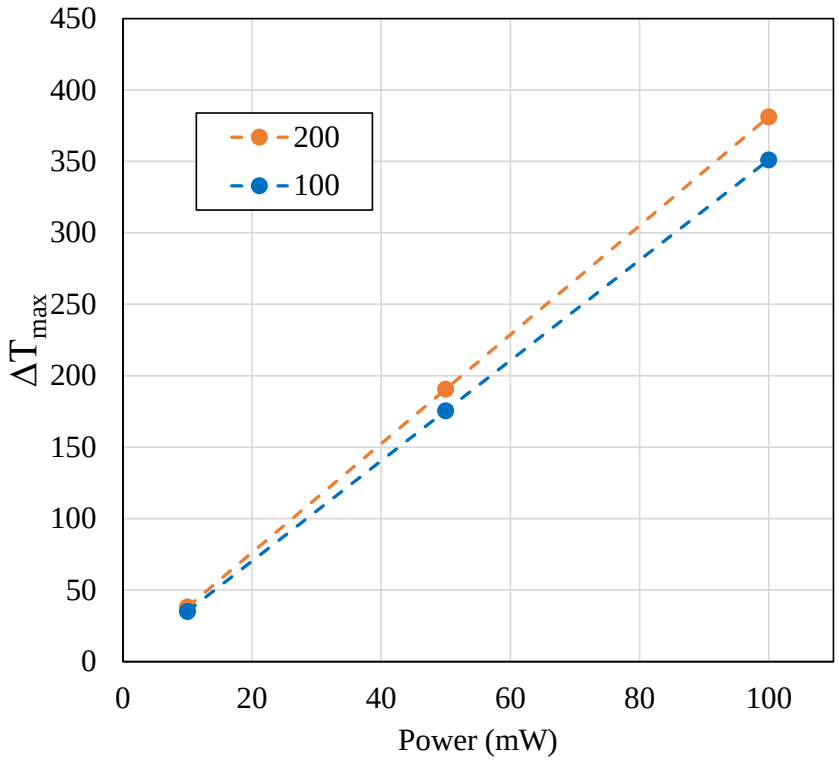

Figure 4.23. Variation of maximum temperature difference between BTE and Fourier for 100 nm and 500 nm GaAs thin films for laser powers of 10 mW, 50 mW, and 100 mW in the same probing wavelength of 532 nm and waist radius of 362 nm.

For the laser power of 10 mW in the 100 nm MLG thin film there is a 1.1 K difference between maximum temperatures while it increases to 1.67 K for the 200 nm thin film in the same power. The initial maximum difference 1.1 K increases to 5.5 K and 11 K for 50 mW and 100 mW powers, respectively. It is deduced from Figure 4.24 that the slope of 200 nm thin film is sharper than the 100 nm one.

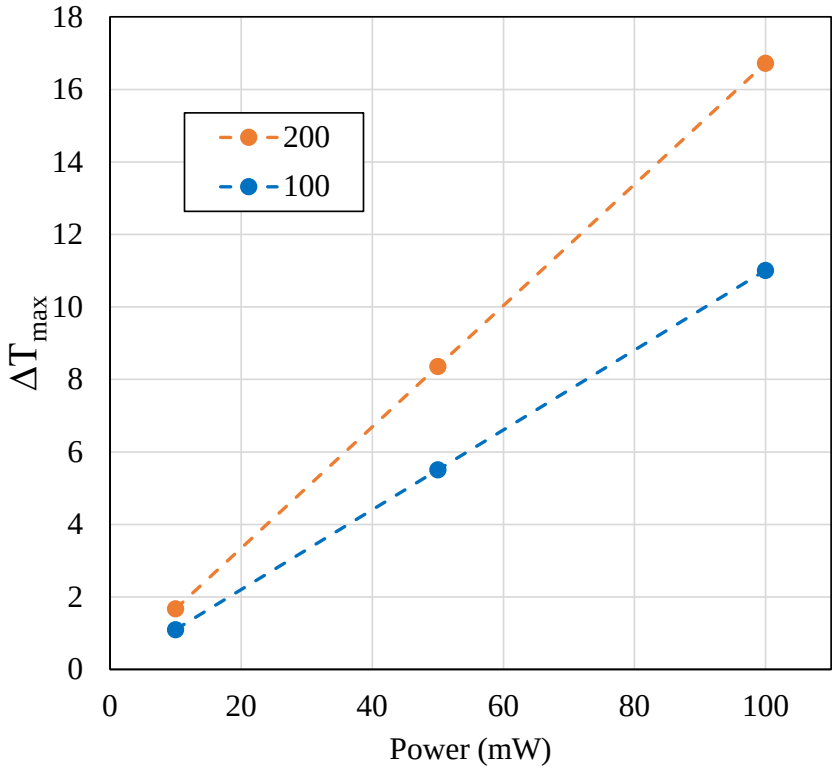

Figure 4.24. Variation of maximum temperature difference between BTE and Fourier for 100 nm and 500 nm MLG thin films for laser powers of 10 mW, 50 mW, and 100 mW in the same probing wavelength of 532 nm and waist radius of 362 nm.

4.3. Conclusions

- Thickness dependent thermal conductivities derived by the simple slab model are in a good agreement with the literature.

- As shown in Figure 4.12, boundary scattering effects become more dominant for materials with longer mean free path. For example, the slab model temperature profile of GaN becomes more distracted from Fourier than the profile of Si since it has a higher mean free path value.

- According to the findings from the slab model, the thickness dependency of thermal conductivity of any material is a function of phonon mean free path.

- With the help of model of virtual Raman experiment, thermal behavior of the specimen during the real experiment conditions can be predicted more accurately by using the phonon BTE solution rather than Fourier.

- The difference between BTE and Fourier maximum temperatures, increase by increasing the laser power as well as increasing the film thickness.

- GaAs is the most sensitive material amongst the others. Therefore, lower laser powers must be used to prevent degradation of the specimen due to high temperatures.

- For its comparatively high thermal conductivity and phonon mean free path, MLG is the least sensitive material to the laser power. Therefore, to observe a detectable temperature rise, a relatively higher laser power should be used in its Raman measurements.

5. ERROR ANALYSIS OF CONVENSIONAL COMPLEMENTARY MODEL

To find the reduced thin film thermal conductivity using the virtual Raman experiment developed in this study, first the maximum BTE temperature is deduced. Then the same problem is simulated with a Fourier solver as shown in Figure 5.1 and its maximum temperature is derived as well. Then the input thermal conductivity to the Fourier solver is reduced until obtaining the same maximum temperature as the BE solution. One thermal conductivity giving the best match to maximum temperatures are recorded as the thin film thermal conductivity by the old technique (k_{tf}^*). To evaluate the results deduced from the virtual Raman experiment developed for this study, the error between thermal conductivity derived from this method and slab model derived thermal conductivity is calculated by equation

$$Error\ (\%) = \frac{k_{tf} - k_{tf}^*}{k_{tf}} \times 100 \tag{5.1}$$

where k_{tf} and k_{tf}^* are thermal conductivities derived from slab model and virtual Raman experiments, respectively.

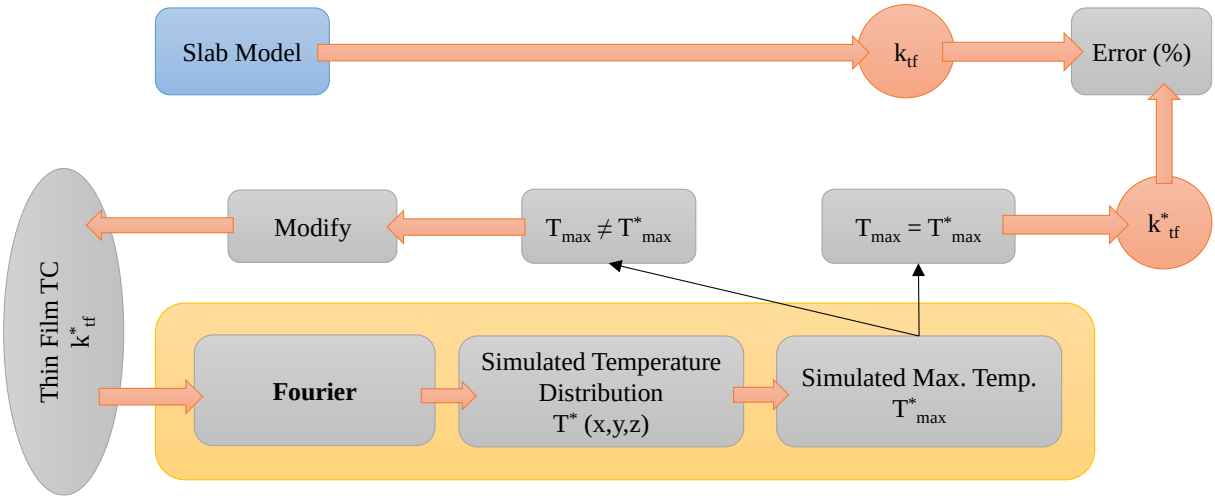

Figure 5.1. The workflow of finding thin film thermal conductivity by the virtual Raman experiment and its error using the slab model.

Table 5.1 includes thermal conductivities of the studied materials derived from the slab model for two different thicknesses (100 nm and 500 nm). This table includes derived maximum Fourier and BTE temperatures with the bulk thermal conductivities as an input. Then the input thermal conductivity for the Fourier solver is reduced down to one represented in Table 5.1 to obtain the maximum temperature deduced from the BTE solver.

Figures 5.2, 5.3, 5.4, and 5.5 show the calculated thermal conductivities through the virtual Raman experiment compared with the results from the slab model for GaAs, Si, GaN, and MLG materials, respectively.

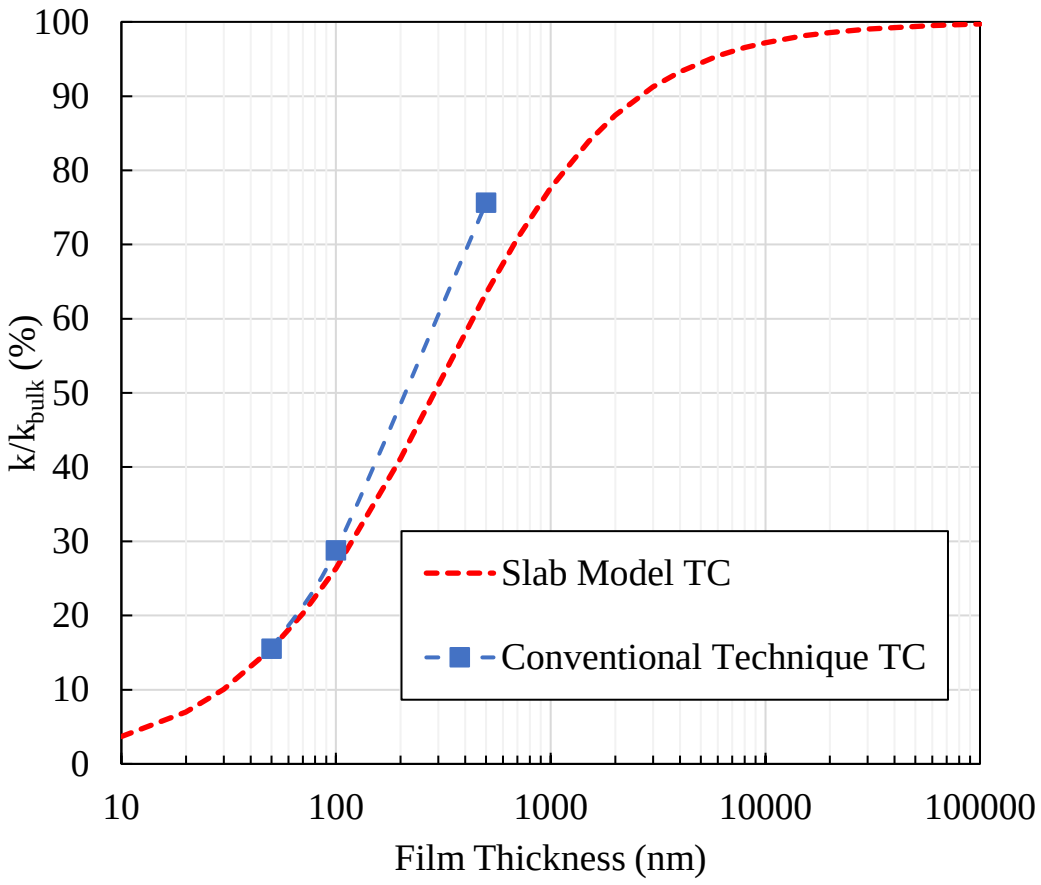

Figure 5.2. Nondimensional thermal conductivity of GaAs compared to the results of the slab model.

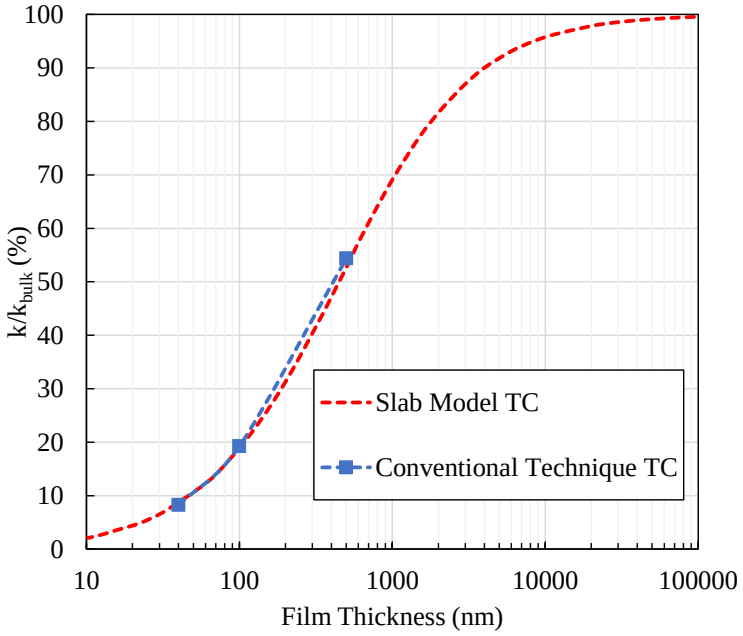

Figure 5.3. Nondimensional thermal conductivity of Si compared to the results of the slab model.

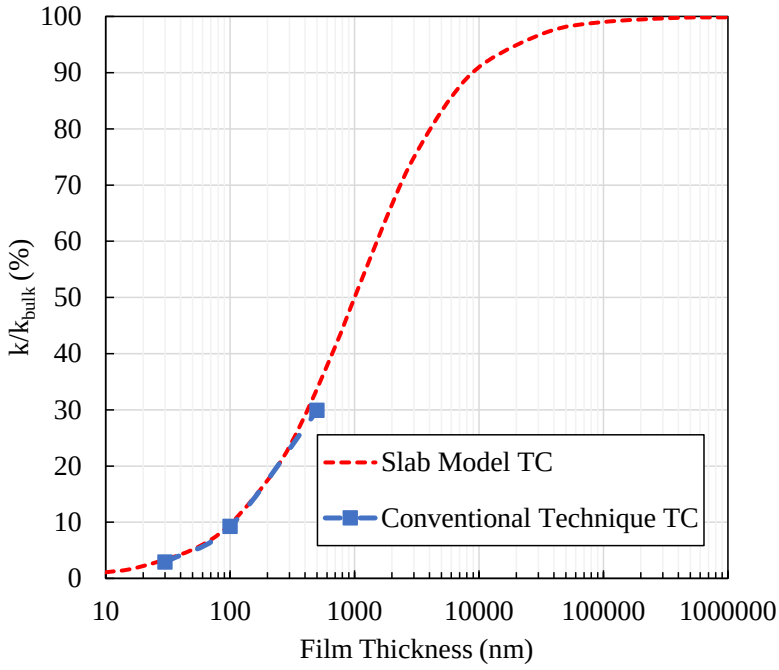

Figure 5.4. Nondimensional thermal conductivity of GaN compared to the results of the slab model.

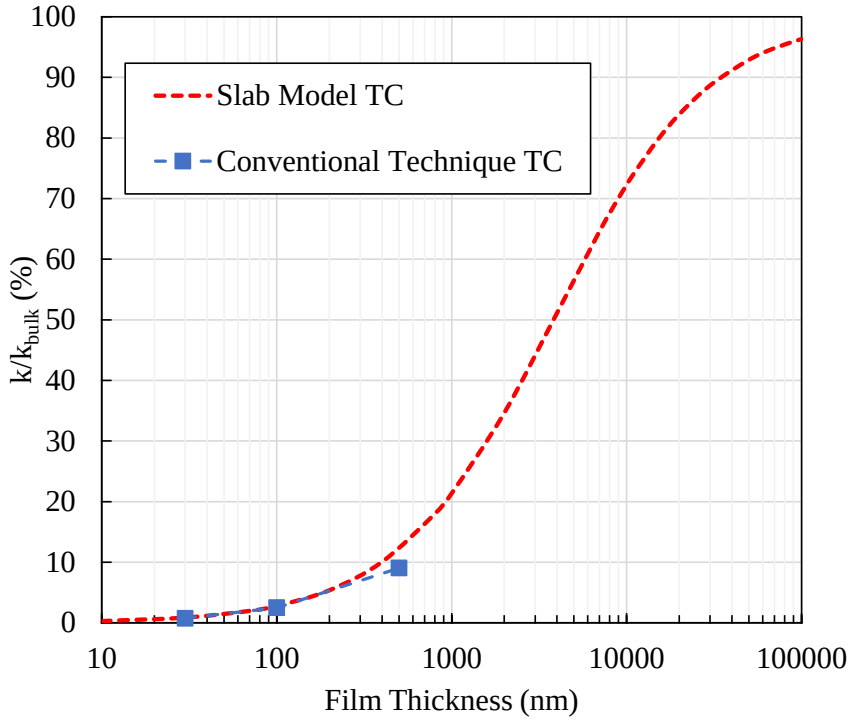

Figure 5.5. Nondimensional thermal conductivity of MLG compared to the results of the slab model.

Table 5.1. Error analysis of virtual Raman-based thermal conductivity measurement.

	GaAs	Si	GaN	MLG	Thickness (nm)
k_{tf}/ k_{bulk} (%)	26.37	19.12	9.66	2.78	100
	63.45	53.07	33.66	12.20	500
$T_{max, Fourier}$ (k_{bulk})	314.2005	300.9114	300.9273	300.0283	100
	376.6387	307.1067	306.9516	300.2338	500

Table 5.1. Error analysis of virtual Raman-based thermal conductivity measurement (cont.).

$T_{max,\ BTE}$ (k_{bulk})	349.3204	304.7476	310.0902	301.1294	100
	401.0361	313.0543	323.2555	302.5891	500
k_{tf}^{*}/ k_{bulk} (%)	28.80	19.26	9.23	2.5	100
	75.65	54.39	29.88	9.03	500
$T_{max,\ Fourier}$ (k_{tf})	349.2998	304.7331	310.046	301.1306	100
	401.596	313.0657	323.2616	302.5886	500
Error (%)	-9.22	-0.73	4.45	10.07	100
	-19.23	-2.49	11.23	25.98	500

5.1. Conclusions

- The old Raman thermometry technique which uses a Fourier based complementary method may overestimate or underestimate thin film thermal conductivity of thin films according to the errors calculated in Table 5.1.

- The performance of virtual Raman experiment to measure thin film thermal conductivity is better for relatively lower thicknesses.

- For a specific thin film thickness, measured thermal conductivity for a material with a higher mean free path is associated with a higher error due to dominant thermal size effects.

6. CONCLUSIONS AND FUTURE WORK DIRECTIONS

6.1. Conclusions

Because of their wide range of application in microelectronic devices, thin films need to be thermally characterized for device thermal management purposes. Theoretical techniques suffer from their high computational time and cost. While experimental methods setups are expensive and hard to calibrate. In this study, a numerical method is introduced as a substitution for the Raman-based thermal conductivity measurement technique. The real conditions during the actual experiment are simulated via the gray Boltzmann Transport Equation. This solver gives a better estimation of the temperature distribution by including thermal size effects originating from localized heating and boundary scattering effects. The resulted thermal conductivities are compared to the data from a simple slab model which is initially validated by the literature data. Thickness dependent thermal conductivities are derived for GaAs, Si, GaN, and MLG materials which are promising candidates in the semiconductor technology. The results show that materials like MLG that have higher phonon mean free paths, undergo larger thermal size effects which can cause erroneous calculation of their thermal conductivity as well as temperature prediction by Fourier law of heat conduction.

6.2. Future Work Directions

To improve the conventional Raman-based thermal conductivity measurement, it is suggested to use the phonon BTE instead of the Fourier based thermal model. In fact, the Fourier law of heat conduction fails to correctly predict the temperature in the presence of thermal size effects. Therefore, it gives an erroneous reduced thermal conductivity of a thin film. Accordingly, the micro-Raman based thermal characterization coupled with the BTE thermal model is more accurate than the one coupled with a Fourier model.

Figure 6.1 shows the suggested procedure for the future micro-Raman based thermal conductivity measurement. According to the modified technique, the complementary thermal model should no longer be a Fourier based one due to the size effects originating from not only the boundary confinement in thin films, but also the localized heating during the Raman experiment as addressed in the results section. In this method, phonon properties like mean free path is guessed instead of thermal conductivity itself. Using this property, the maximum temperature is estimated by the virtual Raman model developed in this study. If the measured and simulated maximum temperatures be not equal, the guessed phonon property is changed until resulting in the same maximum temperatures. Finally, after that the correct phonon properties are deduced, they are put into the simple slab model developed in this work to obtain thickness dependent thermal conductivity of any material.

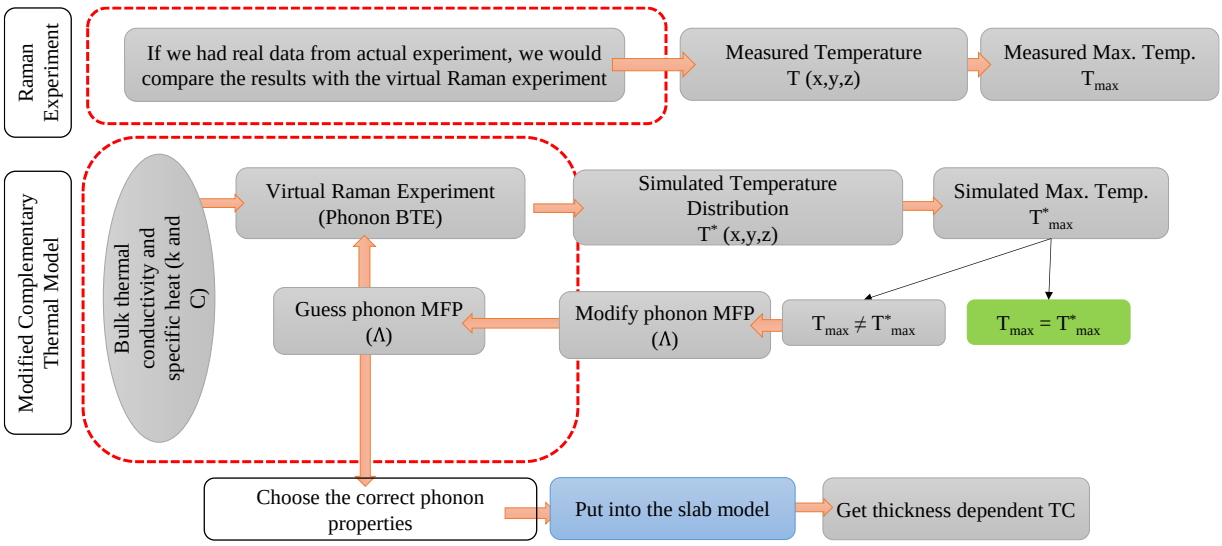

Figure 6.1. Workflow of suggested technique for future works.

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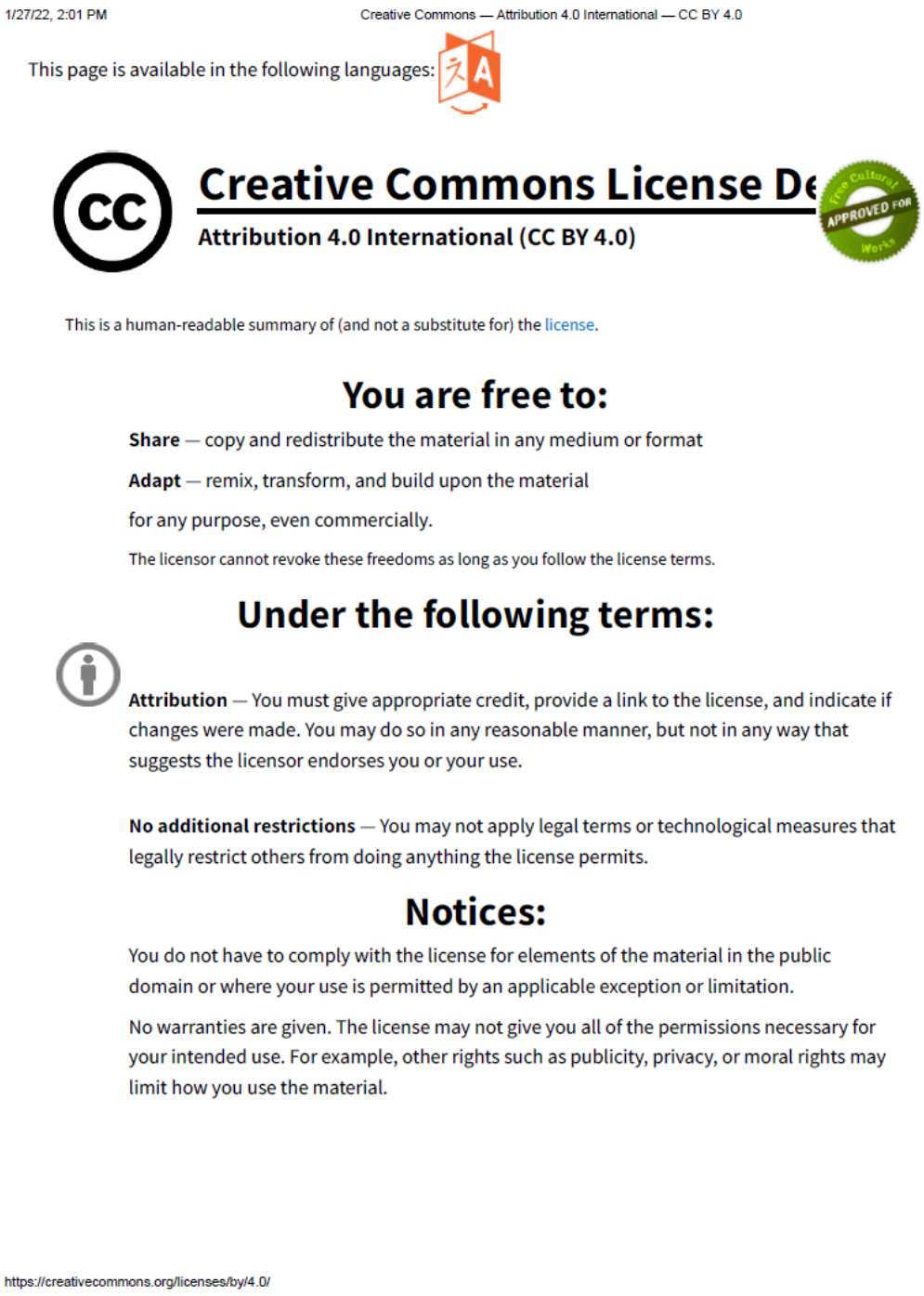

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Study of Thermal Conductivity of Porous Silicon Using the Micro-Raman Method

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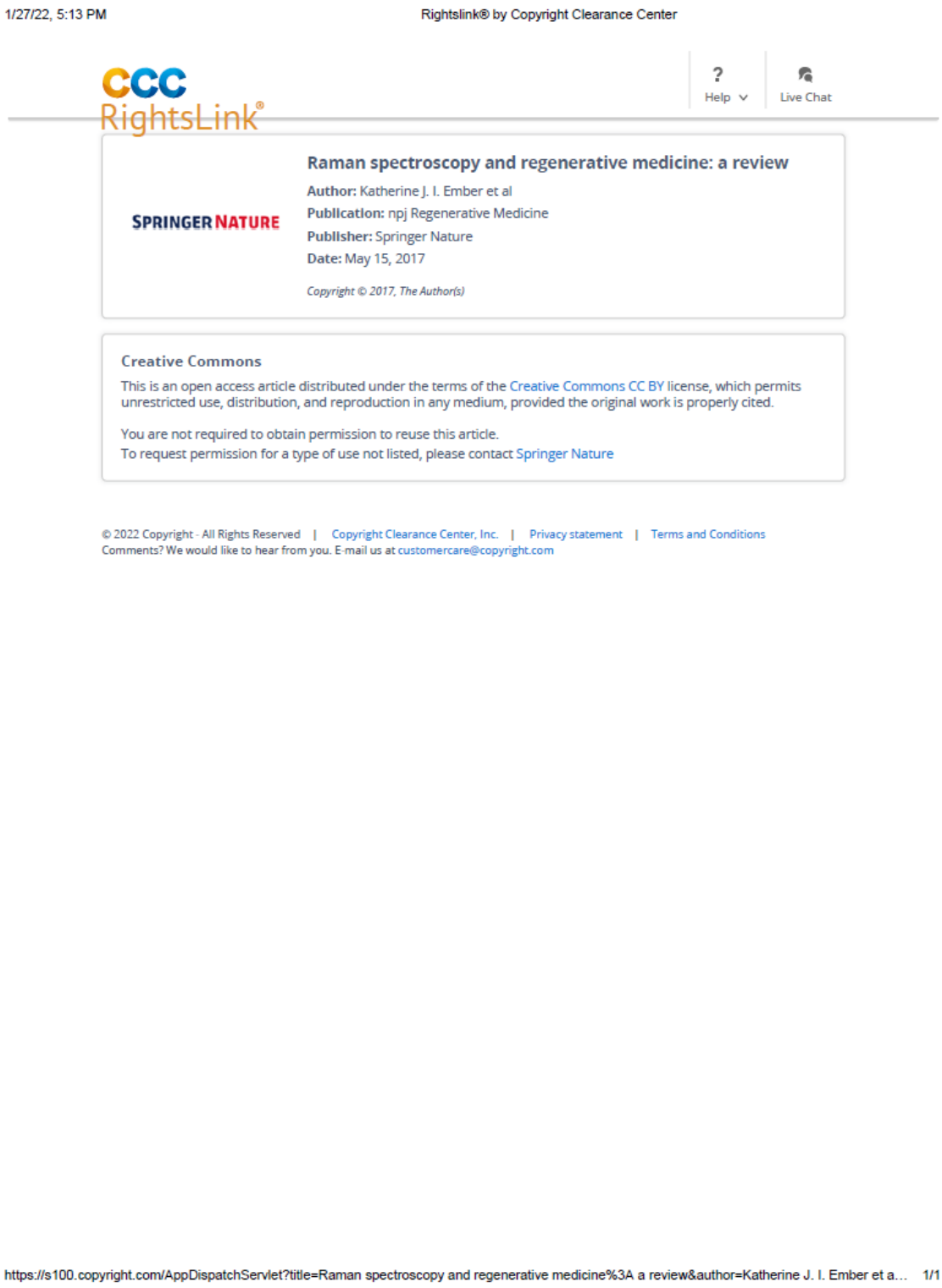

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