A Novel Technique for Interfacial Thermal Resistance Measurement for Nanoscale Thin Films

R. A. Pulavarthy and M. A. Haque¹

Department of Mechanical & Nuclear Engineering, Penn State University

314 Leonhard Building, University Park, PA 16802

Thermal resistance of interfaces is one of the most challenging measurands in experimental heat transfer, particularly for micro and nanoscale thin films. It is also the dominating quantity in thermal management in microelectronic and energy conversion devices. We present a novel technique that exploits the size dependence of thermal resistance in thin films to magnify the discontinuous temperature drop at the interface, which is then measured with infrared thermometry. We show that orders of magnitude amplification in interfacial temperature drop is possible by making the specimen freestanding, which facilitates the measurement. We present experimental results on metal-dielectric interfaces involving aluminum, copper, silicon di-oxide and hafnium oxide for validation of the novel technique.

Keywords: Interfacial thermal resistance, Kapitza resistance, Thermal transport, Thin films

¹ Corresponding author: Tel: 814-865-4248, Fax: 814-865-9693, Email: mah37@psu.edu

Graphical Abstract

Caption: By eliminating the substrate (that act as large heat sinks), orders of magnitude amplification of the interfacial (discontinuous) temperature drop can be achieved in nanoscale thin films, which facilitates interfacial thermal resistance measurement.

Introduction

Interfaces between dissimilar materials are ubiquitous in a wide variety of materials systems from composites and coatings to micro-electronics and micro-electro-mechanical systems. The property of the interface can be as important as the constituent materials, which is particularly true from thermal transport perspective. Thermal contact resistance has been widely studied for imperfect contact between two surfaces due to the presence of microscopic asperities characteristic of engineering surfaces [1]. Even with the perfect contact, interfaces create impedance to thermal transport by developing a discontinuous temperature drop (T_{drop}) in presence of a heat flux q normal to the interface[2]. The first measured interfacial resistance was reported by Kapitza [3] while working with liquid helium. It is essentially a proportionality constant that relates the differences in the densities and phonon propagation speeds in the two materials to measurable terms such as heat flux across an interface and the temperature drop associated with that interfacial region as follows,

$$R_k = \frac{T_{drop}}{q''} \quad (1)$$

While the impact of interfacial thermal resistance on the overall thermal response of systems is acknowledged irrespective of length-scales [4-6], it becomes particularly important for micro and nano scale systems. At nanoscale, the thermal transport phenomenon by phonons is altered due to effects like phonon boundary scattering, modifications in the phonon dispersion relation and quantization of phonons. For example, in the ever-shrinking modern semiconductor devices, very high power dissipation density means that thermal transport across the interface dictates the performance. Due to the difference in acoustic impedances and phonon group velocities, interfaces in these devices can block resist heat flow and cause chip overheating. Fundamental understanding of the interfacial thermal transport can be more important than the thermal conductivity of the materials that form the interface [7]. Similarly, large values of temperature drop impact applications like phase change memory (PCM) devices [8] and thermoelectric energy conversion [4].

The fundamental reason behind the thermal resistance is the interruption of phonons at the interfaces, represented by the phonon transmission coefficient, which enables to estimate the

heat flux across the interface. For perfect contacts, Acoustic Mismatch Model (AMM) [9] and Diffuse Mismatch Model (DMM) [10] have been used to predict the interfacial thermal resistance. The AMM assumes that phonons are governed by continuum acoustics. Thus, phonons impinging on the interface can reflect, refract and/or mode-convert. An isotropic simplification is often made in calculating the phonon transmission probability in the AMM because phonons are affected by the mode of propagation (longitudinal or transverse), the angle of incidence, and the level of anisotropy in each material. The AMM has proven to be successful at low temperatures while the DMM, which assumes that the phonon loses all the previous memory upon scattering, predicts relatively well at higher temperatures. Nevertheless at much higher temperatures (~ 300 K), around which the microelectronic devices operate, it typically underestimates with respect to the experimental values. The underlying assumption of elastic scattering in AMM gives an overestimated value of the interfacial resistance [11]. These models envisage only the phononic contribution to the heat transfer and ignore the heat transport by electrons. Therefore, interfaces involving metals as one of the materials do not give accurate results with these models.

Measurement of interfacial thermal resistance is an extremely challenging because of the small magnitude of temperature drop. Typically, the interface is structurally supported by a thick substrate that acts as a large heat sink. For films with thickness lesser than the penetration depth of the thermal waves, the film conductance cannot be isolated from the interface conductance. This offers a lower limit to the film thickness for measurement of interfacial conductance [12]. Thermally interrogating the interface without the influence of the substrate is very difficult for thin films, and basic requirement becomes ultra-fast probing [13] to minimize the substrate effects. The $3-\omega$ technique can measure interfacial thermal resistance [14, 15], but the stringent need for high frequency AC heating scales unfavorably with thermal penetration depth to match film thickness. A much faster technique, the transient thermo-reflectance [16], is therefore more commonly used. This involves a ‘pump’ and a ‘probe’ light pulse to excite the electrons and sense the change in reflectivity with temperature respectively. This method is applicable to different materials spanning wide range of lengths, thermal conductivity and geometry [17-19]. The basic principle has been the same i.e. parametric variation of the thermal property to obtain the best fit of the model prediction to the experimental data. It is important to note that the technique not only involves sophisticated setup with a high-precision and ultrafast laser system,

lock-in amplifier, polarizing filter etc., but also substantial modeling efforts even after numerous advancements to the data analysis [20-22].

The significance of interfacial thermal resistance for nanoscale thin films and heterostructures and challenges in its measurement motivate us to develop a simpler technique. The basic concept behind the novel technique is shown in Figure 1, where the thin films as well as their interface are nanofabricated and released from the substrate. One end of the freestanding specimen is then heated with a micro-heater to impose controlled thermal boundary condition. The remarkable feature of this setup is that in absence of any substrate, the nanoscale specimen has ultra-high thermal resistance (R_{th}), which is given by,

$$R_{th} = \frac{T_{hot} - T_{cold}}{q_{cond}} = \frac{x}{Ak} \quad (2)$$

where, T_{hot} , T_{cold} , q_{cond} , x , k and A are hot end temperature, cold end temperature, conductive heat transfer rate, length, thermal conductivity and cross-sectional area of the specimen respectively.

Figure 1. Freestanding nanoscale thin films show ultra-high thermal resistance, which can amplify the temperature drop at the interface by orders of magnitude.

For example, 50 microns long, 5 microns wide and 50 nm thick aluminum specimen has thermal resistance of 1.4×10^6 K/W. We propose that such large thermal resistance causes very large temperature drop along the specimen and even more importantly at the interface, which should be easy to measure using relatively simpler techniques such as resistance thermometry or infrared techniques [23]. The heat flux can be measured from the temperature profile and the boundary conditions through energy balance, since the total heat flow into the specimen is the sum of heat convected over its surface area. Therefore, both temperature drop and heat flux can be obtained without any complicated modeling. It is interesting to note that the thermal resistance increases nonlinearly with film thickness, hence accuracy and ease of the proposed technique increases with the decrease film thickness. In contrast, the high frequency requirements for 3- ω or thermo-reflectance techniques become increasingly difficult as film thickness decreases. Also, both these techniques employ a thin metal film (10-50 nm) as the thermal heater and transducer, which may influence the accuracy for specimens with smaller or comparable thickness.

In this study, we present the implementation of the proposed concept using nanofabricated specimens and non-contact infrared microscopy to measure the interfacial thermal resistance between thin films of a metal and an insulator. The next section describes the fabrication processing required for the technique. The choice of a metal-insulator system is based on its prevalence in semi-conductor devices. Also, as already discussed above, the AMM and DMM fall short in accurately predicting the interfacial resistance for thermal transport across materials in which the electrons are the major heat carriers. Section 3 describes the mathematical model while experimental results for Cu-SiO₂, Al-SiO₂ and Al-HfO₂ interfaces are reported in section 4. Finally, the conclusions are drawn on the performance of the proposed technique in section 5.

Materials and Methods

In this study, we consider the specimen geometry shown in Figure 1. For metal part, we used 150 nm thick copper and 100 nm aluminum films. Two insulators, namely 300 nm thick silicon di-oxide and 30 nm thick hafnium oxide were used to create the Cu-SiO₂, Al-SiO₂ and Al-HfO₂ interfaces. All these specimens are 10 microns wide. The length of the metal film is around 200 μ m and 100 μ m for Copper and Aluminum respectively. Figure 2 illustrates the

nanofabrication processing steps developed for specimen preparation. Firstly, the dielectric layer is grown on a Si substrate, either by thermal oxidation (SiO_2) or Atomic Layer Deposition (HfO_2). The second step is to lithographically pattern cantilever type geometry on the insulator and then etch it with reactive ion etching with CF_4 plasma. In the third step, a lift-off process was used to create a negative pattern of the metal film using front side alignment. The metal (copper or aluminum) film is then evaporated on the lift-off pattern to create the aligned metal-dielectric specimen with interface. This specimen is still supported by the silicon substrate. In the fourth step, the substrate is etched using Xenon difluoride (XeF_2), which makes the sample freestanding. The heat radiation from the floor underneath can cause flawed temperature measurements of the sample. Hence, a larger depth of the floor from the sample is desired to minimize the erroneous temperature readings.

Figure 2. Nanofabrication processing steps for freestanding metal-dielectric interfacial specimens.

Experimental Set-Up

Once the freestanding interfacial specimen fabrication is complete, a 2mm x 2mm resistance temperature detector (omega.com) is mounted on the metal side of the chip using a micro-manipulator. This element acts as a heat source upon passing electrical current. In a typical experiment, the heater element is activated with dc current so that large, comfortably measurable temperature drop is established at the interface. Since the experiments are performed under an Infrascop II thermal microscope (Quantum Focus Instruments Corporation), this can be achieved in real time.

Figure 3. (a) Optical micrograph showing a freestanding specimen (b) infrared image of the specimen after activating the heater located at the metal end.

Figure 3 shows an optical image of the sample with interface between Aluminum and HfO_2 after the isotropic etch of silicon underneath. It also shows the infrared image after heating at the metal end. The infrared microscope used in this study has spatial and temperature resolutions of about 1.6 microns and 0.1 K, respectively. The specimen can be divided into three sections; section 1 contains the metal film alone, section 2 has an overlap between the metal and the dielectric film while section 3 is comprised of dielectric film alone. The heat carriers in the metal upon reaching start of the overlap has two paths a) travel across the interface into the dielectric and b) propagate along the metal film. Figure 4a shows how the region of overlap (Section 2) can be broken into elements with temperature nodes to understand the heat transport by conduction along the film and across the boundary. Figure 4b shows the equivalent circuit diagram drawing an analogy to an electrical circuit. $T_{m,1}$, $T_{m,2}$ and $T_{m,3}$ are the temperature nodes along the metal film while $T_{d,1}$, $T_{d,2}$ and $T_{d,3}$ are those along the dielectric film. The part of heat flux traveling across the interface travels past the boundary resistance R_k and shows a temperature drop from $T_{m,1}$ to $T_{d,1}$.

Figure 4. (a) Schematic of the interface depicting various temperature junctions, (b) equivalent thermal resistance circuit (c) simplified version of the circuit.

This is quite a complex model to quantify since it is almost impossible to obtain the temperatures of the metal and dielectric film independently in the overlap region. A simplification can be made by assuming that most of the heat flux is conducted along the metallic film in the overlap region instead of traveling across to the dielectric owing to high interfacial thermal resistance [7]. This is shown in Figure 4c, equivalent to saying that the heat flux goes across the interface only when it reaches the end of the metal film. Since thermal conductivity of the metal is about two orders of magnitude larger than the dielectric, this assumption does not influence the accuracy much. This is experimentally verified in Figure 5, which shows that at the end of section 2, where the metal film ends abruptly, there will be a large temperature drop. Once this temperature drop (T_{drop} in Equation 1) is measured, the interfacial thermal resistance can be calculated if the heat flux flowing across the interface is known. Our previous work [24] showed that heat transfer in rectangular patterned thin films can be modeled as a one-dimensional heat conduction problem with an extended surface. For the geometry considered in this study, the temperature distribution in a rectangular fin with a fixed temperature at the base, T_b , and a constant temperature T_L at $x=L$, the length of the specimen, is given as

$$\frac{\theta}{\theta_b} = \frac{\frac{\theta_L}{\theta_b} \sinh mx + \sinh m(L-x)}{\sinh mL} \quad (3)$$

where $\Theta = T - T_\infty$, $\Theta(0) = \Theta_b$, $\Theta(L) = \Theta_L$ and $m^2 = \frac{hP}{kA_c}$. P is the perimeter of the specimen of constant cross-sectional area A_c . The method for estimation of heat transfer coefficient h , by approximating it with the inclusion of radiative heat transfer is described in detail by Alam et al [24]. Since the sample specimen is heated by a meso-scopic heater element, the heat transfer coefficient is expected to lie in the order of $100 \text{ W/m}^2\text{-K}$ [25].

The heat flux across the interface is obtained by evaluating the gradient of temperature distribution, given by Equation 3, at the tip of the metal film. Since the model prediction by Equation 3 is obtained at each pixel along the sample length, the gradient is obtained using the backward difference using the obtained values at the corresponding pixels. The temperature drop (T_{drop}) is directly obtained from the Infrared image of the specimen when heated under the microscope.

$$q'' = -k_m \frac{dT}{dx} \Big|_{x=L} \quad (4)$$

$$T_{drop} = T_{m,3} - T_{d,3} \quad (5)$$

where k_m is the thermal conductivity of the metal thin film, L is the length to the tip of the metal film from its fixed end. Once these two quantities are known, the thermal interfacial resistance can be calculated as given by Equation 1.

Results

Figure 5 shows the temperature readings of the sample specimen with an interface between 150 nm copper and 300 nm silicon di-oxide. The experimental values in different sections are marked in different colors. The large temperature drop in the metallic part is due to its very high thermal resistance as scaled by Equation (2). The dielectric part has negligible temperature drop because of the combination of high thermal resistance and low thermal conductivity. The effects of these two segments are pronounced at the interface, where ΔT of 3 °C can be measured with most of the available thermometric techniques. In order to verify that the heat flux be evaluated from the gradient of the temperature curve predicted by the fin model, it is also plotted in the same figure. A remarkable fit in metallic part of the sample specimen (Section 1 & Section 2) validates the approximation done in the model. The thermal conductivity values for aluminum ($k= 225$ W/m-K) [26] and copper ($k=250$ W/m-K) [27] were used in this study.

Figure 5. Temperature distribution along the Cu-SiO₂ interfacial specimen.

Table 1. Calculated values of Interfacial Thermal Resistance

	Interfacial Thermal Resistance, R_k [m ² -K/W]
Cu on SiO ₂	7.74×10^{-08}
Al on SiO ₂	8.15×10^{-08}
Al on HfO ₂	3.26×10^{-07}

A similar procedure is followed for the interfaces between the other two pairs viz. Al-SiO₂ and Al-HfO₂. Table 1 lists the computed values of interfacial thermal resistance using our technique for three different combinations of materials. Wang et al [28] computed the interfacial thermal resistance by phonon diffuse mismatch model for 1250 kinds of interfaces and tried to give the range in which each value lies in. The values of Interfacial Thermal Resistance for Cu-SiO₂ and Al-SiO₂ are expected to lie in the order of 10^{-9} m²-K/W as suggested in their work. The discrepancy (an order of magnitude) between our measurement and their computational prediction could arise from (i) the theory based on DMM tends to underestimate interfacial thermal resistance unless the temperature is very low and (ii) less than perfect atomic structure of

the interface in this study. Chien et al. [29] studied the interfaces between metal and dielectric and reported the thermal boundary resistance of $3.54 \times 10^{-8} \text{ m}^2\text{K/W}$ for the Al-SiO₂ interface, which is about 50% of value obtained by our technique. A reason for such discrepancy could be due to larger surface roughness or possible contamination at the interfaces in this study, where the SiO₂ layer undergoes reactive ion etching before the metallization at selected areas using a shadow mask. Since this experiment is carried out in ambience and the sample specimens are heated further by the RTD, the sample temperatures easily go beyond the 300K. At such temperatures, almost all the vibrational modes are excited and the DMM model can be expected to lower resistance compared to experimental measurements.

Experimental Uncertainty Analysis

Evaluation of the Interfacial Thermal Resistance requires a spatial temperature map as per the methodology described. The uncertainties in length (Δx) and temperature (ΔT) measurement will introduce an uncertainty into the derived quantity i.e., the interfacial thermal resistance. The temperature and space resolution of the microscope mentioned earlier are taken as the uncertainty in temperature and length scales. Though the heat flux q'' at the interface is computed from derivative of temperature distribution given by Equation 3, parameters like Θ_b , Θ_L are obtained from the infrared thermograph. Hence, there is an uncertainty associated with the heat flux as well. The propagated uncertainty in the evaluation of the Interfacial Thermal Resistance, R_k , which is given by the following expression

$$\frac{\Delta R_k}{R_k} = \frac{2\Delta T}{T_{drop}} + \frac{\Delta q''}{q''} \quad (6)$$

Evaluating the heat flux q'' at the interface employs the temperature distribution given by Equation 3 and estimating the heat transfer coefficient h to obtain the parameter m . The experimental uncertainty associated with the heat transfer coefficient h , in this methodology, is described in our previous work [30].

$$\Delta q = \frac{\partial q''}{\partial x} \Delta x + \frac{\partial q''}{\partial \theta} \Delta \theta + \frac{\partial q''}{\partial m} \Delta m \quad (7)$$

$$\frac{\Delta R_k}{R_k} = \frac{2\Delta T}{T_{drop}} + \frac{m\left(\frac{\theta_L}{\theta_b}\right) \sinh(mL)\Delta x}{\left(\frac{\theta_L}{\theta_b}\right) \cosh(mL)-1} + \frac{\Delta T}{\theta_b} \left[1 + \frac{\cosh(mL)\left(1+\frac{\theta_L}{\theta_b}\right)}{\cosh(mL)\frac{\theta_L}{\theta_b}-1} \right] + \frac{\Delta h P}{2mkA_c} \left[\frac{L\frac{\theta_L}{\theta_b} \sinh(mL)}{\frac{\theta_L}{\theta_b} \cosh(mL)-1} + \frac{\sinh(mL)-mL\cosh(mL)}{m\sinh(mL)} \right] \quad (8)$$

Evaluating the uncertainty in the heat flux q'' as per Equation 7 and plugging it in Equation 6 will obtain the derived uncertainty in the interfacial thermal resistance, R_k , as given by Equation 8. The corresponding values are plotted in Figure 6 and the uncertainty values of the physical quantities used in Equation 8 are tabulated in Table 2. These are found to lie within 10%, which proves the robustness of this technique.

Figure 6 Uncertainty in estimation of Interfacial Thermal Resistance (R_k)

Table 2 Uncertainty values of each physical parameter

Interface	Δx (μm)	ΔT (K)	Δh ($\text{W}/\text{m}^2\text{-K}$)	$\Delta R_k/R_k$ (%)
Al on SiO ₂	1.6	0.1	2.66	6.39
Al on HfO ₂	1.6	0.1	2.29	4.10
Cu on SiO ₂	1.6	0.1	5.39	8.20

Conclusion

In conclusion, we present a very simple and yet accurate technique to estimate the thermal resistance at the interface between two solids. The technique exploits the ultra-high thermal resistance of thin films when released from the substrate. We demonstrated the concept using freestanding nanoscale metal (copper and aluminum) and dielectric (silicon di-oxide and hafnium oxide) films. Since the temperature drop at the interface is amplified by the absence of the substrate, conventional thermometry (infrared microscopy in this study) could be used to measure the temperature drop. The heat flux is calculated from the temperature boundary conditions after performing an energy balance in the specimen. The results obtained for standard materials are matched against the theoretical predictions by the diffuse mismatch model. The accuracy of the technique is expected to increase with decrease in film thickness (which increases thermal resistance). While technical is based on a simple model compared to 3- ω or thermo-reflectance, specimen preparation required familiarity with nanofabrication techniques.

Acknowledgment

M. A. Haque acknowledges support from the National Science Foundation USA (STTR # 1417173)

References

1. Liu, D., Y. Luo, and X. Shang, *Experimental investigation of high temperature thermal contact resistance between high thermal conductivity C/C material and Inconel 600*. International Journal of Heat and Mass Transfer, 2015. **80**(0): p. 407-410.
2. Balasubramanian, G. and I.K. Puri, *Heat conduction across a solid-solid interface: Understanding nanoscale interfacial effects on thermal resistance*. Applied Physics Letters, 2011. **99**(1): p. 013116 - 013116-3.
3. Kapitza, P.L., *The study of heat transfer in helium II*. Journal of Physics-Ussr, 1941. **4**(1-6): p. 181-210.
4. da Silva, L.W. and M. Kaviani, *Micro-thermoelectric cooler: interfacial effects on thermal and electrical transport*. International Journal of Heat and Mass Transfer, 2004. **47**(10–11): p. 2417-2435.

5. Kothari, R., et al., *Experimental and numerical study of the effective thermal conductivity of nano composites with thermal boundary resistance*. International Journal of Heat and Mass Transfer, 2013. **66**(0): p. 823-829.
6. Wang, L., et al., *Effect of interface on the thermal conductivity of thermal barrier coatings: A numerical simulation study*. International Journal of Heat and Mass Transfer, 2014. **79**(0): p. 954-967.
7. Norris, P.M. and P.E. Hopkins, *Examining Interfacial Diffuse Phonon Scattering Through Transient Thermoreflectance Measurements of Thermal Boundary Conductance*. Journal of Heat Transfer-Transactions of the Asme, 2009. **131**(4).
8. Reifenberg, J.P., D.L. Kencke, and K.E. Goodson, *The impact of thermal boundary resistance in phase-change memory devices*. Ieee Electron Device Letters, 2008. **29**(10): p. 1112-1114.
9. Little, W.A., *THE TRANSPORT OF HEAT BETWEEN DISSIMILAR SOLIDS AT LOW TEMPERATURES*. Canadian Journal of Physics, 1959. **37**(3): p. 334-349.
10. Swartz, E.T. and R.O. Pohl, *Thermal boundary resistance*. Reviews of Modern Physics, 1989. **61**(3): p. 605-668.
11. Zeng, T.F. and G. Chen, *Phonon heat conduction in thin films: Impacts of thermal boundary resistance and internal heat generation*. Journal of Heat Transfer-Transactions of the Asme, 2001. **123**(2): p. 340-347.
12. Cahill, D.G., et al., *Nanoscale thermal transport. II. 2003-2012*. Applied Physics Reviews, 2014. **1**(1).
13. Cahill, D.G., *Heat transport in dielectric thin films and at solid-solid interfaces*. Microscale Thermophysical Engineering, 1997. **1**(2): p. 85-109.
14. Chien, H.-C., et al., *Thermal conductivity measurement and interface thermal resistance estimation using SiO₂ thin film*. Review of Scientific Instruments, 2008. **79**(5): p. 054902.
15. Lee, B., et al., *Simultaneous measurement of thermal conductivity and interface thermal conductance of diamond thin film*. Journal of Vacuum Science & Technology B, 2009. **27**(6): p. 2408-2412.
16. Hopkins, P.E., *Thermal Transport across Solid Interfaces with Nanoscale Imperfections: Effects of Roughness, Disorder, Dislocations, and Bonding on Thermal Boundary Conductance*. ISRN Mechanical Engineering, 2013. **2013**: p. 19.
17. Kato, R. and I. Hatta, *Thermal Conductivity and Interfacial Thermal Resistance: Measurements of Thermally Oxidized SiO₂ Films on a Silicon Wafer Using a Thermo-Reflectance Technique*. International Journal of Thermophysics, 2008. **29**(6): p. 2062-2071.
18. Wang, H.D., et al., *Measurements of electron-phonon coupling factor and interfacial thermal resistance of metallic nano-films using a transient thermoreflectance technique*. Chinese Physics B, 2011. **20**(4).
19. Xu, Y.B., et al., *Measurement of interfacial thermal resistance by periodic heating and a thermo-reflectance technique*. Materials Transactions, 2007. **48**(2): p. 148-150.
20. Cahill, D.G., *Analysis of heat flow in layered structures for time-domain thermoreflectance*. Review of Scientific Instruments, 2004. **75**(12): p. 5119-5122.
21. Costescu, R.M., M.A. Wall, and D.G. Cahill, *Thermal conductance of epitaxial interfaces*. Physical Review B, 2003. **67**(5).
22. Huxtable, S.T., et al., *Interfacial heat flow in carbon nanotube suspensions*. Nature Materials, 2003. **2**(11): p. 731-734.
23. Alam, M.T., et al., *Thermal Conductivity Measurement of Low-k Dielectric Films: Effect of Porosity and Density*. Journal of Electronic Materials, 2014. **43**(3): p. 746-754.
24. Alam, M.T., et al., *Structural size and temperature dependence of solid to air heat transfer*. International Journal of Thermal Sciences, 2013. **73**: p. 1-7.

25. Pulavarthy, R.A., M.T. Alam, and M.A. Haque, *Effect of heated zone size on micro and nanoscale convective heat transfer*. International Communications in Heat and Mass Transfer, 2014. **52**(0): p. 56-60.
26. Lee, H.F., S. Kumar, and M.A. Haque, *Role of mechanical strain on thermal conductivity of nanoscale aluminum films*. Acta Materialia, 2010. **58**(20): p. 6619-6627.
27. Nath, P. and K.L. Chopra, *Thermal conductivity of copper films*. Thin Solid Films, 1974. **20**(1): p. 53-62.
28. Wang, H., et al., *Computation of interfacial thermal resistance by phonon diffuse mismatch model*. Materials Transactions, 2007. **48**(9): p. 2349-2352.
29. Chien, H.-C., D.-J. Yao, and C.-T. Hsu, *Measurement and evaluation of the interfacial thermal resistance between a metal and a dielectric*. Applied Physics Letters, 2008. **93**(23): p. 231910.
30. Alam, M.T., et al., *Mechanical Strain Dependence of Thermal Transport in Amorphous Silicon Thin Films*. Nanoscale and Microscale Thermophysical Engineering, 2014. **19**(1): p. 1-16.