Understanding Thermal Transport in Polymer – Silver Nanowire Composites

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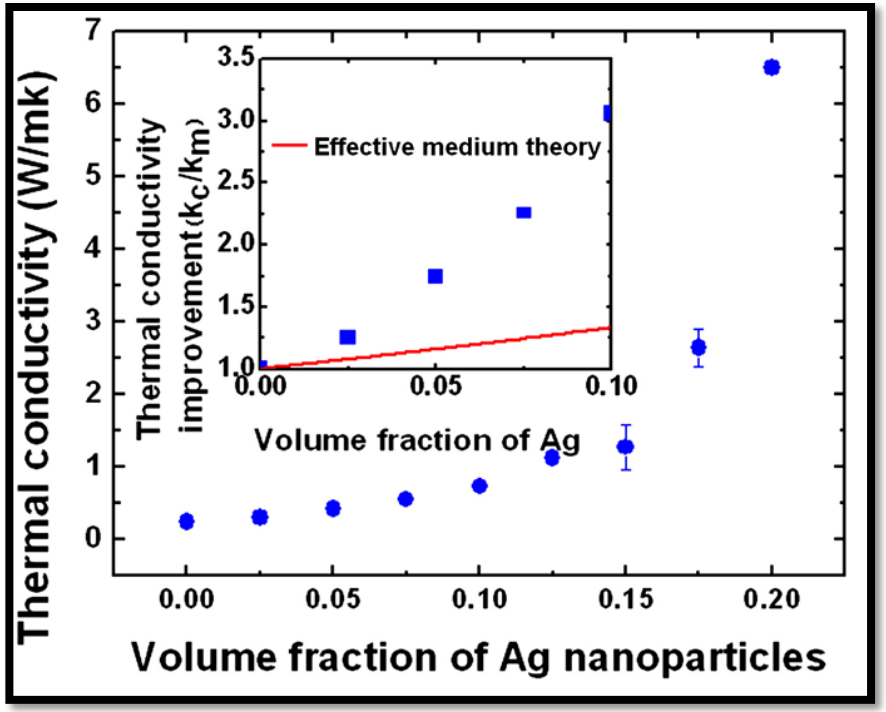
Outline

- Brief Overview of Previous Work on Polymer – Metal Nanocomposites
  - Ag-Nanoparticle (AgNP) and Au-Nanowire (AuNW) Studies from Literature
  - The Difficulty of Defining Geometry in Bulk Samples
  - The Need for Nanoscale Measurements

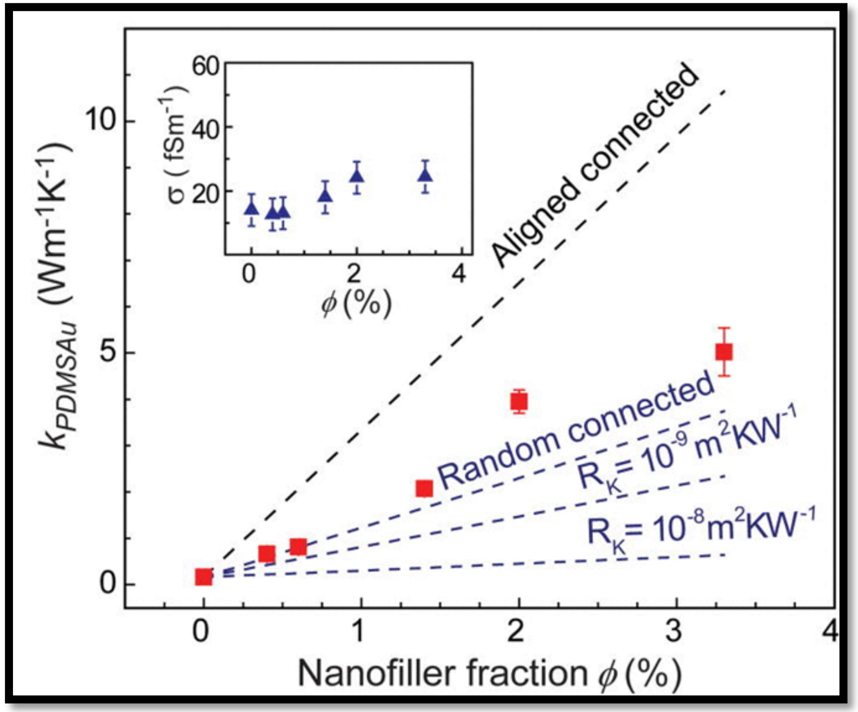
- Thermal Transport Measurements
  - Thermal Bridge Measurement Scheme
  - Manually Prepared Nanocomposites
  - Electrospun Nanocomposites

Problem Statement

PVDF - AgNP



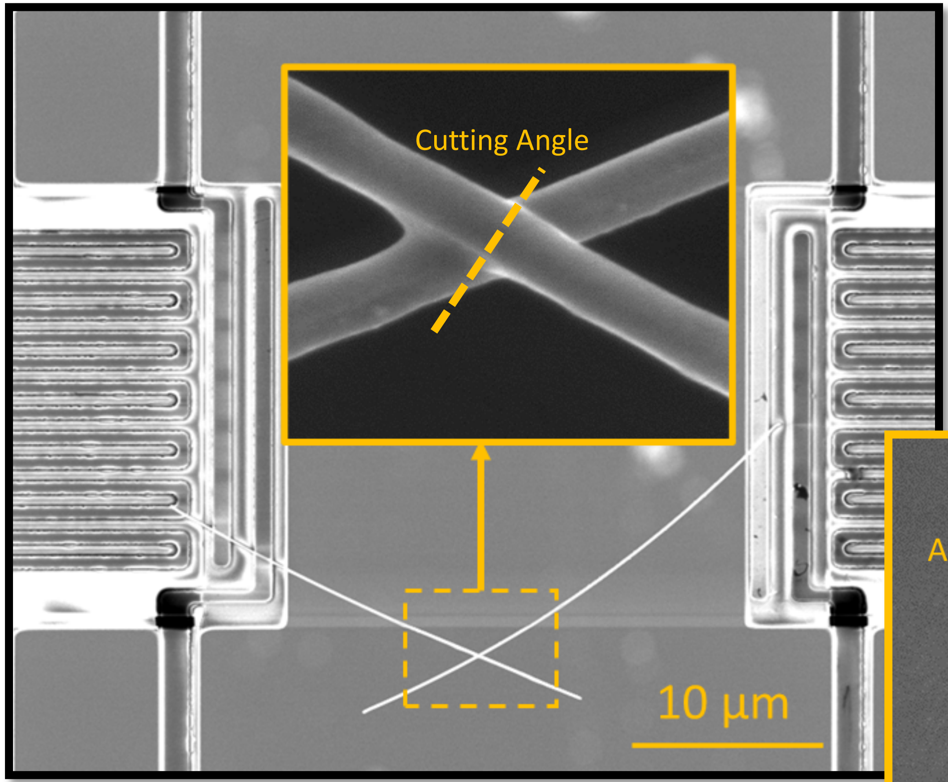
PDMS - AuNW

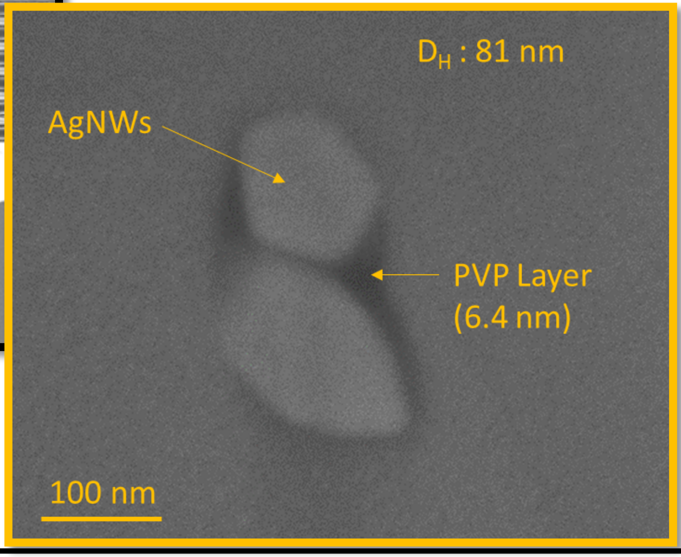


- Metallic fillers outperform the predictions of constitutive equations without accounting for the interfacial thermal resistance.
- Because an interfacial thermal resistance certainly exists, it illustrates the need for measurements where geometries can be controlled.

References: Huang, Xingyi, et al. *Applied Physics Letters* 95.24 (2009) & Balachander, Nikhil, et al. Applied Physics Letters 102.9 (2013)

Samples Manually Prepared via Micromanipulator

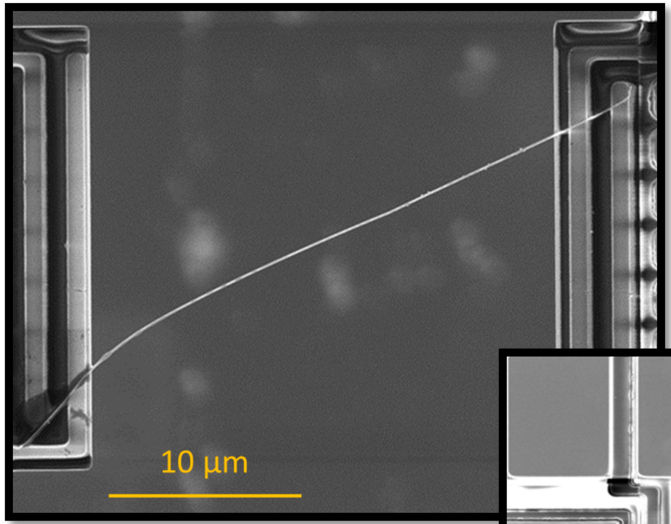




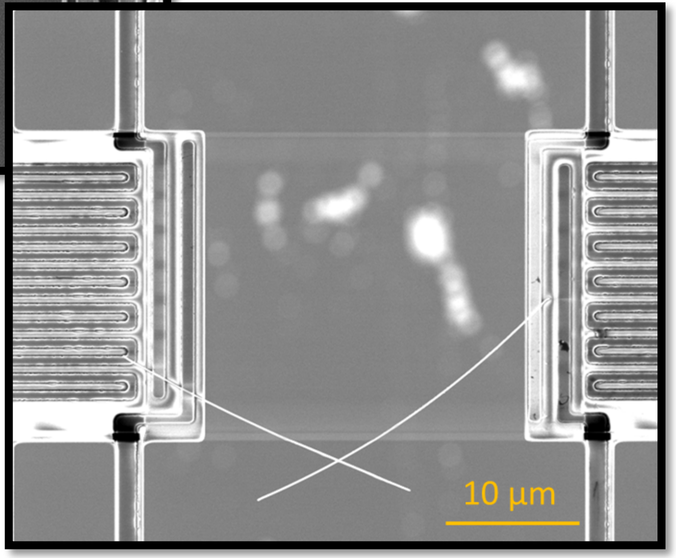
- AgNWs are suspended in a solution of 1% PVP in Ethanol to form residual PVP layer. Typically in solution overnight (>16 hours).
- Individual AgNWs (>80 µm) are broken into 3 parts, one for a continuous reference sample (not shown) and two which are used to form a contact sample.
- By using the same AgNW for both samples, any reduction in the measured thermal conductance can be attributed to the presence of the contact and thin PVP layer.
- Lastly, Ion Milling (FIB) is used to cut the contact samples at the overlap to observe the overlap geometry.

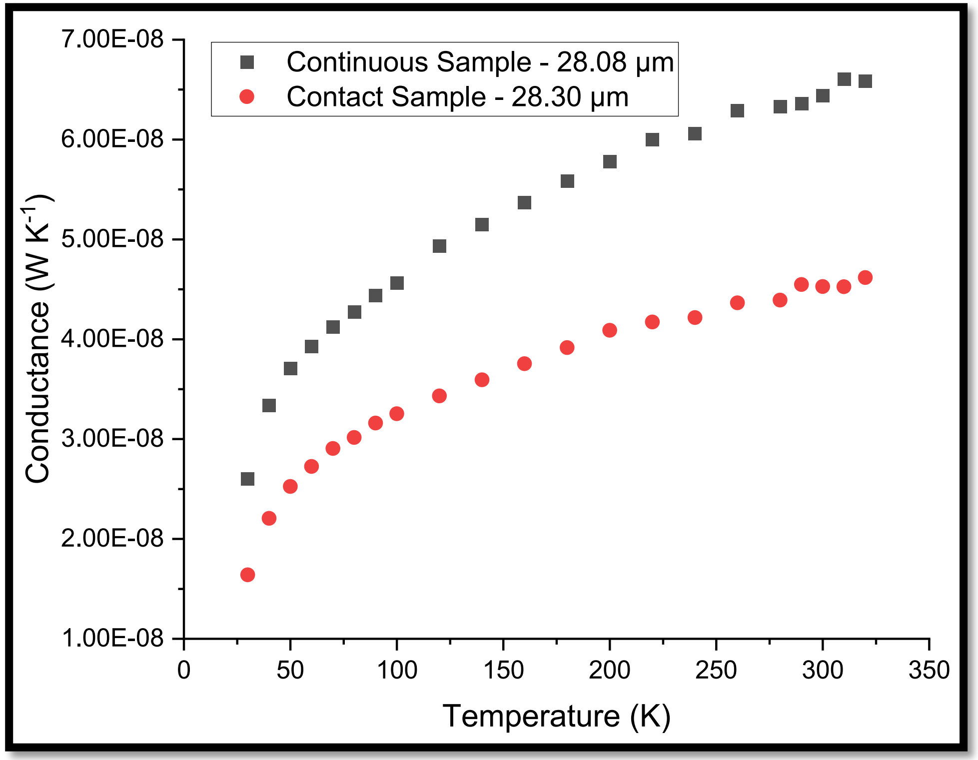
Measured Total Thermal Conductances

Continuous Sample



Contact Sample



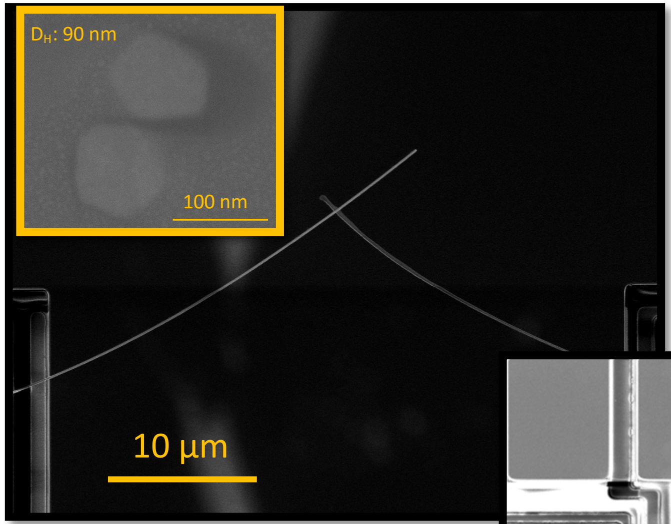


Measured Thermal Conductances: 20 – 320 K.

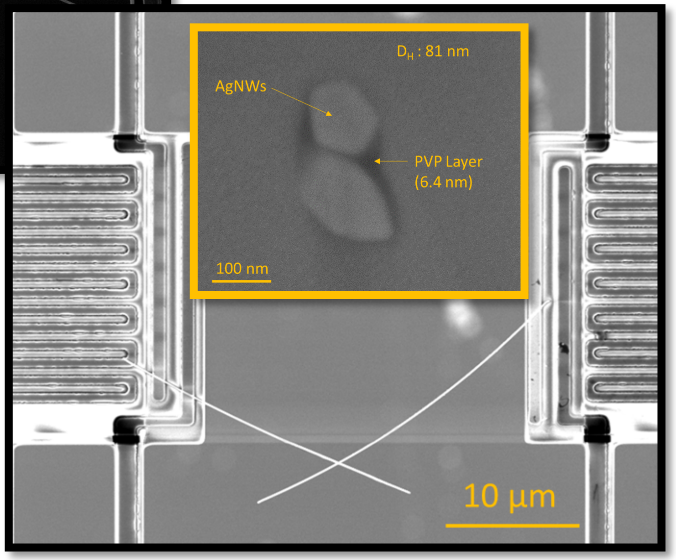
- Thermal conductance reduction arises from the presence of the PVP-Ag interfaces and the low conductivity PVP layer separating the adjacent AgNWs.

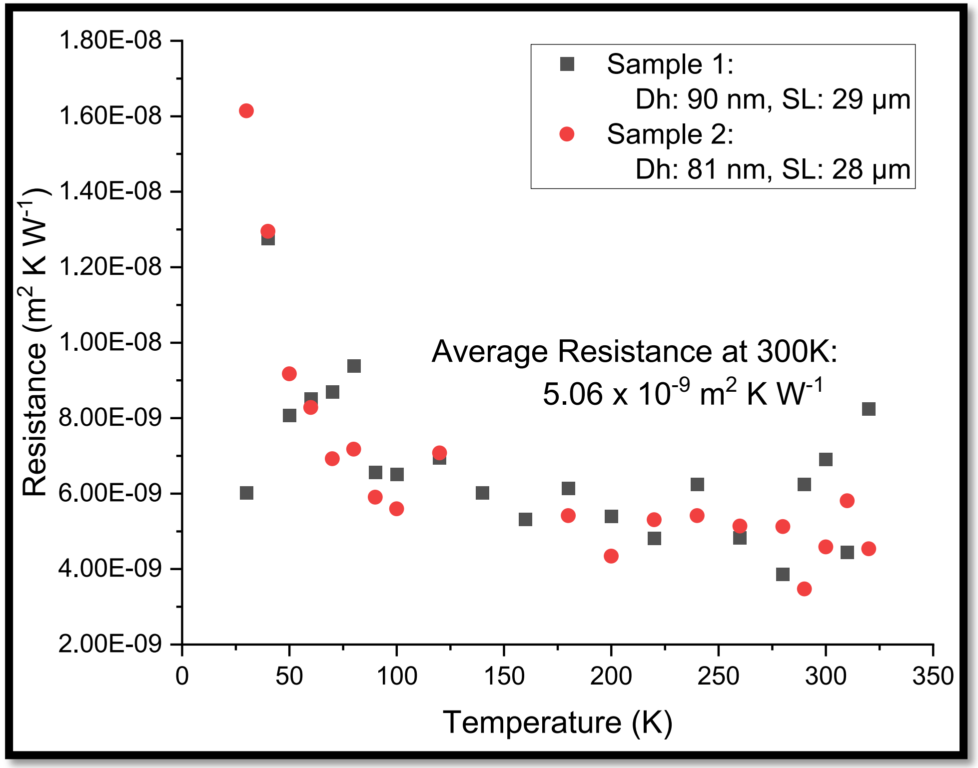
Calculated Interfacial Thermal Resistance, PVP-Ag

Sample 1



Sample 2





Interfacial thermal resistance between PVP and the AgNWs

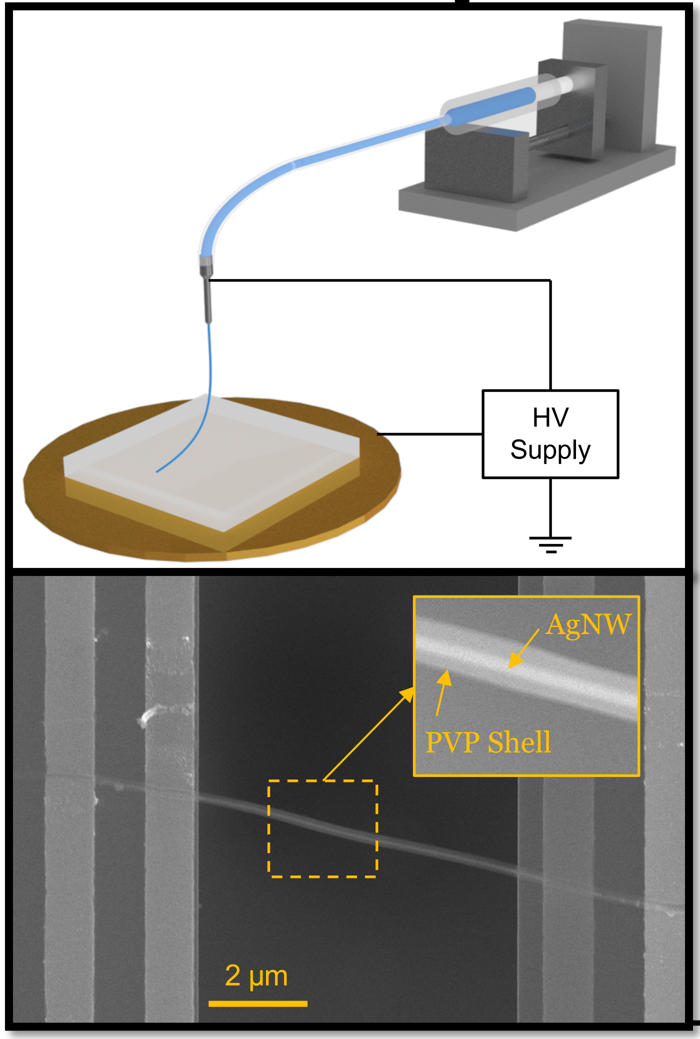
Resistor Circuit:

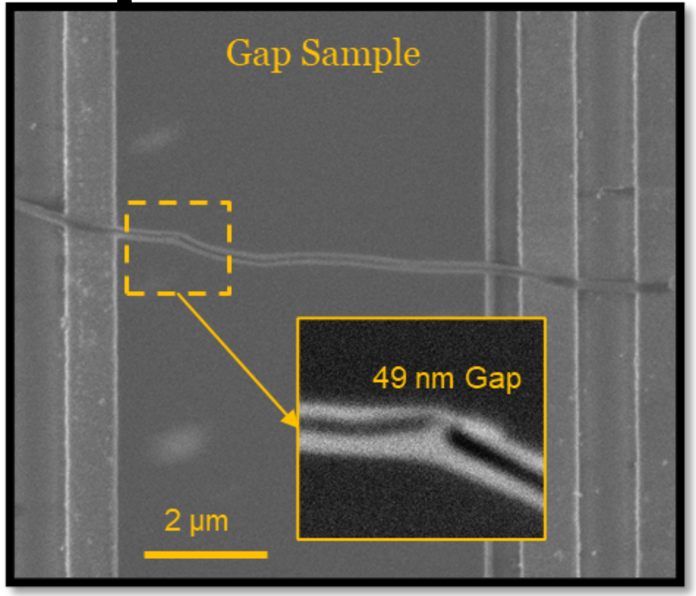
$$R_{continuous,\ total} - R_{contact,\ total} = 2R_{interface} + R_{PVP\text{-}interlayer}$$

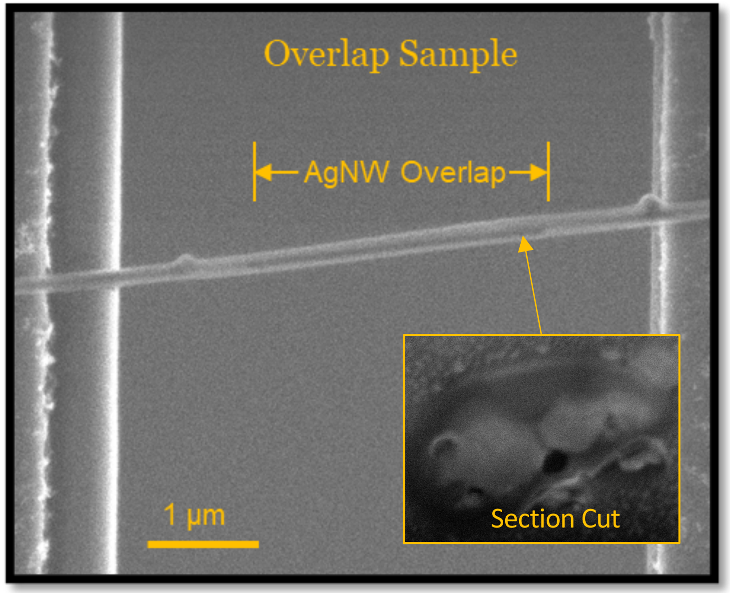
Where: R_{total} = (Total Conductance)$^{-1}$

- A simple 1-D resistor circuit is used to calculate the area specific interfacial thermal resistances.

Electrospun Samples

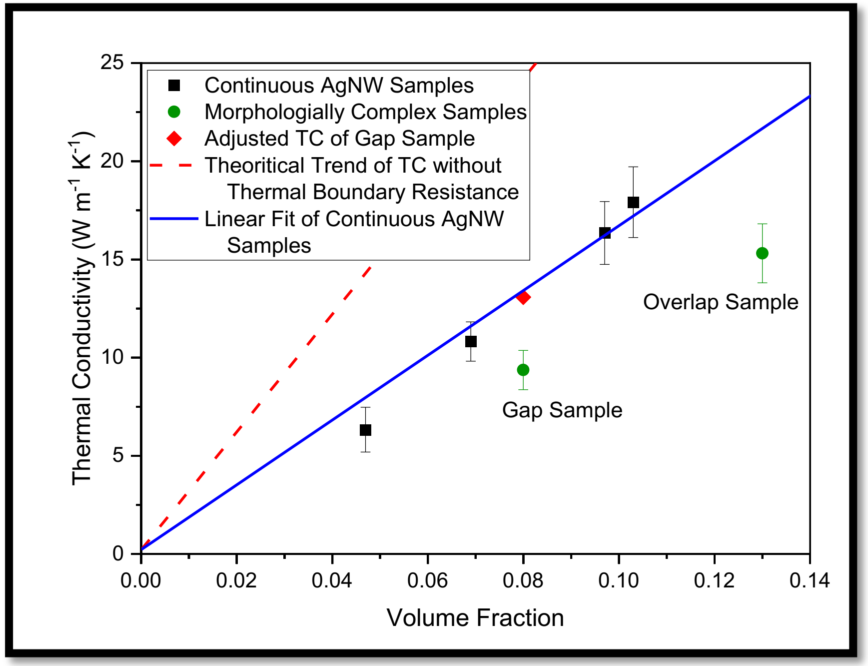


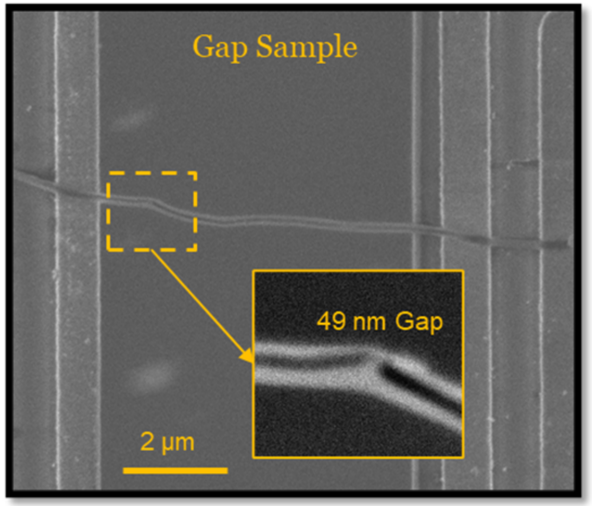




- Electrospinning allowed for the fabrication of both continuous AgNW samples (lower left) and morphologically complex samples such as gaps between AgNWs and overlapping AgNWs as would be found in bulk composites.
- By comparing the different types of samples, we can attribute the additional resistances to the added features and interfaces.

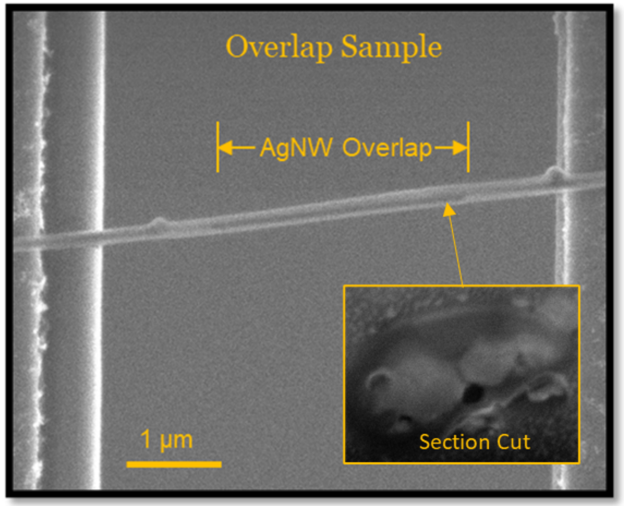
Electrospun Samples





$R_{total} = R_{continuous\ fiber} + 2R_{interface} + R_{PVP\text{-}gap}$

$R_{total} = R_{continuous\ fiber} + 2R_{interface} + R_{PVP\text{-}interlayer}$

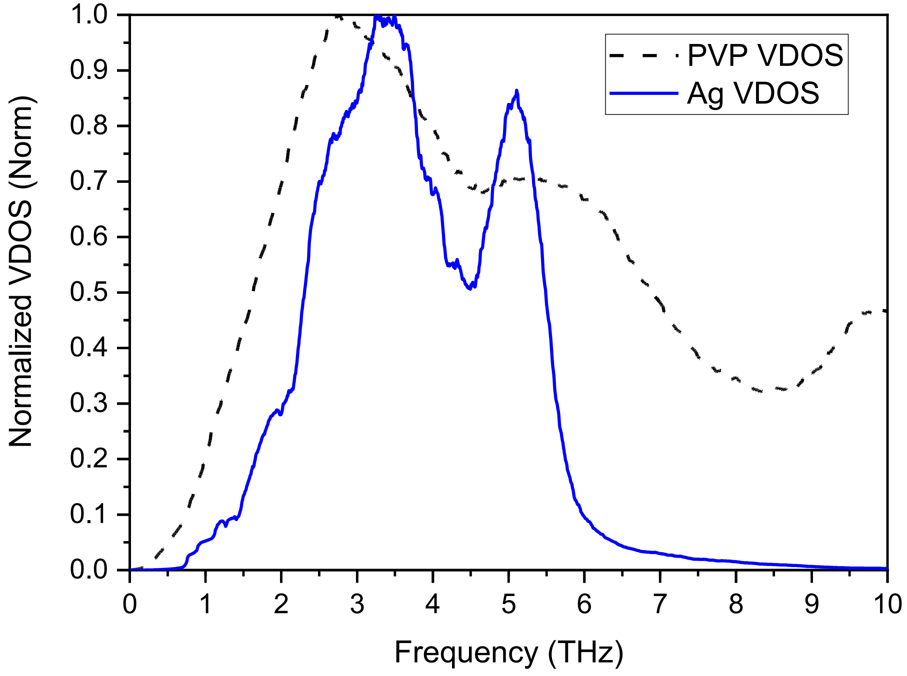


- Linear trend of thermal conductivity with volume fraction of silver was established for continuous samples and compared against the morphologically complex samples.
- 1-D resistor network again used to calculate specific resistances.
- The average resistance at 300 K was found to be 8.98 x 10^{-9} m^2 K W^{-1} corresponding to a Kapitza Length of ~2 nm (compared to the 10-20 nm estimated for CNT-Polymer composites, Huxtable et al.)

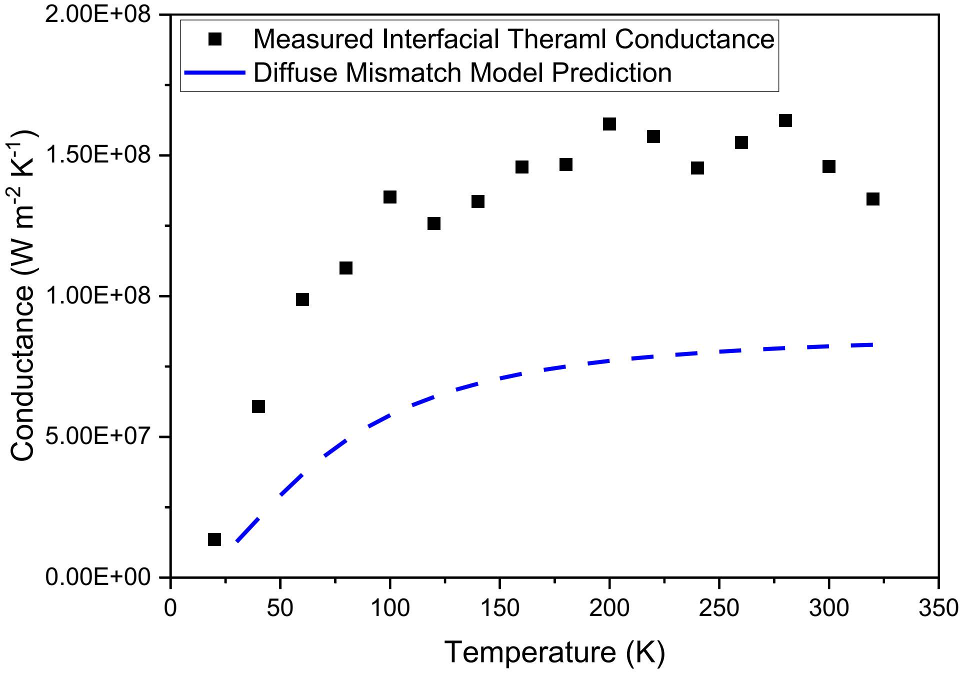
References: Huxtable, Scott T., et al. "Interfacial heat flow in carbon nanotube suspensions." Nature materials 2.11 (2003): 731-734

Diffuse Mismatch Model

Vibrational Density of States (VDOS) of PVP and Ag



DMM Prediction of Interfacial Thermal Conductance



- At frequencies generally associated with van der Waals modulated heat transfer (<10 THz), there exists significant overlap between the available phonon modes of PVP and silver.
- In general, the DMM demonstrated good agreement both in the magnitude of the thermal conductance prediction and the predicted trend of thermal conductance with temperature.

References: DMM - Majumdar, Arun, and Pramod Reddy. "Role of electron–phonon coupling in thermal conductance of metal–nonmetal interfaces." Applied Physics Letters 84.23 (2004): 4768-4770.

Summary and Conclusions

- In this work we measured individual composite nanofibers prepared by both manual manipulation and via electrospinning.
  - We determination of the interfacial thermal resistance/ conductance at the PVP-Ag boundary
  - The average resistance at 300 K was found to be 7.02 x 10^{-9} m^{2} K W^{-1} (a Kapitza Length of just 1.6 nm!)

- Additionally, molecular dynamics simulations were preformed which help to shed light on the mechanism of heat transfer between metallic fillers and polymer hosts.
  - There is considerable overlap in the VDOS of PVP and silver at frequencies generally associated with van der Waals modulated heat transfer (<10 THz).
  - All Ag phonon modes exist below 10THz (a sharp contrast to stiffer materials, such as CNTs, which have many higher frequency phonon modes).

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Thank you! Questions?

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