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Radiative Thermal Transport with Nanowire-Based Uniaxial Electromagnetic Metamaterials

Liping Wang
ARIZONA STATE UNIVERSITY

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14. ABSTRACT
This YIP project aims to obtain a deep fundamental understanding of radiative heat transfer between nanowire metamaterials from both theoretical and experimental studies. Over the 3-year duration, significant progress has been made. In particular, silicon-cored tungsten nanowires have been successfully fabricated and characterized, which exhibited excellent spectral selectivity with enhanced absorption within solar spectrum and low infrared thermal emission. By developing a lab-scale test platform, the solar-to-heat efficiency of these selective nanowire structures have been carefully measured to confirm the effect of spectral selectivity in enhanced thermal energy conversion. On the other hand, effective uniaxial materials properties (i.e., electric permittivity and magnetic permeability) of metallic nanowire structures have been retrieved from far-field optical responses to successfully capture the effect of artificial magnetic resonance. With fluctuational electrodynamics calculation, the artificial magnetic resonance from the nanowires is theoretically demonstrated to greatly affect the near-field radiative heat transfer. Lastly, in order to experimentally study the near-field radiative heat transfer, a plate-plate thermal metrology is developed to study that between planar samples. Polystyrene nanoparticles were first used to create 215nm vacuum gaps between mm-scale aluminum thin film samples, which demonstrated more than 6 times enhancement over far-field blackbody limit between these metallic surfaces previously known as bad emitters. With patterned SU8 polymer posts, capacitance measurement was implemented to determine the gap distance in-situ during the near-field experiment for heavily doped silicon, which exhibits more than 11 times super-blackbody radiation heat transfer. The knowledge and results obtained here would facilitate the thermophotonic applicat

15. SUBJECT TERMS
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AFOSR YIP Final Performance Report

Title: Radiative Thermal Transport with Nanowire-based Uniaxial Electromagnetic Metamaterials
Principal Investigator: Liping Wang, Ph.D., Arizona State University
Grant No.: FA9550-17-1-0080 Duration: 12/01/2016 – 11/30/2019
Program: Plasma and Electro-Energetic Physics

1. Project Overview

This YIP project aims to obtain a deep fundamental understanding of the radiative heat transfer between nanowire-based metamaterials (MMs) from both theoretical and experimental studies. The near-field heat transfer is predicted by considering the nanowire array as a homogeneous uniaxial medium, and the theoretical method has been further developed to study that between layered uniaxial nanowire structures. Nanowire samples will be fabricated and their far-field optical properties will be studied. Experimental methods will be developed to measure near-field radiative heat transfer. In sum, this project seeks to understand following fundamental questions:

- Could magnetic response be achieved artificially with nanowire metamaterials?
- Could nanowire metamaterials improve thermophotovoltaic energy conversion?
- How does the artificial magnetic response impact the near-field radiative transfer?
- How to experimentally validate the effects of nanowire metamaterials in both far-field and near-field radiative thermal transport?

2. Major Research Accomplishments

(1) Nanowire Fabrication and Optical Characterization.

A silicon-cored tungsten nanowire array was successfully fabricated and studied. Figure 1a shows the configuration of a nanowire sample where the tungsten nanowires were cored by single crystalline silicon. The fabrication process started with a silicon nanowire stamp (Lightsmyth, S2D-18B2-0808-350-P), while the sample size is 8 mm × 8 mm × 0.675 mm. The geometric characteristics of the Si nanowire array was P = 600 nm, H = 350 nm, and D_{in} = 275 nm. The sample was then sputtered with tungsten by a thickness of about 37.5 nm. As shown in Fig. 1b, this sample was a good candidate for solar absorber since it was very absorbing in the visible and near-IR range with black color. For further verification of the thickness of tungsten, Figs. 1c and 1d respectively showed the SEM and AFM images of the sputtered sample. The top SEM view of the sample proved that the nanowire array period did not change with the sputtering process but the nanowire diameter however, changed from 275 nm to about 350 nm. A more accurate profile of the sputtered sample was obtained by AFM scanning. The diameter after sputtering, D_{out}, was around 347 nm as revealed by the red solid curve. For comparison, the profile of silicon nanowire which showed the diameter before sputtering, D_{in}, was around 275 nm. The spectral absorptance of the sample was then characterized by Fourier-transform infrared spectroscopy (FTIR) as shown in Fig. 1e. This nanowire sample exhibited high absorptance in the visible and near-infrared range such that it can absorb most of the solar energy as well as d low emittance (spectral absorptance is equal to spectral emittance due to Kirchhoff's law) in the mid-IR range so as to prevent radiative heat loss. On the other hand, bare tungsten with the same thickness (sputtered at the same time as the tungsten nanowire sample) was sputtered on top of silicon for comparison. In addition, there existed two distinct absorption peaks at λ =1.22 μm and 0.62 μm in wavelength. In order to understand the mechanism of these two enhancement peaks, FDTD simulation with intrinsic silicon cored tungsten nanowire array with the same geometry was analyzed, and showed two

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peaks of absorption at nearby wavelengths of 1.64 μm and 0.60 μm. The electromagnetic fields distributions were plotted with FDTD in Fig. 1f at λ = 1.64 μm where a strong magnetic field confinement is located between two nanowires and the electrical field forms a loop. This can be confirmed as the first harmonic mode of magnetic polariton (MP).

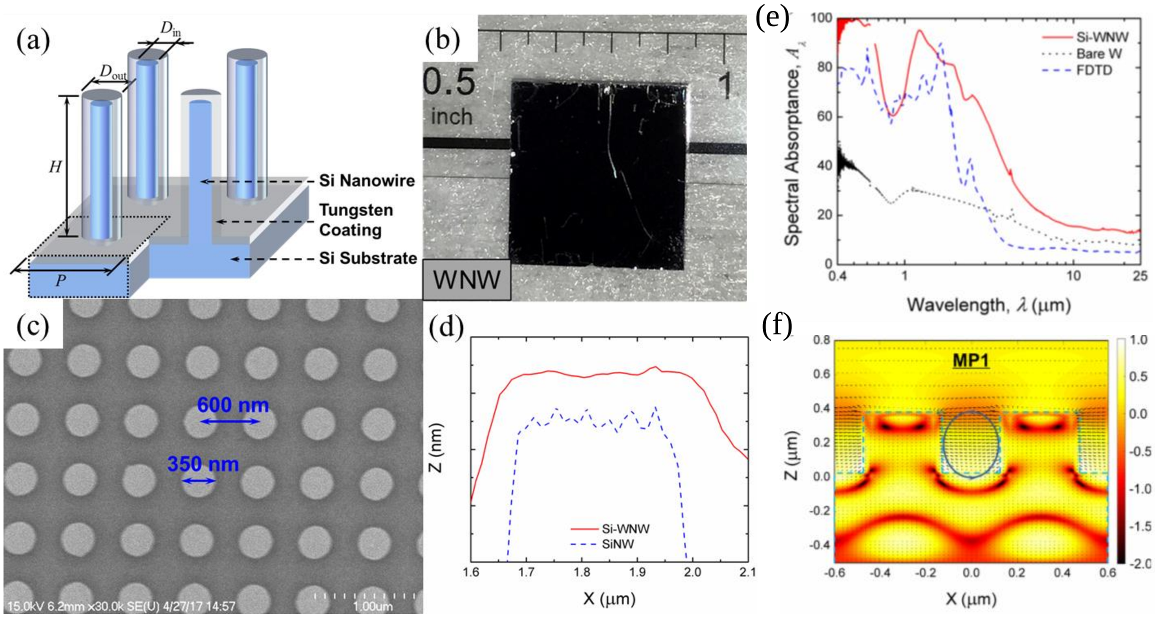

Figure 1. (a) Schematic, (b) picture, (c) SEM top view, and (d) AFM profile of a silicon-cored tungsten nanowire array sample. (e) Spectral absorptance of the silicon-cored tungsten nanowire array sample measured by FTIR. (f) The electromagnetic fields distribution at (a) MP1 (λ = 1.64 μm). The direction of the electrical field is marked by the blue circles.

(2) Performance Improvement for Thermal Energy Conversion.

In order to experimentally study the effect of spectral selectivity of the tungsten nanowires on converting solar energy to heat, a lab-scale solar test platform was built. As shown in Fig. 2a, the platform mainly involves a solar simulator (Xenon lamp), a vacuum chamber, temperature monitors, optical filters and mirrors. For a sample of 1 cm square, the setup could reach up to 50 suns of solar concentration. A RTD thermal sensor was attached to the backside of the sample with thermal pastes to measure the sample temperature, while a significant amount of energy was lost via the conduction through the RTD wires, besides the thermal emission from the top, sides, and bottom surfaces of the sample. The top surface of the sample was heated up by concentrated sunlight from the solar simulator, while several neutral density filters were used to change the concentrations. A turbo vacuum pump was used to achieve pressure less than 1 Pa inside the vacuum chamber to eliminate the effect of convection. A black sample was measured first to obtain its steady state temperature at different concentrations, from which the conduction heat loss via the RTD wires (treated as useful heat gain) was correlated to the sample temperature. With this correlation, by simply measuring the steady-state temperature of the nanowire samples at different suns, the conduction heat gain, and the solar-thermal efficiency as its ratio to the incident solar energy can be found. As shown in Fig. 2b, the measured solar-thermal efficiency of tungsten nanowires was from 50% to 25% for solar concentrations from 1.7 to 20 suns. In practical applications where the absorber is attached to the tubular surface, the thermal emission losses from the sides and bottom surfaces can be eliminated. In this case, the solar-thermal efficiency with tungsten nanowire samples could be further enhanced by 30%~40% from theoretical projection.

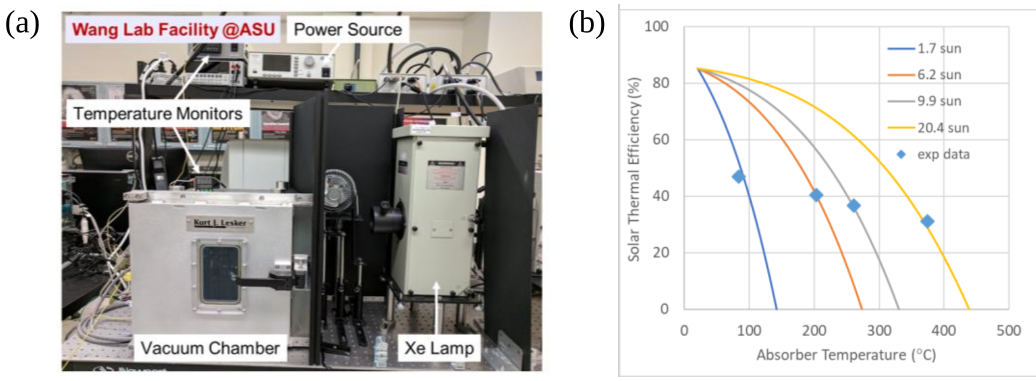

Figure 2. (a) Lab-scale setup for solar-thermal efficiency measurements of nanowire samples under different solar concentrations. (b) Measured solar-thermal efficiency at multiple suns for tungsten nanowires.

Besides, enhanced selective absorption with nanodisk metasurfaces was also theoretically studies in order to enhance the thermophotovoltaic (TPV) energy conversion. TPV has been known as a promising technology to convert thermal energy to electricity with versatile heat sources and high energy density. One major challenge is how to enhance its conversion efficiency. To do so, we have designed TPV cells made of ultrathin semiconductor layer covered by Ag nanodisk metasurfaces. With FDTD simulations, we found the optical absorption can be spectrally enhanced right above the bandgap of GaSb with very low sub-bandgap absorption, as shown in Fig. 3a. With electromagnetic field plot in Fig. 3b, it is understood that the enhanced absorption at this particular wavelength is due to the excitation of magnetic resonance between the Ag nanodisk and bottom Ag film, which localizes the optical energy within the nanometric GaSb layer. By absorbing useful photons only above the bandgap, the TPV cell efficiency can be dramatically enhanced. With the calculations in Fig. 3c, the TPV efficiency can reach 30% at thermal source temperature 1500 K with 2D metasurface TPV cells.

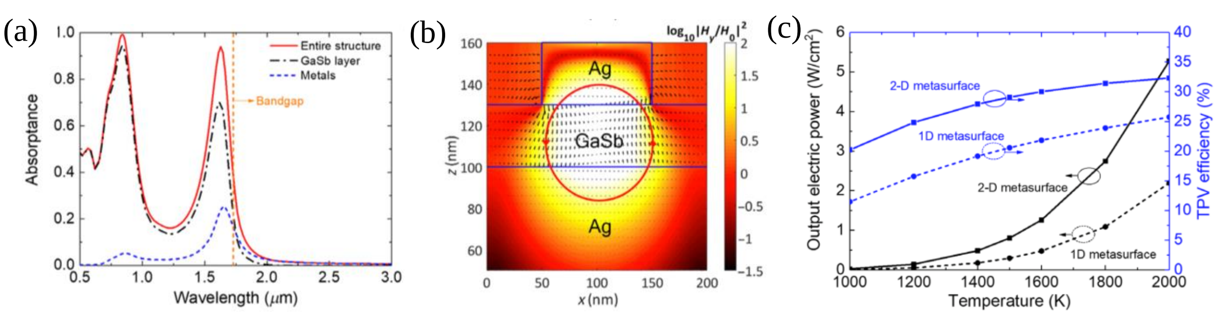

Figure 3. (a) Simulated spectral absorption for the ultrathin TPV cell made of Ag nanodisk array and GaSb layer with strong spectral selectivity right above the cell bandgap. (b) Simulated electromagnetic field distribution at the resonant wavelength that explains the enhanced absorption is due to magnetic resonance excitation with strongly localized optical energy within GaSb layer. (c) Calculated theoretical TPV conversion efficiency and output power density with 1D and 2D metasurface TPV cells as a function of thermal source temperature.

(3) Theoretical Study of Near-field Radiative Transfer with Nanowires.

Besides the far-field studies, the radiative heat transfer between nanowires in the near-field, i.e., the distance is much smaller than the characteristic thermal wavelengths, was also investigated theoretically, in particular, considering artificial magnetic resonances. An example structure is a freestanding Ag nanowire array as shown Fig. 4a. The diameter of the nanowires D is chosen to be 200 nm while the period P is 400 nm and the height H is 1000 nm. The host material selected here is vacuum for simplicity.

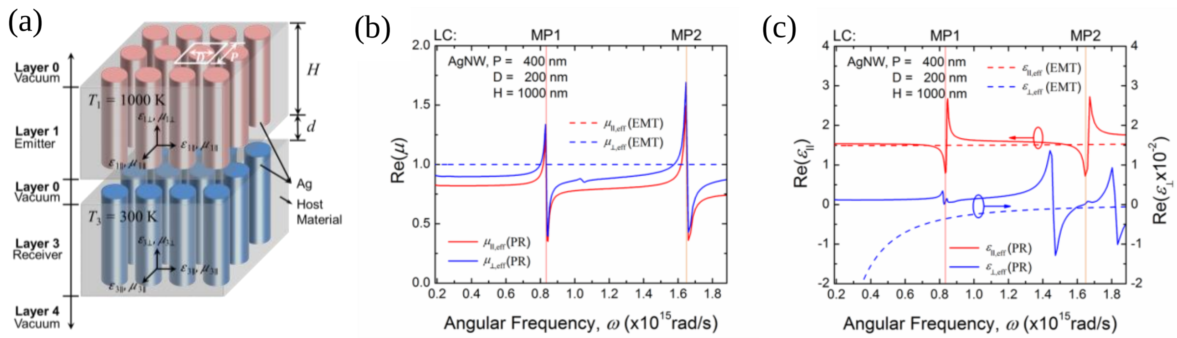

Figure 4. (a) Schematic of a 5-layer near-field radiative heat transfer model between two identical freestanding Ag nanowire arrays with different temperatures. Uniaxial (b) permeability and (c) permittivity retrieved by parameter retrieval compared with effective medium theory (EMT) and inductor-capacitor (LC) circuit model MP peak predictions when the nanowire diameter is 200 nm.

In order to capture the artificial magnetic resonance behaviors from the nanowire MMs, parameter retrieval method was first applied to obtain effective uniaxial electrical permittivity and magnetic permeability from full-wave simulations of the far-field optical responses. The reflection and transmission coefficients, r and t respectively of the free-standing nanowire array, were obtained under different incident angles (0° and 45°) with FDTD simulations for the retrieval of uniaxial material properties. Note that, since nanowire arrays are symmetric in both in-plan directions (i.e., ∥ direction), the coefficients obtained at normal incidence are not polarization angle dependent. Figure 4b and 4c show the retrieved angular independent uniaxial material properties. As clearly seen, the retrieved properties present two Lorentz-like mu-near-pole (MNP) behavior at two different frequencies, 8.30×10^{14} and 1.65×10^{15} rad/s. These two peaks are in fact correlated to the excitation of magnetic polariton as it matches the prediction by the inductor-capacitor (LC) circuit model. Therefore, the retrieved material properties successfully captured the effect of artificial magnetic resonance. On the other hand, the conventional effective medium theory without considering the magnetic responses, gives unity magnetic permeability and wrong effective permittivity.

By using the retrieved uniaxial material properties, Figure 5 shows the predicted near-field spectral heat fluxes of Ag nanowires for different wave polarizations at different vacuum gap distances. For s-polarized waves as shown in Fig. 5a, the magnetic excitation causes narrow band and strong spectral enhancements at both resonance frequencies. In fact, the spectral heat flux is enhanced for more than two orders of magnitude at both resonance frequencies. Furthermore, the spectral heat flux between two Ag plates is also plotted at 100 nm vacuum gap for comparison. It is clear that the spectral heat flux between Ag nanowire arrays is higher at higher frequency range where magnetic resonance is excited. As for p-polarized waves presented in Fig. 5b, the spectral heat flux is suppressed around the magnetic resonance frequencies. On the other hand, there also exists a small enhancement band around 1.5×10^{15} rad/s due to the magnetic hyperbolic mode as can be seen in Fig. 4c where the ∥ component is positive and the ⊥ component is negative.

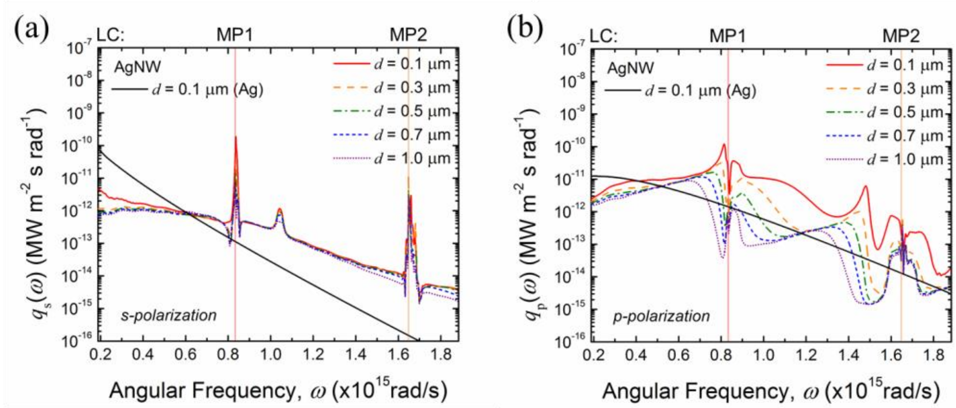

Figure 5. Predicted near-field spectral radiative heat fluxes for (a) s and (b) p wave polarizations at different vacuum gap distances by retrieved properties of Ag nanowire arrays.

(4) Measurements of Super-Planckian Near-field Radiation Heat Transfer.

We have successfully developed novel thermal metrologies to measure the radiation heat transfer between metallic thin film and doped silicon samples with size up to 1 cm square and vacuum gap down to 200 nm, and experimentally demonstrate the near-field radiative heat transfer exceeding well-known blackbody limit. To do so, we have overcome the challenges such as surface contaminants, inherent bow or curvature of cm-size samples, accurate and in-situ determination of gap distance.

Figure 6a shows the schematic and heat transfer model of the plate-plate method, while an actual setup inside a vacuum chamber developed in the PI's lab is shown in Fig. 6b. Al thin films of different thicknesses from 10 nm to 80 nm were deposited on the 5×5 mm^2 polished silicon chips to experimentally study the near-field radiative flux. Polystyrene nanoparticles with nominal 200nm diameter were carefully prepared and dispersed onto the sample surface with a dilute concentration to minimize the conduction. These nanoparticles created a vacuum gap between the two Al thin film samples when stacked together, while the vacuum gap was fitted to be 215^{+55}_{-50} nm based on the measurement data from bare Si chips. As shown in Fig. 6c, the near-field radiative heat flux between 13-nm-thick Al thin films at 215 nm gap distance was measured to be 6.4 times over the blackbody limit and 420 times to the far-field radiative heat transfer between metallic surfaces with a temperature difference of 65 K with receiver at room temperature. Theoretical predictions from fluctuational electrodynamics validated the experimental results with the reasonable agreement, and clarified the large enhancement was because of augmented contributions from s polarization with non-resonant coupling within the subwavelength vacuum gap (i.e., near-field effect) and resonant coupling within the nanometric Al thin film (i.e., thin-film effect). The advances of experimental measurements and fundamental understanding of near-field radiation between metallic surfaces here could greatly facilitate the applications of various near-field thermophotonic devices for noncontact thermal energy conversion and heat control.

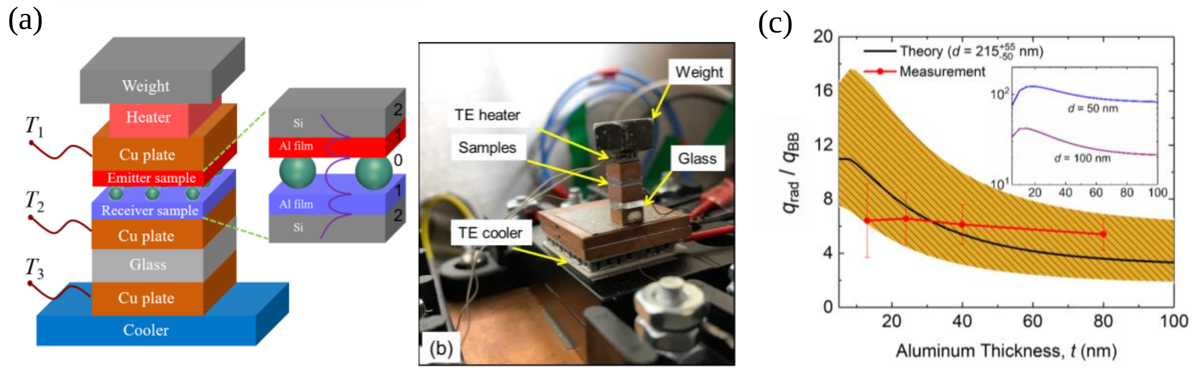

Figure 6. (a) Schematic and heat transfer model of plate-plate method with spacers for near-field radiation measurement. (b) Photo of plate-plate setup for measuring near-field radiation developed in the PI's lab. (c) Measured and calculated near-field radiative heat flux normalized to the blackbody limit as a function of Al thin film thickness at the vacuum gap of 215 nm and temperature difference of 65 K.

Moreover, in order to more accurately determine the vacuum gap in particular during the near-field measurement, we fabricated patterned SU-8 polymer as posts to create the vacuum gaps and in-situ characterized the gap distance with capacitance method as shown in Figs. 7a and 7b. SU-8 polymer posts, which significantly reduced the conduction below 6% of the total heat transfer due to its low thermal conductivity, were carefully fabricated with different heights to directly create vacuum gaps from 507±47 nm down to 190±20 nm precisely determined in-situ by capacitance measurement. We experimentally demonstrated the near-field thermal radiation enhancement over the blackbody limit by 11 times between highly doped silicon chips with 1×1 cm^2 size at a vacuum gap distance of 190±20 nm under a temperature difference of 74.7 K above room temperature. Experimental results were validated by theoretical calculations based on fluctuational electrodynamics, which revealed the enhancement mechanism mainly as coupled surface plasmon polariton. Note that SU-8 can be readily used for bonding two samples together to realize near-field radiative thermal devices. The gap capacitance method presented here enables precise determination of vacuum gap distances in-situ in particular for optically-opaque but electrically-conductive samples. With ultraflat samples and better-controlled SU-8 etching processes, it is possible to reduce the vacuum gaps down to 100 nm or less where near-field thermal radiation could be further enhanced, and thus spur the novel applications of near-field radiative thermal devices.

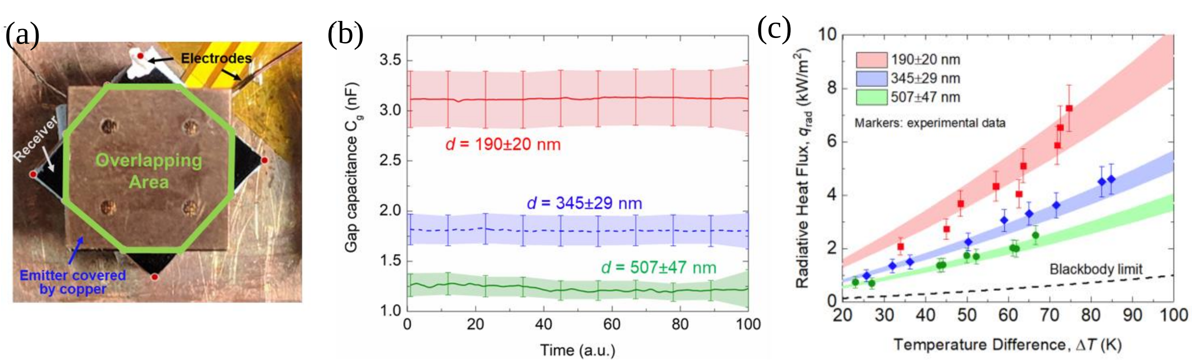

Figure 7. (a) Photo of experimental setup; (b) Gap capacitance measurement with different SU-8 polymer post heights. (c) Measured and calculated near-field radiative heat transfer between heavily doped silicon chips as a function of temperature at multiple vacuum gap distances.

3. Future Directions

While significant amount of fundamental understanding in both experiment and theory has been gained during the 3-year YIP project, thanks to the support of AFOSR, following would outline future research directions on nanowire metamaterials and its applications:

1) Low cost and large area fabrication nanowire metamaterials. While nanowire stamps are commercially available but expensive with very limited materials and geometric options. In order to achieve large area and low cost fabrication of nanowire structures with more materials selection and more controllable geometries, fabrication techniques such as anode aluminum oxide membrane, metal assisted chemical etching, and in particular, nanoimprinting can be utilized. After all, these fabrications have been demonstrated to be successfully for silicon nanowires, which can be used as cores for fabricating metallic nanowires by sputtering as demonstrated here.
2) Thermophotovoltaic test. The spectral selectivity of nanowire structures, which has been demonstrated to improve solar-thermal efficiency, could also in principle improve the thermophotovoltaic energy conversion by emitting narrowband thermal photons right above the cell bandgap. The developed solar-thermal platform can be readily used for solar thermophotovoltaic experiment with proper cell materials. Experimental demonstration of improved heat-to-power efficiency with selective nanowire emitters will bridge the gap between the fundamental study and its practical applications.
3) Theoretical study of near-field interaction between nanowires and 2D materials. As the effect of artificial magnetic resonance from nanowire structures has been theoretically understood from this project, it would be interesting to study how the magnetic nanowire structures interact with 2D materials such as graphene, boron nitride, BP when coated at the nanowire surface for near-field radiative heat transfer. These 2D materials are known to have strong plasmonic or phononic behaviors in the infrared which could contribute greatly to near-field heat transfer with the interaction of nanowire structures.
4) Near-field measurement of nanowires at sub-200nm gaps. While from this project we have successfully demonstrated super-Planckian radiation heat transfer beyond blackbody limit at 200nm vacuum gaps between planar surfaces of 1 cm in size, it remains a great challenge to experimentally measure nanowire structures, which has much large chance of contaminants and surface curvatures during sample fabrication processes, in particular to achieve sub-200nm gap distances where near-field effect is profound. Instead of plate-plate near-field setup, sphere-surface or tip-surface setups by utilizing AFM based methods have been demonstrated to be effective for measuring near-field radiation down to tens of or even single nanometer gap distance.

4. Student Training

Besides the research accomplishments, this 3-year YIP project provided many student training opportunities. Three PhD students (Dr. Jui-Yung Chang, Dr. Payam Sabbaghi, Xiaoyan Ying) have been supported by the YIP project for their dissertations, and two of them have successfully graduated. One Postdoc Fellow (Dr. Qing Ni) has been supported in part on the study of thermophotovotalic conversion. One MS student (Ramteja Kondakindi) worked on the near-field radiation measurement for his thesis. Besides, 4 undergraduate students (Lee Lambert, Ryan McBurney, Christian Messner, Nicole Sluder) have been involved. In particular, Lee Lambert continued his graduate study at Air Force Academy in Utah, and Ryan McBurney worked as an engineer at Naval Air Weapons Station in California after their graduations.

5. Journal Publications and Conference Presentations

The following lists the fruitful outcomes from the 3-year YIP project, with 6 journal publications (J), 3 journal manuscripts currently under review (S), 2 manuscripts to be submitted within next two weeks (T), along with 14 oral and poster presentations at top international and national conferences, meetings and workshops:

J1. Ying, X.Y., Sabbaghi, P., Sluder, N., and Wang, L.P., 2020, "Super-Planckian Radiative Heat Transfer between Macroscale Surfaces with Vacuum Gaps Down to 190 nm Created by SU-8 Posts and Characterized by Capacitance Method," *ACS Photonics*, Vol. 7, pp. 190-196.

J2. Ni, Q., McBurney, R., Alshehri, H., and Wang, L.P., 2019, "Theoretical Analysis of Solar Thermophotovoltaic Energy Conversion with Selective Metafilm and Cavity Reflector," *Solar Energy,* Vol.191, pp. 623-628.

J3. Long, L.S., Ying, X.Y., Yang, Y., and Wang, L.P., 2019, "Tuning the Infrared Absorption of SiC Metasurfaces by Electrically Gating Monolayer Graphene with Solid Polymer Electrolyte for Dynamic Radiative Thermal Management and Sensing Applications," *ACS Applied Nano Materials,* Vol. 2, pp. 4810-4817.

J4. Long, L.S., Taylor, S., Ying, X.Y. and Wang, L.P., 2019, "Thermally-switchable Spectrally-selective Infrared Metamaterial Absorber/Emitter by Tuning Magnetic Polariton with a Phase-change VO_2 Layer," *Materials Today Energy,* Vol. 13, pp. 214-220.

J5. Sabbaghi, P., Yang, Y., Chang, J.-Y., and Wang, L.P., 2019, "Near-Field Thermophotovoltaic Energy Conversion by Excitation of Magnetic Polaritons inside Nanometric Vacuum Gaps with Nanostructured Drude Emitter and Backside Reflector," *Journal of Quantitative Spectroscopy and Radiative Transfer,* Vol. 234, pp. 108-114.

J6. Ni, Q., Alshehri, H., and Wang, L.P., 2018, "Highly Efficient Sub-100-nm Thermophotovoltaic Cells Enhanced by Spectrally Selective Two-dimensional Metasurface," *Journal of Photonics for Energy*, Vol. 9, p. 032704.

S1. Sabbaghi, P., Long, L.S., Ying, X.Y., Lambert, L., Messner, C., and Wang, L.P., "Super-Planckian Near-Field Radiative Heat Flux between Metallic Surfaces with Near-field and Thin-film Effects," *Physical Review Applied*, revision submitted.

S2. Alshehri, H., Ni, Q., Taylor, S., McBurney, R., and Wang, L.P., "High Temperature Solar Thermal Energy Conversion Enhanced by Selective Metafilm Absorber under Multiple Solar Concentrations," *Applied Energy*, submitted.

S3. Chang, J.-Y., Sabbaghi, P., and Wang, L.P., "Retrieval of Uniaxial Permittivity and Permeability for the Study of Near-Field Radiative Transport between Metallic Nanowire Arrays," *Journal of Heat Transfer*, revision submitted.

T1. Chang, J.-Y., Taylor, S., McBurney, R., Ying, X.Y., Chen, Y.-B., and Wang, L.P., "Solar Thermal Energy Conversion with Selective Solar Absorber Made of Silicon-Cored Tungsten Nanowires," to be submitted.

T2. Chang, J.-Y., Sabbaghi, P., and Wang, L.P., "Near-field Radiation between Nanowire Based Dual Uniaxial Electromagnetic Metamaterials," to be submitted.

C1. Sabbaghi, P., Long, L.S., Ying, X.Y., Messner, C., and Wang, L.P., 2019, "Super-Planckian Radiative Heat Flux between Metallic Surfaces with Near-Field and Thin-Film Effects," *ASME International Mechanical Engineering Congress and Exposition (IMECE)*, Oral Presentation, Abstract No. IMECE2019-12553, Salt Lake City, UT, November 10-14.

C2. Chang, J.-Y., Sabbaghi, P., Chen, Y.-B., and Wang, L.P., 2019, "Retrieval of Uniaxial Permittivity and Permeability for the Study of Near-Field Radiative Transport between Metallic Nanowire Arrays," *6th ASME International Conference of Micro/Nanoscale Heat and Mass Transfer*, Oral Presentation, Abstract No. MNHMT2019-4096, Dalian, China, July 8-10.

C3. Chang, J.-Y., Ying, X.Y., Taylor, S., Chen, Y.-B., and Wang, L.P., 2019, "Selective Solar Absorber Made of Silicon-Cored Tungsten Nanowires," *6th ASME International Conference of Micro/Nanoscale Heat and Mass Transfer*, Oral Presentation, Abstract No. MNHMT2019-4095, Dalian, China, July 8-10.

C4. Sabbaghi, P., Yang, Y., Chang, J.-Y., and Wang, L.P., 2019, "Near-Field Thermophotovoltaic Energy Conversion by Excitation of Magnetic Polaritons inside Nanometric Vacuum Gaps with Nanostructured Drude Emitters," *9th International Symposium on Radiative Transfer (RAD-19)*, Oral Presentation and Conference Paper #20, Athens, Greece, June 3-7.

C5. Ni, Q., McBurney, R., Alshehri, H., and Wang,[§] L.P., 2019, "Concentrating Solar Thermophotovoltaic Energy Conversion Enhanced by Selective Metafilm," *9th International Symposium on Radiative Transfer (RAD-19)*, Oral Presentation and Conference Paper #19, Athens, Greece, June 3-7.

C6. Wang, L.P., Ying, X.Y., and Taylor, S., 2019, "Regulating Near-field Radiative Heat Transfer with Tunable Materials," *MRS Spring Meeting & Exhibit*, Oral Presentation, Abstract No. 3122081, Phoenix, AZ, April 22-26.

C7. Ramesh, R., Ni, Q., McBurney, R., Alshehri, H., and Wang, L.P., 2019, "Metasurface Filter Made of Plasmonic Nanodisk Array for Enhancing Thermophotovoltaic Energy Conversion," *MRS Spring Meeting & Exhibit*, Poster Presentation, Abstract No. 3121976, Phoenix, AZ, April 22-26.

C8. Kondakindi, R., Chang, J.-Y., and Wang, L.P., 2019, "AFM Cantilever Based Near Field Radiation Heat Transfer Measurement," *MRS Spring Meeting & Exhibit*, Poster Presentation, Abstract No. 3122018, Phoenix, AZ, April 22-26.

C9. McBurney, R., Ni, Q., Alshehri, H., and Wang, L.P., 2019, "Experimental Study of Solar Thermophotovoltaic Energy Conversion Enhanced with Selective Metafilm Coatings," *MRS Spring Meeting & Exhibit*, Poster Presentation, Abstract No. 3121909, Phoenix, AZ, April 22-26.

C10. Wang, L.P., and Ying, X.Y., 2018, "Near-field Radiative Thermal Regulation with Electrically Tunable Monolayer Graphene," *ASME International Mechanical Engineering Congress and Exposition (IMECE)*, Oral Presentation, Abstract No. IMECE2018-89213, Pittsburgh, PA, November 9-15.

C11. Chang, J.-Y., Sabbaghi, P., and Wang, L.P., 2017, "Retrieval of Uniaxial Permittivity and Permeability for the Study of Near-Field Radiative Transport between Nanowire Electromagnetic Metamaterials," *3rd International Workshop on Nano-Micro Thermal Radiation (NanoRad)*, Oral Presentation, Abstract No. OP-015, Daejeon, South Korea, June 26-28.

C12. Alshehri, H., Ni, Q., Wang, H., and Wang, L.P., 2017, "Optical and Thermal Characterizations of an Ultrathin Metafilm Selective Solar Thermal Absorber with Excellent High Temperature Stability," *MRS Spring Meeting & Exhibit*, Oral Presentation, Abstract No. 2658365, Phoenix, AZ, April 17-21.

C13. Sabbaghi, P., Yang, Y., and Wang, L.P., 2017, "Near-Field Thermophotovoltaic Energy Conversion by Excitation of Magnetic Polaritons inside Nanometer Vacuum Gaps with Nanostructured Drude Emitters," *MRS Spring Meeting & Exhibit*, Oral Presentation, Abstract No. 2657420, Phoenix, AZ, April 17-21.

C14. Ni, Q., Yang, Y., and Wang, L.P., 2017, "Plasmonic Light Trapping for Enhanced Infrared Photon Absorption in Ultrathin Wide-Bandgap Semiconductors," *MRS Spring Meeting & Exhibit*, Poster Presentation, Abstract No. 2657423, Phoenix, AZ, April 17-21.