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# Nanoscale Energy Transport

Emerging phenomena, methods and applications



# Nanoscale Energy Transport

Emerging phenomena, methods and applications

**Edited by**

**Bolin Liao**

*Department of Mechanical Engineering, University of California, Santa Barbara, USA*

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# Contents

<b>Preface</b>	<b>xiii</b>
<b>Editor biography</b>	<b>xvi</b>
<b>Contributors</b>	<b>xvii</b>
<b>Part I Theory and Computation</b>	
<b>1 Hydrodynamic phonon transport: past, present and prospects</b>	<b>1-1</b>
1.1 Introduction	1-1
1.2 Collective phonon flow	1-5
1.3 Peierls–Boltzmann transport equation	1-7
1.4 Steady-state phonon hydrodynamics	1-12
1.4.1 Infinitely large sample	1-13
1.4.2 Sample with an infinite length and a finite width	1-13
1.4.3 Sample with an infinite width and a finite length contacting hot and cold reservoirs	1-15
1.5 Unsteady phonon hydrodynamics (second sound)	1-18
1.6 Summary and future perspectives	1-21
Acknowledgments	1-23
References	1-23
<b>2 Higher-order phonon scattering: advancing the quantum theory of phonon linewidth, thermal conductivity and thermal radiative properties</b>	<b>2-1</b>
2.1 Overview	2-2
2.2 Formalism of four-phonon scattering	2-6
2.3 Strong four-phonon scattering potential	2-14
2.3.1 High temperature	2-15
2.3.2 Strongly anharmonic materials	2-19
2.4 Large four-phonon or suppressed three-phonon phase space	2-21
2.4.1 Materials with large acoustic–optical phonon band gaps	2-22
2.4.2 Optical phonons	2-25
2.4.3 Two-dimensional materials with reflection symmetry	2-29

2.5	Further discussion	2-33
2.5.1	Scaling with frequency	2-33
2.5.2	Strong Umklapp scattering	2-34
2.5.3	Negligible three-phonon scattering to the second order	2-34
2.6	Summary and outlook	2-37
	References	2-40
<b>3</b>	<b>Pre-interface scattering influenced interfacial thermal transport across solid interfaces</b>	<b>3-1</b>
	References	3-11
<b>4</b>	<b>Introduction to the atomistic Green's function approach: application to nanoscale phonon transport</b>	<b>4-1</b>
4.1	Introduction	4-1
4.2	Atomistic Green's function	4-2
4.2.1	Deduction of atomistic Green's functions	4-2
4.2.2	Self-energy and surface Green's function	4-7
4.2.3	Phonon transport in one-dimensional systems	4-8
4.3	Recent progress	4-16
4.3.1	From one dimension to three dimensions	4-17
4.3.2	Polarization-specific transmission coefficient	4-18
4.3.3	Anharmonic Green's function	4-21
4.4	Summary	4-25
	Acknowledgments	4-25
	References	4-25
<b>5</b>	<b>Application of Bayesian optimization to thermal science</b>	<b>5-1</b>
5.1	Introduction	5-1
5.2	Bayesian optimization	5-2
5.2.1	Bayesian algorithm theory	5-2
5.2.2	Bayesian optimization implemented as a black-box tool	5-5
5.3	Applications of Bayesian optimization in thermal science	5-6
5.3.1	Thermal conductance modulation	5-6
5.3.2	Thermal radiation engineering	5-8

5.4	Summary and perspectives	5-11
	Acknowledgments	5-12
	References	5-12
<b>6</b>	<b>Phonon mean free path spectroscopy: theory and experiments</b>	<b>6-1</b>
6.1	Introduction	6-1
6.2	Principles of MFP spectroscopy	6-2
6.3	Theory	6-5
	6.3.1 Nonlocal theory of heat conduction	6-5
	6.3.2 Solving the inverse problem	6-11
6.4	Experiments	6-16
	6.4.1 Size-dependent thermal conductivity measurements	6-16
	6.4.2 TTG spectroscopy	6-17
	6.4.3 Thermorefectance and diffraction techniques	6-20
6.5	Summary	6-25
	References	6-25
<b>7</b>	<b>Thermodynamics of anharmonic lattices from first principles</b>	<b>7-1</b>
7.1	Introduction	7-1
	7.1.1 Motivation	7-1
	7.1.2 Lattice dynamics theory and the self-consistent phonon idea	7-2
	7.1.3 Implementation example of the variational approach	7-5
7.2	Overview: historical development	7-8
7.3	Modern interpretations and implementations	7-11
	7.3.1 Selection and extraction of force constants	7-11
	7.3.2 Sampling of the configuration space for effective theories at finite temperature	7-17
7.4	A recent extension to SCHA-4	7-23
	7.4.1 Formulation	7-23
	7.4.2 Minimization equations with strain included	7-25
	7.4.3 Application to a simple model	7-26
7.5	Conclusions	7-28
	Acknowledgement	7-29
	Appendix A Thermodynamic properties of harmonic oscillators	7-29
	Appendix B Normal modes and Gaussian averages	7-29
	Appendix C Formal SCHA equations	7-31
	References	7-32



**Part II Measurements and applications**

<b>8</b>	<b>Experimental approaches for probing heat transfer and energy conversion at the atomic and molecular scales</b>	<b>8-1</b>
8.1	Introduction	8-1
8.2	Theoretical concepts	8-2
	8.2.1 Energy transport in atomic-scale junctions	8-2
	8.2.2 Heat dissipation and thermoelectric energy conversion in molecular junctions	8-4
8.3	Heat transfer and energy conversion at the atomic scale: experiments	8-5
	8.3.1 Quantum heat transport in single-atom junctions	8-6
8.4	Heat dissipation in atomic- and molecular-scale junctions	8-10
8.5	Peltier cooling in molecular-scale junctions	8-11
8.6	Measurement of thermal conductance of single-molecule junctions	8-14
8.7	Concluding remarks and outlook	8-16
	References	8-16
<b>9</b>	<b>Ultrafast thermal and magnetic characterization of materials enabled by the time-resolved magneto-optical Kerr effect</b>	<b>9-1</b>
9.1	Introduction	9-2
	9.1.1 Background and motivation	9-2
	9.1.2 Ultrafast-laser-based metrology for transport studies	9-3
9.2	TR-MOKE measurement technique	9-4
	9.2.1 The physical foundation	9-4
	9.2.2 Optical set-up of time-resolved magneto-optical Kerr effect	9-7
9.3	Thermal measurements	9-9
	9.3.1 Temperature information from TR-MOKE signals	9-9
	9.3.2 Measurement process and data analysis of TR-MOKE	9-11
	9.3.3 High-sensitivity thermal measurements enabled by TR-MOKE	9-11
9.4	Ultrafast magnetization dynamics	9-16
	9.4.1 Magnetization information from TR-MOKE signals	9-17
	9.4.2 Magnetic anisotropy and damping	9-18
9.5	Advanced capabilities for broader research directions	9-22
	9.5.1 Propagating spin waves	9-22
	9.5.2 Ultrafast energy carrier coupling	9-23
	9.5.3 Straintronics (coupling between spin and strain)	9-24
	9.5.4 Spin caloritronics	9-24

9.6	Summary and outlook	9-24
	Acknowledgements	9-25
	References	9-25
<b>10</b>	<b>Investigation of nanoscale energy transport with time-resolved photoemission electron microscopy</b>	<b>10-1</b>
10.1	Introduction	10-1
	10.1.1 The era of semiconductor technologies	10-2
	10.1.2 The importance of reaching the ultrafast frontier in semiconductor research	10-3
	10.1.3 The grand unification of electron microscopy and femtosecond spectroscopy	10-3
10.2	Unlocking high spatial–temporal resolution in studies of ultrafast dynamics in semiconductors	10-5
	10.2.1 Ultrafast transient absorption microscope (ultrafast TAM)	10-5
	10.2.2 Ultrafast techniques utilizing electron microscopes	10-8
10.3	Studies of semiconductors utilizing TR-PEEM	10-15
10.4	Outlook and perspective of TR-PEEM technique	10-22
	10.4.1 Ultrafast light sources with optimal repetition rate, peak power, pulse duration and energy bandwidth depending on application	10-22
	10.4.2 Parallel data acquisition for multidimensional data	10-23
	10.4.3 Resolving electron spin in TR-PEEM	10-24
10.5	Final remarks	10-26
	References	10-26
<b>11</b>	<b>Exploring nanoscale heat transport via neutron scattering</b>	<b>11-1</b>
11.1	Introduction	11-1
	11.1.1 A short history	11-1
	11.1.2 Neutron advantages	11-2
	11.1.3 Neutron sources	11-3
	11.1.4 Scattering theory	11-3
	11.1.5 Neutron instruments	11-5
11.2	Inelastic neutron scattering and phonon transport	11-6
	11.2.1 Thermal transport and measurable phonon properties	11-6
	11.2.2 Data reduction and analysis	11-7
	11.2.3 Some examples	11-8
	11.2.4 Summary	11-13
	References	11-13

<b>12 Thermal transport measurements of nanostructures using suspended micro-devices</b>	<b>12-1</b>
12.1 Introduction	12-1
12.2 Suspended micro-device platform	12-2
12.2.1 Basic principles and configuration	12-2
12.2.2 Sensitivity and uncertainties	12-5
12.2.3 Thermal contact resistance	12-7
12.3 Recent developments	12-11
12.3.1 The differential bridge method	12-11
12.3.2 Modulated heating	12-13
12.3.3 Background conductance	12-17
12.3.4 Characterization of heat loss from suspended beams	12-20
12.3.5 Electron-beam heating	12-21
12.3.6 Four-point thermal measurement	12-24
12.3.7 Integrated devices	12-25
12.4 Summary and outlook	12-27
Acknowledgments	12-28
References	12-28
<b>13 Recent advances in structured surface enhanced condensation heat transfer</b>	<b>13-1</b>
13.1 Introduction	13-1
13.2 Advancements in coating materials and the durability of coatings	13-3
13.2.1 Self-assembled monolayers	13-3
13.2.2 Polymers	13-3
13.2.3 Diamond-like carbon (DLC)	13-5
13.2.4 Rare earth oxides (REOs)	13-5
13.2.5 Hydrocarbon adsorption	13-6
13.2.6 Slippery omniphobic covalently attached liquids (SOCALs)	13-6
13.2.7 Degradation of coatings	13-7
13.3 Structured surfaces for low-surface-tension fluids	13-8
13.3.1 Re-entrant structured surfaces	13-9
13.3.2 Slippery liquid-infused porous surfaces (SLIPSs) and lubricant-infused surfaces (LISs)	13-10
13.3.3 LIS/SLIPS stability	13-11
13.3.4 Durability of LISs/SLIPs	13-13

13.4	Electric field enhanced (EFE) condensation	13-14
13.4.1	Electrohydrodynamic (EHD) enhancement of condensation heat transfer	13-15
13.4.2	Electric field induced condensation (EIC)	13-16
13.4.3	Electric field enhanced (EFE) jumping-droplet condensation	13-17
13.4.4	Potential research avenues for EFE condensation	13-18
	References	13-19
<b>14</b>	<b>Thermionic energy conversion</b>	<b>14-1</b>
14.1	Introduction	14-1
14.2	History of thermionic converters	14-2
14.3	Theory of thermionic converters	14-4
14.3.1	Basic working principle	14-4
14.3.2	Ideal output current, voltage and power	14-6
14.4	Design of thermionic converters	14-8
14.4.1	Vacuum-state thermionic converters	14-8
14.4.2	Solid-state thermionic converters	14-15
14.5	Application of thermionic converters	14-20
14.6	Summary and future directions	14-23
	References	14-24
<b>15</b>	<b>Recent advances in frosting for heat transfer applications</b>	<b>15-1</b>
15.1	Introduction	15-1
15.2	Classical condensation frosting theory	15-3
15.3	Anti-frosting superhydrophobic surfaces	15-7
15.4	Fabrication of superhydrophobic surfaces	15-7
15.5	Durability/robustness/fouling of superhydrophobic anti-frosting surfaces	15-9
15.6	Anti-frosting coatings for HVAC&R heat exchangers	15-11
15.6.1	Existing scalable coating methods	15-11
15.6.2	Performance quantification, testing methods and frost growth models	15-12
15.6.3	Frosting, defrosting and re-frosting	15-12
15.7	Defrosting	15-14
	References	15-16

<b>16</b>	<b>Reliably measuring the efficiency of thermoelectric materials</b>	<b>16-1</b>
16.1	Introduction	16-1
16.2	Prediction of efficiency from mathematical methods	16-2
16.2.1	Prediction of efficiency from the FDM	16-2
16.2.2	Prediction of efficiency from equations	16-2
16.3	Efficiency measurement	16-6
16.3.1	Challenges of efficiency measurement	16-6
16.3.2	Methods of efficiency measurement	16-7
16.3.3	TE module	16-12
16.4	Double four-point probe method	16-13
16.5	Conclusions	16-16
	References	16-16
<b>17</b>	<b>Thermophotovoltaic energy conversion: materials and device engineering</b>	<b>17-1</b>
17.1	Introduction	17-1
17.2	Framework for analyzing the performance of TPV systems	17-3
17.2.1	Spectral efficiency	17-4
17.2.2	Quantum efficiency	17-12
17.2.3	Bandgap utilization	17-13
17.2.4	Fill factor	17-16
17.3	Discussion and summary	17-19
	Appendix: Emitter data	17-21
	References	17-23

# Preface

Nanoscale energy transport is a fast-developing research field that studies the transport processes of fundamental energy carriers, including electrons, phonons, photons, magnons, etc, in devices and material structures with characteristic sizes in the nanometer range. Fundamentally, new physical phenomena emerge at the nanoscale due to the classical and quantum confinement effects of the energy carriers, leading to the breakdown of macroscopic constitutive laws, such as Fourier's law of heat conduction and Planck's law of blackbody radiation. Practically, as the advancement of nanotechnology has enabled routine fabrication of devices and materials at the nanoscale, a fundamental understanding of energy transport in these systems is crucial for achieving better efficiency and performance. Indeed, the improved understanding of nanoscale energy transport in the past two decades has led to better thermal management for microelectronic devices, more efficient thermoelectric modules and new strategies to efficiently harvest the full spectrum of solar power, to name a few examples. Therefore, nanoscale energy transport is a field of both fundamental interest and practical relevance. In this light, this multi-contributor volume aims to cover new developments in both the scientific basis and the practical relevance of nanoscale energy transport, with a particular emphasis on the emerging effects at the nanoscale that qualitatively differ from those at the macroscopic scale.

Excellent texts and monographs on nanoscale energy transport are available, for example by Chen [1], Zhang [2], Fisher [3], Volz [4] and others, where the fundamentals and the research developments at the time of publication are clearly elaborated. However, as this is an active field of research, new effects, experimental and computational methods, and applications are emerging at a fast pace. Complementary to these existing books, the goal of this volume is to cover recent developments in the theory, methods and applications of nanoscale energy transport from the past few years, and help researchers in this field obtain an overview of the current frontiers. To this end, I have invited active researchers in nanoscale energy transport to contribute chapters on their specialty topics and offer their expert perspectives on the important advancements in the past decade as well as future directions. In the end, 17 chapters were selected for this multi-contributor volume that cover a broad range of topics. In terms of microscopic energy carriers, the transport of phonons, electrons, photons and magnons in the nanoscale are discussed in various chapters. In terms of methods, state-of-the-art computational and experimental approaches are reviewed, including a chapter on the emerging material informatics method (chapter 5). In terms of material systems, a broad range from interfaces and molecular junctions to nanostructured bulk materials is included. While I believe this volume is a comprehensive survey of the state of the art of nanoscale energy transport, by no means does this book cover all significant new developments in the field. Notable omissions include spin caloritronics, where the coupling effects of phonons and magnons are investigated, and the energy

transport in two-dimensional materials. For these topics, the interested reader is referred to excellent recent review articles such as [5] and [6].

The chapters are organized into two parts. Part I focuses on emerging theory and computational methods. Chapter 1 by Sangyeop Lee's group at the University of Pittsburgh discusses hydrodynamic phonon transport, particularly in two-dimensional materials, where normal phonon-phonon scatterings dominate Umklapp scatterings and the phonon thermal transport mimics fluid flow. Chapter 2, by Tianli Feng from Oak Ridge National Laboratory and Xiulin Ruan from Purdue University, reviews the recent development of calculating higher order phonon scattering rates, e.g. four-phonon processes, and its relevance to thermal transport in technologically important materials. Chapter 3, by Tengfei Luo's group at the University of Notre Dame, provides a detailed account of how bulk phonon scattering events affect interfacial thermal transport from first-principles and molecular dynamics simulations. Chapter 4, by Zhiting Tian's group at Cornell University, gives an introduction to the state-of-the-art atomistic Green's function (AGF) method for calculating interfacial phonon transport properties and interfacial thermal resistance. Chapter 5, by Junichiro Shiomi's group at the University of Tokyo, elaborates on using material informatics methods, in particular Bayesian optimization, for nanoscale thermal transport problems. This is an emerging front in computational materials science that has attracted intense interest recently due to the fast advancement of data science and machine learning methods. Chapter 6, by Chengyun Hua at Oak Ridge National Laboratory, reviews the current status of resolving the phonon mean free path distribution in real materials from both the computational and experimental perspectives, which is essential for engineering materials at the nanoscale to achieve desirable thermal transport properties. Chapter 7, by Keivan Esfarjani's group at the University of Virginia, provides a historic view of incorporating the lattice anharmonicity into first-principles phonon calculations at finite temperature, which is necessary to correctly describe phonon softening and phase transitions.

Part II focuses on the developments of experimental techniques and practical applications enabled by fundamental advancements. Chapter 8, by Professors Edgar Meyhofer and Pramod Reddy's group at the University of Michigan, details state-of-the-art measurement techniques to resolve thermal and thermoelectric transport across atomic and molecular junctions with extreme sensitivity. Chapter 9, by Xiaojia Wang's group at the University of Minnesota, reviews the recent applications of emerging time-resolved magneto-optical Kerr effect (TR-MOKE) spectroscopy to characterize both phonon and magnetization dynamics. Chapter 10, by Keshav Dani's group at Okinawa Institute of Science and Technology in Japan, introduces a class of powerful tools—ultrafast electron microscopy, in particular time-resolved photoemission electron microscopy (TR-PEEM)—and their applications in nanoscale energy transport. Chapter 11, by Chen Li's group at the University of California, Riverside summarizes recent results utilizing the inelastic neutron scattering (INS) technique to understand phonons and magnons in energy materials. Chapter 12, by Renkun Chen's group at the University of California, San Diego, reviews the historic development and recent applications of suspended

micro-devices to characterize the thermal transport properties of nanomaterials. Chapters 13 and 15, by Nenad Miljkovic's group at the University of Illinois, Urbana–Champaign, discuss how micro- and nanostructured surfaces can significantly enhance condensation heat transfer and help combat frosting and icing in practical energy systems. Chapter 14, by Mona Zebarjadi's group at the University of Virginia, introduces the mechanisms and current frontiers of using thermionic emission to convert thermal energy into electricity as an alternative to thermoelectric conversion. Chapter 16, by Zhifeng Ren's group at the University of Houston, addresses a critical problem at the current development stage of thermoelectric materials—how to reliably measure the thermoelectric transport properties and energy conversion efficiency of thermoelectric materials. Chapter 17, by Andrej Lenert's group at the University of Michigan, reviews the recent development of thermophotovoltaic energy conversion, including both the material and the device aspects, and particularly the opportunities offered by the recent advancement of nanophotonics.

I wish to acknowledge all the authors for their valuable input and hard work, which have made this volume possible. I also want to thank the Institute of Physics Publishing for providing me the opportunity to work on this project, in particular Michael Slaughter and John Navas who initiated this project, and Caroline Mitchell, Daniel Heatley and Robert Trevelyan for their generous help (and patience) during the editing and production process. Last, but not least, I want to thank the support for research provided by the US Department of Energy, National Science Foundation and US Army Research Office.

Bolin Liao  
University of California, Santa Barbara  
November 2019

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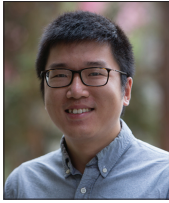
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- [6] Gu X, Wei Y, Yin X, Li B and Yang R 2018 Colloquium: phononic thermal properties of two-dimensional materials *Rev. Mod. Phys.* **90** 041002



# Editor biography

## Bolin Liao

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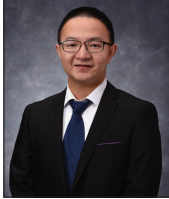
**Bolin Liao** is currently an assistant professor in the Department of Mechanical Engineering at the University of California, Santa Barbara. His main research interest is in nanoscale energy transport and its application to sustainable energy technologies. Specifically, his research aims to understand the transport and interaction processes of fundamental energy carriers, such as electrons, phonons, photons and magnons, at the smallest length and time scales, and then use this knowledge to develop more efficient clean energy devices, e.g. thermoelectric modules and photovoltaic cells. Current projects include first-principles and multiscale simulation of energy carrier transport, visualization of photophysics in space and time with scanning ultrafast electron microscopy, ultrafast optical techniques for thermal and thermoelectric characterization, and applied clean energy devices and systems.

Bolin obtained his PhD in mechanical engineering from MIT in March 2016, advised by Gang Chen. He was a Kavli Postdoctoral Fellow at the California Institute of Technology from May 2016 to June 2017, hosted by the late Ahmed Zewail, where he worked on scanning ultrafast electron microscopy.

# Contributors

## Xun Li

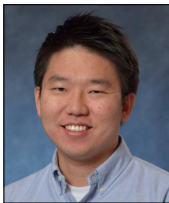
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**Xun Li** received his BS degree in energy engineering from Zhejiang University, the People's Republic of China, in 2015. He is currently a PhD candidate in the Department of Mechanical Engineering and Materials Science at the University of Pittsburgh, PA. His research focuses on the computational study of first-principles based phonon transport in graphitic materials and interfacial phonon transport in semiconductors.

## Sangyeop Lee

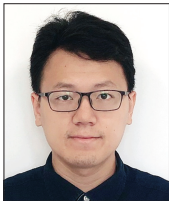
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**Sangyeop Lee** is an Assistant Professor in the Department of Mechanical Engineering and Materials Science at the University of Pittsburgh, PA. He received his PhD from the Department of Mechanical Engineering at Massachusetts Institute of Technology in 2015. His current research interests are first-principles based simulation of hydrodynamic phonon transport and thermal transport in partially/fully disordered phases.

## Tianli Feng

---



**Tianli Feng** is a postdoctoral fellow at Oak Ridge National Laboratory, TN. He received his BS in physics from the University of Science and Technology of China in 2011. He received his MS and PhD in mechanical engineering from Purdue University, IN in 2013 and 2017, respectively. His research interests include developing new atomistic-scale predictive simulation methods for thermal energy transport, and using these methods to guide the development of high-performance materials.

## Xiulin Ruan

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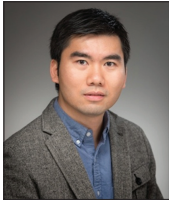


**Xiulin Ruan** is a Professor in the School of Mechanical Engineering and the Birck Nanotechnology Center at Purdue University, IN. He received his BS and MS in engineering thermophysics from Tsinghua University in 2000 and 2002, respectively. He received an MS in electrical engineering and a PhD in mechanical engineering from the University of Michigan at Ann Arbor in 2006 and 2007, respectively. His research interests include multiscale multiphysics simulations and experiments of phonon, electron, and photon transport and interactions, for various emerging applications. Ruan has been recognized with

many awards, including the NSF CAREER Award (2012), the ASME Heat Transfer Division Best Paper Award (2015) and the Air Force Summer Faculty Fellowship (2010, 2011 and 2013). He currently serves as an associate editor for the *ASME Journal of Heat Transfer*.

### **Tengfei Luo**

---



**Tengfei Luo** is the Dorini Family Collegiate Chair and Associate Professor in the Department of Aerospace and Mechanical Engineering (AME) at the University of Notre Dame (UND), IN. Before joining UND, he was a postdoctoral associate at Massachusetts Institute of Technology from 2009 to 2011, after obtaining his PhD from Michigan State University in 2009. At UND, Luo leads an interdisciplinary group focusing on nanoscale thermal transport, electronics thermal management, novel material design and manufacturing, and water treatment.

### **Eungkyu Lee**

---



**Eungkyu Lee** is the Research Assistant Professor in the Department of Aerospace and Mechanical Engineering (AME) at the University of Notre Dame (UND), IN. He was a postdoctoral associate at the Department of AME at UND. He obtained his PhD from Seoul National University in 2015. At UND, Lee studies light–matter interaction involving nanophotonics and multiphase thermofluids and interfacial thermal transport.

### **Ruiyang Li**

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**Ruiyang Li** is currently pursuing a PhD degree at the University of Notre Dame, IN under the supervision of Tengfei Luo. He received his BS degree in energy and power engineering from Huazhong University of Science and Technology in 2018. His research interests include nanoscale thermal transport at semiconductor material interfaces, and the prediction of thermal properties using machine learning based techniques.

### **Zhiting Tian**

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**Zhiting Tian** is an Assistant Professor and a Eugene A Leinroth Sesquicentennial Faculty Fellow in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, NY. Between 2014 and 2018 she was an Assistant Professor of Mechanical Engineering at Virginia Tech. Zhiting obtained her PhD in mechanical engineering from MIT in 2014. Zhiting’s research focuses on the fundamental understanding of nanoscale thermal

transport and energy conversion using experimental and computational tools. Zhiting's recent awards include the Office of Naval Research (ONR) Young Investigator Award, NSF CAREER Award, ACS Petroleum Research Fund Doctoral New Investigator Award and 3M Non-Tenured Faculty Award.

### Jinghang Dai

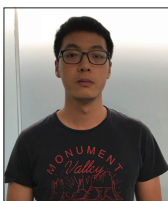
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**Jinghang Dai** is a PhD student in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, NY. His research interests focus on the modeling of transport processes at interfaces and thermoelectric materials and experimental characterization of thermal transport properties.

### Renjiu Hu

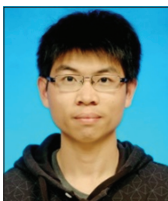
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**Renjiu Hu** is a PhD student in the Sibley School of Mechanical and Aerospace Engineering at Cornell University, NY. His research focuses on interfacial thermal transport and Anderson localization.

### Jiang Guo

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**Jiang Guo** is currently a PhD student in the Department of Mechanical Engineering at the University of Tokyo, working on tailoring thermal radiative properties for energy applications via optimizing metamaterials using machine learning methods.

### Shenghong Ju

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**Shenghong Ju** received his PhD in 2014 from Tsinghua University, PRC. He is now an associated professor at the China–UK Low Carbon College, Shanghai Jiao Tong University, and a visiting scholar at the University of Tokyo. He is working on developing new energy materials, fundamental nanoscale heat transfer studies and materials informatics.

### Junichiro Shiomi

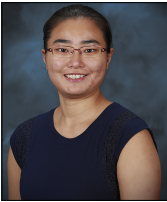
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**Junichiro Shiomi** received his PhD in 2004 from the Royal Institute of Technology (KTH), Sweden. He is currently a Professor in the Department of Mechanical Engineering, The University of Tokyo. His research interests include heat conduction of nanomaterials, polymer composites, thermoelectrics, phase change and fluidics in the nanoscale, interfacial thermofluid dynamics, thermal convections and materials informatics.

### Chengyun Hua

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**Chengyun Hua** received her BS in engineering physics from the University of Michigan in 2011, and her PhD in mechanical engineering from the California Institute of Technology in 2016. She joined the Oak Ridge National Laboratory, TN, in 2016 as a Liane B Russell Fellow and is currently working as an R&D associate. Her research focuses on gaining a comprehensive picture of how heat is transported in a solid at the scales of heat carriers, i.e. electrons and phonons (quantized vibrations in the lattice). Using both computation and experiments, she is currently working on using structures at the nanoscale as a tunable physical parameter to control and manipulate heat.

### Keivan Esfarjani

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**Keivan Esfarjani** obtained his general-engineering degree at the Ecole Centrale de Paris in France. He then pursued his studies in theoretical solid-state physics with a Master's (DEA) from the University of Paris followed by a PhD at the University of Delaware and a postdoc at Washington University in Saint Louis, MO. During his career, Esfarjani has held various positions at the Institute for Materials Research of Tohoku University, Sharif University of Technology, University of California Santa Cruz, MIT and Rutgers University. Currently he is an Associate Professor at the Departments of Mechanical Engineering, Materials Science and Physics at the University of Virginia. His research interests include the electronic structure calculation of materials from first-principles, lattice dynamics and phase change, electrical and thermal transport, and finally the storage and conversion of energy and information.

## Yuan Liang

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**Yuan Liang** received his BSc in applied physics from the University of Science and Technology of China, in Hefei, Anhui, in 2015. He was a member of the YAN Ji-Ci Elite Program in Physics, School of Gifted Young, working on the super-hydrophobicity of nano-membranes. He is currently working on his PhD in physics at the University of Virginia, Charlottesville. His current research interests include free energy computation and phase transition studies based on self-consistent phonon theory, computational schemes to extract anharmonic force constants in finite temperature—specifically stochastically designing a sampling method of lattice snapshots— and material properties analysis by applications of deep learning neural network packages.

## Pramod Reddy

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**Pramod Reddy** received a BTech and MTech in mechanical engineering from IIT-Bombay in 2002, and a PhD in applied science and technology from the University of California, Berkeley in 2007. He is currently a Professor in the Departments of Mechanical Engineering and Materials Science and Engineering at the University of Michigan, Ann Arbor.

## Edgar Meyhofer

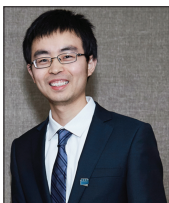
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**Edgar Meyhofer** received a BS in biology from the University of Hannover in Germany, and an MS from Northeastern University in Boston, MA. In 1991 he earned a PhD from the University of Washington, Seattle. Since 2001 he has been a Professor of Mechanical Engineering and Biomedical Engineering at the University of Michigan in Ann Arbor. His current interests include nanoscale radiative heat transfer, energy transport in molecular junctions and nanoscale energy conversion.

## Longji Cui

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**Longji Cui** joined the faculty of the Mechanical Engineering and Materials Science and Engineering program of CU Boulder, CO, as an Assistant Professor in January 2020. Cui received his PhD in mechanical engineering in 2018 from the University of Michigan, Ann Arbor, under the supervision of Pramod Reddy and Edgar Meyhofer. From August 2018, he served as a Visiting Assistant Professor in the Mechanical Engineering department of CU and has been the J Evans Attwell-Welch Fellow of Rice University, and performed postdoctoral research in the Smalley-Curl Institute and Department of Physics and Astronomy (Natelson Research Group) at Rice University. Cui is a recipient of the

Robert M Caddell Memorial Award, the Richard and Eleanor Towner Prize for Outstanding PhD Research at U-M, the Chinese Government Award for Outstanding Student Abroad and the Material Research Society (MRS) Graduate Student Gold Medal.

### Dustin Lattery

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**Dustin Lattery** is currently a PhD student in mechanical engineering at the University of Minnesota, Twin Cities. He received his Bachelor's and Master's degrees in mechanical engineering from the University of Minnesota, Twin Cities in 2014 and 2017, respectively. His research focuses on magnetization dynamics in thin films. During his research, Lattery has optimized the signal from time-resolved magneto-optical Kerr effect measurements of perpendicular magnetic thin films, successfully combining both experimental and numerical methods. He has applied this method to a range of technologically important magnetic materials, for extracting information about their magnetic anisotropy and Gilbert damping.

### Jie Zhu

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**Jie Zhu** is currently an Associate Professor in the School of Energy and Power Engineering at Dalian University of Technology in China. He was previously a research associate in the Department of Mechanical Engineering at the University of Minnesota, Twin Cities. He received his BS in thermal science and energy engineering in 2004 from the University of Science and Technology of China, and a PhD from the Institute of Engineering Thermophysics, Chinese Academy of Sciences in 2011. Zhu's research interests include ultrafast non-equilibrium heat transfer, thermal transport across interfaces, the thermophysical properties of novel materials and the development of related experimental methods.

### Dingbin Huang

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**Dingbin Huang** is currently a PhD student in mechanical engineering at the University of Minnesota, Twin Cities. Mr Huang received his Master's degree in mechanical engineering from Shanghai Jiao Tong University in 2018, and a Bachelor's degree from Xi'an Jiaotong University in 2015. Mr Huang's research interests are the time-resolved study of magnetization dynamics and spin-heat coupling of novel materials for spintronic and data storage applications.

### **Xiaoja Wang**

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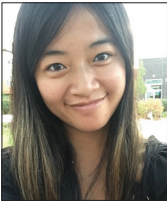


**Professor Xiaoja Wang** is an assistant professor in the Department of Mechanical Engineering at the University of Minnesota, Twin Cities. Prior to this, she was a postdoctoral research associate in the Department of Materials Science and Engineering at the University of Illinois at Urbana–Champaign. She received her PhD in mechanical engineering from the Georgia Institute of Technology in 2011. She received her MS in 2007 and BS in 2004 from Xi'an

Jiaotong University, China, studying mechanical engineering. Her current research explores thermal and magnetic transport in functional materials and across material interfaces, using ultrafast optical techniques. These investigative efforts have a wide range of applications, including solid-state energy conversion and harvesting, data storage and spintronic devices.

### **Rebecca Wong**

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**Rebecca Wong** obtained her Bachelor's degree in physics and environmental science from Grinnell College. She has worked on various energy-related research projects at universities and national laboratories in the United States and abroad, and has experience in optics research at Osaka University and more recently the Okinawa Institute of Science and Technology Graduate University. Her research interests include novel semiconductor materials and devices, in particular for solar and renewable energy.

### **Michael Man**

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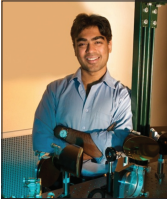
**Michael Man** received his Masters and PhD from Hong Kong University of Science and Technology. He moved to Okinawa and joined the Okinawa Institute of Science and Technology (OIST) as a postdoctoral researcher in 2012. Currently, he is a staff scientist in the Femtosecond Spectroscopy Unit at OIST. His research focuses on the development of ultrafast techniques in photoemission electron microscopy and in the study of electron dynamics and

ultrafast phenomena in two-dimensional materials. He also has expertise in the field of surface science, covering phase transition, growth and magnetism in ultrathin films and two-dimensional materials.



## Keshav Dani

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**Keshav Dani** is currently an Associate Professor at the Okinawa Institute of Science and Technology (OIST), Graduate University in Okinawa, Japan. He joined OIST in November 2011 as a tenure-track Assistant Professor after completing a Director's Postdoctoral Fellowship at the Center for Integrated Nanotechnologies at Los Alamos National Laboratory, NM. Keshav graduated from UC Berkeley in 2006 with a PhD in physics, where he explored the nonlinear optical response of the quantum Hall system under the supervision of Daniel Chemla at LBNL. Prior to his PhD, he obtained a BS from Caltech in mathematics with a senior thesis in quantum information theory under John Preskill and Hideo Mabuchi. His current research interests lie in the use of ultrafast techniques to study the electron dynamics of two-dimensional materials and energy materials, develop optoelectronic applications in the terahertz regimes, and pursue interdisciplinary projects with OIST colleagues in neuroscience and art conservation.

## Chen Li

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**Chen Li** joined the Department of Mechanical Engineering and Materials Science and Engineering Program at the University of California, Riverside as an assistant professor in July 2016. Prior to joining UCR, Li worked as a research scientist for EFree (Energy Frontier Research in Extreme Environment Center), a DOE Energy Frontier Research Center (EFRC) centered at the Geophysical Laboratory of the Carnegie Institute of Washington and a joint faculty at Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, TN.

Li obtained a BSc in physics from the Department of Physics, Peking University, and a PhD in materials science from the Department of Applied Physics and Materials Science, California Institute of Technology. After graduation, he worked as a postdoc for the Scattering and Thermophysics Group, Materials Science and Technology Division, at Oak Ridge National Laboratory.

## Qiyang Sun

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**Qiyang Sun** is a PhD student in the Mechanical Engineering Department, University of California, Riverside. Before joining UCR, Qiyang Sun obtained his BSc in engineering from the Energy and Power Engineering department, Huazhong University of Science and Technology, PRC.

### Sunmi Shin

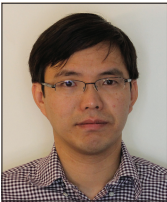
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**Sunmi Shin** joined the Department of Mechanical Engineering at the National University of Singapore as a Research Assistant Professor in August 2019 and will be an Assistant Professor from July 2020. She received her PhD degree in materials science and engineering from the University of California, San Diego in 2019. She specializes in the experimental and theoretical investigation of fundamental nanoscale heat transport for thermal management and the development of personalized thermoregulators and energy harvesting devices using thermoelectric energy conversion. Her research interests include multidisciplinary approaches for efficient and active thermal energy technologies.

### Renkun Chen

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**Renkun Chen** is an Associate Professor in the Department of Mechanical and Aerospace Engineering at the University of California, San Diego (UCSD). He received his BS in thermophysics from Tsinghua University, Beijing in 2004, and his PhD in mechanical engineering from the University of California, Berkeley in 2008. He was a postdoctoral researcher at Berkeley prior to joining UCSD in 2009. His research group at UCSD is interested in the fundamentals and applications of thermal energy transport and conversion, including nanoscale energy transport phenomena, thermoelectric and solar–thermal energy conversion, phase-change heat transfer and thermal insulation technologies.

### Hyeongyun Cha

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**Hyeongyun Cha** received BS and MS degrees in mechanical engineering from the University of Illinois at Urbana–Champaign in 2014 and 2016, respectively, where he is currently pursuing a PhD degree in mechanical engineering. His current research focuses on the study of functional coating degradation using scanning probe microscopy techniques.

### Soumyadip Sett

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**Soumyadip Sett** received his BE degree in power engineering from Jadavpur University, India in 2011, and a PhD degree in mechanical engineering from the University of Illinois at Chicago (UIC) in 2016. He is currently a postdoctoral researcher with the University of Illinois at Urbana–Champaign (UIUC). His research interests intersect the multidisciplinary fields of thermofluid science, interfacial phenomena and renewable energy. His current work focuses on the phase-change heat transfer performance of

micro/nanostructured surfaces, in particular involving low surface tension fluids and refrigerants. He was the recipient of the Deans Graduate Fellowship from UIC in 2015 for outstanding graduate research during his PhD, and in 2014 received the Chicago Consular Corps award for academic achievements as an international student.

### Patrick Birbarah

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**Patrick Birbarah** received his BE degree (with a high distinction) in mechanical engineering from the American University of Beirut, Lebanon in 2014. He received a PhD degree in mechanical science and engineering from the University of Illinois at Urbana–Champaign in 2019, where his work focused on phase-change heat transfer enhancement. He is currently working at Trane as a thermal systems engineer.

### Tarek Gebrael

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**Tarek Gebrael** received a BE degree (with a high distinction) in mechanical engineering with a minor in applied mathematics from the American University of Beirut, Lebanon in 2017. He is currently pursuing a PhD degree in mechanical engineering at the University of Illinois at Urbana–Champaign. His current research interests include electric field actuated droplet jumping during condensation and advanced phase-change thermal management techniques for next-generation high power density electronics.

### Junho Oh

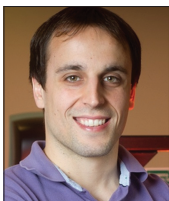
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**Junho Oh** received BS and MS degrees in mechanical engineering from Sungkyunkwan University, Seoul, South Korea in 2013 and 2015, respectively, and a PhD degree in mechanical engineering from the University of Illinois at Urbana–Champaign. He is currently a Research Fellow at University College London, UK. His current research interests include nanoengineering, fluid mechanics and interfacial sciences for enhancing phase-change heat transfer and biomedical applications.

### Nenad Miljkovic

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**Nenad Miljkovic** received a BAsC degree in mechanical engineering from the University of Waterloo, ON, Canada, in 2009, and MS and PhD degrees in mechanical engineering from the Massachusetts Institute of Technology in 2011 and 2013, respectively. He is currently an Associate Professor of mechanical science and engineering with the University of Illinois at Urbana–Champaign

(UIUC) where he leads the Energy Transport Research Laboratory. He has courtesy appointments in Electrical and Computer Engineering and the Materials Research Laboratory. His group's research intersects the multidisciplinary fields of thermo-fluid science, interfacial phenomena and renewable energy. Miljkovic was a recipient of the National Science Foundation CAREER Award, the American Chemical Society Petroleum Research Fund Doctoral New Investigator Award, the Office of Naval Research Young Investigator Award, a Distinguished Visiting Fellowship from the United Kingdom Royal Academy of Engineering, a US National Academy of Sciences Arab American Frontiers Fellowship, the ASME ICNMM Young Faculty Award, the ASME Pi Tau Sigma Gold Medal, the CERL Research and Development Technical Achievement Award, and the UIUC Dean's Award for Excellence in Research. He is the associate director of the Air Conditioning and Refrigeration Center, which is an NSF-founded I/UCRC at UIUC supported by 30 industrial partners.

### **Mona Zebarjadi**

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**Mona Zebarjadi** is a Joint Professor of the Electrical and Computer Engineering and Materials Science and Engineering Departments at the University of Virginia, Charlottesville, where she is leading the Energy Science and Nanotechnology Laboratory (ESNL). Prior to her current appointment she was a Professor at the Mechanical Engineering Department at Rutgers University. She received her Bachelor's and Master's degree in physics from Sharif University and her PhD in electrical engineering from University of California, Santa Cruz in 2009, after which she spent three years at MIT as a postdoctoral fellow working jointly with the Electrical and Mechanical Engineering Departments. Her current research interests include electron and phonon transport in thermoelectric, thermionic and thermomagnetic materials, and devices with a focus on two-dimensional structures.

### **Golam Rosul**

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**Md Golam Rosul** obtained his Bachelor of Science degree in electrical and electronic engineering from the Bangladesh University of Engineering and Technology (BUET) in 2015. He joined the PhD program in electrical engineering at the University of Virginia in the fall of 2017. His current research interest is thermionic transport in two-dimensional materials.

### Sabbir Akhanda

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**Md Sabbir Akhanda** obtained BS and MS degrees in applied physics, electronics and communication engineering and in electrical and electronic engineering, respectively, from the University of Dhaka, Bangladesh, in 2013 and 2015, respectively. He is currently a PhD student with the University of Virginia, Charlottesville. His current research interest is focused on thermoelectric and thermomagnetic materials.

### Shreyas Chavan

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**Shreyas Chavan** received his Bachelor of Technology degree in mechanical engineering from the Indian Institute of Technology Bombay in 2014, and MS and PhD degrees from the University of Illinois at Urbana–Champaign in 2016 and 2019, respectively.

During his PhD he worked with Nenad Miljkovic in the Energy Transport Research Laboratory. His primary research involved understanding the underlying fundamental physics of phase-change processes on structured superhydrophobic surfaces. He focused on the investigation of frosting and defrosting on superhydrophobic and biphilic surfaces.

### Kalyan Boyina

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**Kalyan Boyina** received a BS degree (Hons) in mechanical engineering from Oklahoma State University in 2014, and an MS degree from the University of Illinois, Urbana–Champaign in 2016. He is currently a doctoral student at the University of Illinois, Urbana–Champaign, where he works with Nenad Miljkovic in the Energy Transport Research Laboratory. His primary research interests include the large scale fabrication and performance characterization of anti-frosting

superhydrophobic heat exchangers under a wide range of ambient conditions, optimization of superhydrophobic coating technologies, advanced defrosting techniques and brazed joint strength enhancement through surface modification.

### Longnan Li

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**Longnan Li** received a PhD degree in mechanical engineering from Sogang University, Seoul, South Korea in 2017. He was an engineer in the Haier group and Midea group before pursuing his PhD degree from 2007 to 2011. He is currently a Postdoctoral Research Associate in the Department of Mechanical Science and Engineering, University of Illinois Urbana–Champaign. His current research interests include developing durable and scalable coatings

for high efficiency phase-change applications, micro/nanoscale fluid mechanics, electronics cooling and energy harvesting devices.

## Qing Zhu

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**Qing Zhu** is currently a PhD candidate in materials science and engineering at the University of Houston, TX. He received his Bachelor's degree in materials science and engineering from Northwestern Polytechnical University in China. His current research is focused on the measurement of conversion efficiency in thermoelectric materials.

## Zhifeng Ren

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**Zhifeng Ren** is the M D Anderson Chair Professor of Physics at the University of Houston, TX, and the director of the Texas Center for Superconductivity at the University of Houston (TcSUH). He received his BS degree from Xihua University in 1984, his MS degree from Huazhong University of Science and Technology in 1987, and his PhD degree from the Institute of Physics, Chinese Academy of Sciences, in 1990. He has published 510 peer-reviewed journal papers and has been awarded 55 patents. His research interests include high-performance thermoelectrics, ultrahigh thermal conductivity, amphiphilic Janus nanosheets for enhanced oil recovery, efficient catalysts for water splitting, including seawater, aligned carbon nanotubes, superconductivity, transparent flexible electrodes, etc.

## Tobias Burger

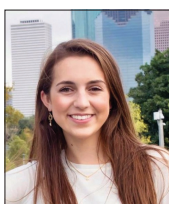
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**Tobias Burger** is a PhD candidate in chemical engineering at the University of Michigan. He received his MSE in chemical engineering from the University of Michigan and his BS in chemical engineering from the New Mexico Institute of Mining and Technology. He is working to develop thin-film PV devices for more affordable, high-performance thermophotovoltaic generators.

## Caroline Sempere

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**Caroline Sempere** is pursuing a BSE in chemical engineering at the University of Michigan. Her research experience includes the modeling of novel self-doped semiconductors and spectral control methods for thermophotovoltaic systems.

## Andrej Lenert

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**Andrej Lenert** is an Assistant Professor in the Department of Chemical Engineering at the University of Michigan. He completed his PhD at MIT in 2014, under the supervision of Evelyn Wang. He was a postdoctoral fellow at the University of Michigan, working with the Nanoscale Transport Laboratory and the Center for Photonic and Multiscale Nanomaterials. In 2016, he was named on the Forbes 30 under 30 list in Science for his contributions to the field of thermophotovoltaic energy conversion.