

UC San Diego

UC San Diego Electronic Theses and Dissertations

Title

Nanophotonic Thermal Energy Transport and Conversion

Permalink

<https://escholarship.org/uc/item/70k4m4fg>

Author

Pei, Yu

Publication Date

2024

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA SAN DIEGO

Nanophotonic Thermal Energy Transport and Conversion

A Dissertation submitted in partial satisfaction of the requirements
for the degree Doctor of Philosophy

in

Engineering Sciences (Mechanical Engineering)

by

Yu Pei

Committee in charge:

Professor Renkun Chen, Chair
Professor Shengqiang Cai
Professor Zhaowei Liu
Professor Jeffrey Rinehart

2024

Copyright

Yu Pei, 2024

All rights reserved.

The Dissertation of Yu Pei is approved, and it is acceptable in quality and form for publication on microfilm and electronically.

University of California San Diego

2024

DEDICATION

To my reader, for making this journey worthwhile.

TABLE OF CONTENTS

DISSERTATION APPROVAL PAGE	iii
DEDICATION	iv
TABLE OF CONTENTS.....	v
LIST OF FIGURES	vii
LIST OF TABLES	x
LIST OF ABBREVIATIONS	xi
ACKNOWLEDGEMENTS.....	xii
VITA	xiv
ABSTRACT OF THE DISSERTATION	xvii
Chapter 1 SURFACE PHONON POLARITON PROPERTIES	1
1.1 Introduction	1
1.2 Dispersion relation and Propagation length of SPhP	3
1.3 SPhP Thermal Conductance.....	6
1.4 SPhP waveguide and absorber design.....	12
1.5 Mode size for absorption efficiency	15
Acknowledgements	20
Chapter 2 HEAT CONDUCTION IN SURFACE PHONON POLARITON WAVEGUIDE	21
2.1 Introduction	21
2.2 SiO ₂ nanoribbons waveguide device fabrication	23
2.3 Thermal conductivity measurement	29
2.3 Measured apparent thermal conductivity of SiO ₂ NRs	36
2.4 Extracting the SPhP conductance	40
2.5 SPhP thermal conductance of the SiO ₂ NRs	50
2.6 Conclusion	60

Acknowledgements	61
Chapter 3 MOLTEN META-MATERIAL (MMM) SELECTIVE EMITTER.....	62
3.1 Introduction	62
3.2 Proposed structure and simulation	66
3.3 Mid-infrared selective MMM emitter	69
3.4 Near-infrared selective MMM emitter	73
Acknowledgements	75
REFERENCES	76

LIST OF FIGURES

Figure 1-1: Dispersion relation of SPhP modes supported on SiO ₂ NRs.	4
Figure 1-2: Propagation length of SPhP modes supported on SiO ₂ NRs.	5
Figure 1-3: Wave vector and mode profile of quasi-TM and quasi-TE modes. (a) Numerical calculated wave vector of quasi-TM and quasi-TE modes of SiO ₂ NR with 50 nm in thickness and 10 μ m in width. The gray area marks the metallic regime of SiO ₂ and the light green area marks the region with $n + ik < 1$ where no mode is supported. (b) and (c) The electric field distribution ($ E ^2$) of each mode at $\lambda = 10 \mu$ m.	9
Figure 1-4: Propagation wave on the sensing beam. (a) Propagation length of two supported modes (solid and dash curve) as a function of Fe ₃ O ₄ thickness. (b) and (c) The corresponding electric field ($ E ^2$) distributions.	10
Figure 1-5: SPhP contributed thermal conductance and conductivity. (a) SPhP contributed thermal conductance for nanoribbons of $t = 50$ nm, $W = 2 \mu$ m, $L = 50 \mu$ m (black) and $t = 50$ nm, $W = 2 \mu$ m, $L = 50 \mu$ m (red). The black curve overlaps with the red curve. (b), The corresponding thermal conductivity contributed by SPhP.....	11
Figure 1-6: Schematic of heat conduction measurement of a SiO ₂ NR waveguide device.....	12
Figure 1-7: Propagation length of SPhP along the thermal reservoir.	13
Figure 1-8: SEM images of a representative SiO ₂ NR device.	14
Figure 1-9: SPhP mode volume of SiO ₂ NR with different dimensions. a, SPhP mode size of NR with 10 μ m width and different thickness. b, SPhP mode size of NR with 50 nm thickness and different width. c, Dependence of SPhP mode size on wavelength (solid curve: quasi-TE mode, dash curve: quasi-TM mode). Inset: SEM image showing the gap between suspended SiO ₂ NR and Si substrate.	15
Figure 1-10: Possible mode couplings from the SiO ₂ NR to the sensing beam. Each of the two modes on the SiO ₂ nanoribbons can be coupled to either one of the two modes on the sensing beam, i.e., four possible coupling pathways which are marked as A, B, C and D, respectively. The red line arrows mark the two couplings that make the dominant contribution to the thermal conductance. The inset in the dash line box shows the cross section of our structure.	17
Figure 2-1: SiO ₂ nanoribbons waveguide device fabrication process.	23
Figure 2-2: SiO ₂ NR thickness measurement. (a) Schematic of SiO ₂ NR thickness reducing after BOE etching, the red line is the surface profiler scan route. We denote the thickness after the BOE etching as t_0 . (b)(c) Surface profile measurement results for the sample of $L = 49 \mu$ m, $W = 9.9 \mu$ m, $t = 44$ nm before and after BOE etching. The thickness is reduced from the original thermal oxide layer thickness of 100 nm to 62 nm. (d) Schematic of Pt marker on SiO ₂ . (e)(f) Surface profile measurement results for the sample before and after XeF ₂ etching, showing the 15 nm etching (δt) of the SiO ₂ layer by XeF ₂ . This is a very small but non-negligible etching of SiO ₂ considering that the Si is etched by more than 10 μ m. For the SiO ₂ NR, the thickness reduction due to the XeF ₂ etching is expected to be between δt and $2\delta t$ because the NR is suspended during the etching process, after which the bottom surface of the NR is also etched. 26	
Figure 2-3: SEM image of sputter deposited Fe ₃ O ₄ film.....	27

Figure 2-4: SEM images of SiO ₂ NR with different widths and lengths. (a) $L = 44\ \mu\text{m}$, $W = 2.4\ \mu\text{m}$, $t = 21\ \text{nm}$. (b) $L = 94\ \mu\text{m}$, $W = 2.3\ \mu\text{m}$, $t = 21\ \text{nm}$. (c) $L = 44\ \mu\text{m}$, $W = 2.26\ \mu\text{m}$, $t = 35\ \text{nm}$. (d) $L = 94\ \mu\text{m}$, $W = 2.2\ \mu\text{m}$, $t = 32\ \text{nm}$. (e) $L = 99\ \mu\text{m}$, $W = 1.18\ \mu\text{m}$, $t = 44\ \text{nm}$. (f) $L = 49\ \mu\text{m}$, $W = 1.1\ \mu\text{m}$, $t = 44\ \text{nm}$. (g) $L = 49\ \mu\text{m}$, $W = 9.9\ \mu\text{m}$, $t = 44\ \text{nm}$. (h) $L = 49\ \mu\text{m}$, $W = 9.9\ \mu\text{m}$, $t = 44\ \text{nm}$	28
Figure 2-5: Schematic of the thermal conductivity measurement platform.	30
Figure 2-6: Temperature distribution on the measurement device, including the left heating and right sensing beams and the NR bridging the two.	32
Figure 2-7: Heating and sensing beam temperature rise (ΔT_h , ΔT_s) versus input power. (a) ΔT_h and (b) ΔT_s with different Q_h at 300 K and 550 K for the NR sample with $L = 49\ \mu\text{m}$, $W = 9.9\ \mu\text{m}$, and $t = 44\ \text{nm}$	33
Figure 2-8: Combined thermal transport and tomographic measurements to determine NR thickness. (a) SiO ₂ NR thickness fitting result through frequency-dependent temperature rise measurement. (b) Atomic Force Microscopy (AFM) thickness measurement result of the same NR; inset is an AFM image of the SiO ₂ NR and the red line is the scan route.	35
Figure 2-9: Comparison of thermal conductivity of samples with and without the Fe ₃ O ₄ absorber.	36
Figure 2-10: The measured apparent thermal conductivity of NR samples with $t = 21\text{-}22\ \text{nm}$. ..	37
Figure 2-11: The measured apparent thermal conductivity of NR samples with W around 1 and 10 μm	38
Figure 2-12: Apparent thermal conductivity of NR samples with similar width and thickness and different lengths, showing the radiation heat loss on long samples.	39
Figure 2-13: Simulation result for the emissivity of the thin SiO ₂ NRs. (a) Schematic of the simulated structure calculating the absorption of incident light from varies directions by the SiO ₂ NR. (b) Directionally averaged emissivity vs. wavelength for NRs with different thicknesses and widths. (c) Total effective emissivity vs. temperature.	43
Figure 2-14: Comparison between the simulated results and the experimentally extracted emissivity from the 400 μm long NR sample (shown in Figure 2-12). The NR thickness is 30 nm. The error bars for emissivity are derived from the errors of the thermal conductivity in Figure 2-12.	44
Figure 2-15: The background conductance for devices of different gaps. (a) Background thermal conductance for devices without a NR. (b) ΔT_s as a function of heating power for 400 μm gap device, showing only noise with this gap size, meaning no measurable background conductance.	47
Figure 2-16: Schematic of the background signal canceling measurement platform.	48
Figure 2-17: Background signal canceling measurement results. (a) The apparent thermal conductivity and (b) the calculated SPhP thermal conductance of the SiO ₂ NR measured with and without BG canceling circuit, separately.	49
Figure 2-18: Length-dependence of SPhP thermal conductance (G_{SPhP}) of the SiO ₂ NRs at 550 K. Inset: normalized G_{SPhP} with the value of $\sim 50\ \mu\text{m}$ long samples.	52

Figure 2-19: Simulated mode profile of the SiO ₂ NR waveguide quasi-TM mode at the wavelength of 10 μm in the thickness direction for two samples: $t = 22$ nm and $W = 0.93$ μm (blue) and $t = 44$ nm and $W = 9.9$ μm (black).....	54
Figure 2-20: Temperature-dependent GSP_{hP} of the SiO ₂ NRs with different thickness and different widths of ~1 and ~10 μm, showing close to T and T^2 dependence respectively. The apparent thermal conductivity of these samples is shown in Figure 2-11.	55
Figure 2-21: Dependence of GSP_{hP} on the NR cross-section area compared to the calculated phonon thermal conductance of 50-μm-long NRs (solid black line) and the 1D and 2D quantum limits of GSP_{hP} (red and green dashed lines) in the small and large cross-section area regimes respectively. The experiment data corresponding to the ~ 50-μm-long NRs in Fig. 3a. Red dots for samples with small cross section (1D), green dot for sample with larger width (2D).	57
Figure 2-22: Thickness and width-dependence of SPhP thermal conductance. (a) Thickness, and (b) width-dependence of SPhP thermal conductance of SiO ₂ NRs.	58
Figure 3-1: Structure of emitter (a) Molten Meta-Material emitter design (b) top view (c) side view of emitter as fabricated, at 940K, and at 1800K.	66
Figure 3-2: Side view of MMM with (a) and without (b) bottom mirror. Simulation result of MMM emitter emittance at 1800K. (c) Black dash curve is the normalized blackbody emission.	68
Figure 3-3: Mid-infrared selective MMM emitter spectrum.	69
Figure 3-4: (a) Pt mirror and Al ₂ O ₃ spacer on sapphire wafer. (b) Al and Cu composite disks on substrate. (c) Porous Al disk by copper etchant wet etching. (d) Al ₂ O ₃ encapsulation layer.	70
Figure 3-5: Stability test at high temperature for (a) solid Al disks sample and (b) porous Al disks sample.	71
Figure 3-6: Absorptance spectrum for the emitters before and after annealing.	72
Figure 3-7: (a) Self-assembled monolayer of PS spheres in close-packed hexagonal array. (b) PS spheres after the RIE process with oxygen plasma. (c) Al disks array after RIE of the Al and removal of the PS mask. (d) Porous Al disks after Al etching using Cr etchant. (e) Device with Al ₂ O ₃ encapsulation to prevent Al oxidation.	73
Figure 3-8: Absorptance spectrum for the Near-infrared emitters before and after annealing.	74

LIST OF TABLES

Table 3-1: Performance of representative selective thermal emitters.....	64
--	----

LIST OF ABBREVIATIONS

SPhP	Surface phonon polaritons
NRs	Nanoribbons
G_{SPhP}	SPhP Thermal Conductance
MMM	Molten meta-materials
TPV	Thermophotovoltaic
PS	Polystyrene

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Prof. Renkun Chen, for his detailed and patient guidance throughout my research. His constant encouragement and unwavering support have been invaluable to my academic journey. His insights and expertise have profoundly shaped my understanding of the field, and I am incredibly fortunate to have had the opportunity to work under his supervision.

I am also deeply appreciative of my dissertation committee members. Prof. Zhaowei Liu directed both of the projects in this dissertation, providing crucial insights and guidance that have been instrumental to the success of my research. His expertise and feedback have significantly enhanced the quality of my work. Prof. Shengqiang Cai and Prof. Jeffrey Rinehart have also offered invaluable feedback and support throughout my work.

My heartfelt thanks go to my collaborators, whose contributions have been integral to my research. Li Chen's expertise in SPhP modeling and our numerous discussions have significantly deepened my understanding of the theoretical aspects of my work. His willingness to share his knowledge and provide guidance has been immensely helpful. Wonjae Jeon played a critical role in our research, conducting most of the thermal conductivity measurements and creating the beautiful figures that enhanced our paper. His meticulous work and creativity have greatly contributed to the success of our projects.

I am grateful to my lambastes for their support and camaraderie. Tianshi Feng, Xintong Zhang, Ka Man Chung, Sarath Reddy Adapa, Jian Zeng, Haowen Zhang, and Tobias Hang have all contributed to a productive and enjoyable research environment. Their collaboration, friendship, and support have made my time in the lab a rewarding experience. Each of them has

contributed in unique ways, from offering technical assistance to providing moral support during challenging times.

Lastly, I would like to thank my family and friends, especially my fiancé Yuanghang Zhang, for their unwavering support and encouragement throughout this journey. Their belief in me has been a source of strength and motivation.

I appreciate my collaborators allowing me to use the following publications in my dissertation:

Chapter 1, in full, is a reprint of the materials as it appears in "Low-dimensional Heat Conduction in Surface Phonon Polariton Waveguide." Yu Pei, Li Chen, Wonjae Jeon, Zhaowei Liu, Renkun Chen. Nature Communications 14, no. 1 (2023): 8242.

Chapter 2, in full, is a reprint of the materials as it appears in "Low-dimensional Heat Conduction in Surface Phonon Polariton Waveguide." Yu Pei, Li Chen, Wonjae Jeon, Zhaowei Liu, Renkun Chen. Nature Communications 14, no. 1 (2023): 8242.

Chapter 3, in part is currently being prepared for submission for publication of the material. "High-Temperature Molten Meta-Material Based Selective Thermophotovoltaic Emitter". Yu Pei, Li Chen, Jie Hu, Renkun Chen, and Zhaowei Liu. The dissertation author was the primary researcher and author of this material.

VITA

- 2016 Bachelor of Science in Thermal Energy and Power Engineering, Northeastern University
- 2019 Master of Science in Power Engineering and Engineering Thermophysics, University of Science and Technology of China
- 2024 Doctor of Philosophy in Engineering Sciences (Mechanical Engineering), University of California San Diego

PUBLICATIONS

1. Tianshi Feng, Bhabana Pati, Ka Man Chung, Yu Pei, and Renkun Chen. "Ceramic-to-metal bonding using rare-earth containing Sn–Bi solder." *Journal of Materials Science: Materials in Electronics* 35, no. 6 (2024): 369.
2. Yu Pei, Li Chen, Wonjae Jeon, Zhaowei Liu, Renkun Chen. "Low-dimensional Heat Conduction in Surface Phonon Polariton Waveguide." *Nature Communications* 14, no. 1 (2023): 8242.
3. Jian Zeng, Ka Man Chung, Qingyang Wang, Xiaoxin Wang, Yu Pei, Peiwen Li, and Renkun Chen. "Measurement of high-temperature thermophysical properties of bulk and coatings using modulated photothermal radiometry." *International Journal of Heat and Mass Transfer* 170 (2021): 120989.

4. Jian Zeng, Ka Man Chung, Xintong Zhang, Sarath Adapa, Tianshi Feng, Yu Pei, and Renkun Chen. "Thermal conductivity modeling of monodispersed microspheres using discrete element method." *Journal of Applied Physics* 130, no. 16 (2021).
5. Xin Wang, Qian Wang, Jian Cai, Changming Song, Yang Hu, Yang Zhao, and Yu Pei. "Preparation and Characterization of Electroplated Cu/Graphene Composite." In *2019 IEEE 69th Electronic Components and Technology Conference (ECTC)*, pp. 2234-2239. IEEE, 2019.
6. Hongmei Zhong, Yu Pei, Zhijiang Hu, Peng Zhang, Jian Guo, Xinglong Gong, and Yang Zhao. "A study of the heat transfer properties of CIP doped magnetorheological elastomers." *Smart Materials and Structures* 28, no. 2 (2019): 025027.
7. Yu Pei, Hongmei Zhong, Mengyu Wang, Peng Zhang, and Yang Zhao. "Effect of contact pressure on the performance of carbon nanotube arrays thermal interface material." *Nanomaterials* 8, no. 9 (2018): 732.
8. Ya Liu, Chaolun Dai, Yu Pei, Peng Zhang, Yi Tao, Yunfei Chen, and Yang Zhao. "Thermal interfacial coupling between electroplated copper and indium." *Materials Research Express* 5, no. 9 (2018): 096416.

FIELD OF STUDY

Major Field: Mechanical Engineering
Studies in Thermal energy transport
Professor Renkun Chen

ABSTRACT OF THE DISSERTATION

Nanophotonic Thermal Energy Transport and Conversion

by

Yu Pei

Doctor of Philosophy in Engineering Sciences (Mechanical Engineering)

University of California San Diego, 2024

Professor Renkun Chen, Chair

Thermal engineering plays an important role in our daily lives, such as thermal management for electronics, electric vehicles and buildings, solar thermophotovoltaic, refrigeration systems, thermal insulation, and so on. Photonic thermal engineering could give us some solutions to those application scenarios, for example, selective radiative coating on the roof

could realize passive cooling for the house. This dissertation focuses on Nanophotonic thermal energy transport and conversion, particularly surface phonon polaritons (SPhPs) for heat conduction and molten meta-materials (MMM) for high-efficiency thermophotovoltaic (TPV) systems.

The first part of my dissertation is about non-Fourier heat conduction by Surface Phonon Polaritons. In classical textbooks of thermal physics, there are three modes of thermal transport: conduction, radiation, and convection. Heat conduction in solids follows Fourier's law, and is normally described by a diffusion process with a short mean free path associated with the main heat carriers, such as phonons and electrons. Photons for radiation, on the other hand, usually have very long propagation length unless they are scattered by disordered media, or absorbed by participating media. However, photons are typically not confined and their energy intensity is orders of magnitude lower than that of heat conduction in solids. These two separated ways can intersect in the form of surface phonon polariton, which emerges due to the collective oscillation of atoms on the surface of a polar dielectric induced by electromagnetic (EM) waves. SPhPs are evanescent surface waves resulting from the coupling between optical phonons and photons, which have longer wavelengths and propagation lengths, making them ideal for extraordinary heat transfer. Our research demonstrated that SPhPs mediate thermal conductivity in SiO₂ nanoribbon waveguides, showing non-Fourier behavior over distances of 50-100 μm at room and high temperatures. This was achieved by designing the waveguides to control the mode size of SPhPs, clearly differentiate the SPhP contribution from phonons, and ensure efficient coupling to thermal reservoirs. We observe an increased thermal conductivity in nanoribbons of SiO₂, by as much as 34% over its well-known phonon thermal conductivity limit. This work establishes a foundation

for manipulating heat conduction beyond traditional limits, with potential applications in advanced thermal management and energy conversion.

The second part of this dissertation discussed the design and fabrication of Molten Meta-Materials selective emitter. We developed high-temperature plasmonic selective emitters using a novel concept of MMMs. These selective narrowband emitters can significantly boost thermophotovoltaic efficiency by emitting photons around the TPV cell's bandgap. Molten Al, with its superior plasmonic properties at high temperatures, enables a high Q-factor emission spectrum. Our emitter involves an array of nanoscale porous aluminum (Al) elements embedded in alumina, which acts as an oxygen barrier. This design solved the main problems for the previous high-temperature emitters in preventing reaction and releasing thermal stress. Aluminum and alumina are thermodynamically stable metamaterials at high temperatures. Besides, the voids in the porous aluminum will compensate for the volume expansion difference after the aluminum melts. In the future, we will integrate these MMM emitters into TPV systems, aiming for highly efficient thermal-to-electrical energy conversion exceeding 50%.

Chapter 1 SURFACE PHONON POLARITON PROPERTIES

1.1 Introduction

The importance of heat transfer research cannot be overstated, as it is fundamental to the efficiency and reliability of countless technologies and systems that shape our modern world. Effective heat transfer processes are essential to optimizing energy conversion, transportation, and storage, which are critical to power generation, industrial manufacturing, and renewable energy solutions. Additionally, advanced thermal management technologies are essential to maintaining the performance and longevity of electronic devices, aerospace systems, and electric vehicles¹⁻⁴. Research in heat transfer and thermal management will reduce energy consumption, and enhance functionality in a wide range of applications.

In diffusive heat conduction in solids, thermal conductance is proportional to the cross-section area of the solid and inversely proportional to its length under the traditional Fourier heat transfer systems. Non-Fourier heat conduction has only been observed in exotic systems under unusual conditions, such as phononic and electronic waveguides at sub-Kelvin temperature^{5, 6}, atomic and molecular structures⁷⁻⁹, carbon nanotubes¹⁰, and graphene¹¹. Surface phonon polariton (SPhP) in polar dielectric solids possess long wavelength, on the order of a few μm , and thus could lead to non-Fourier thermal conduction in solid structures with larger dimensions around room temperature. SPhP are evanescent surface waves due to the collective oscillation of atoms on the surface of polar dielectric materials induced by electromagnetic (EM) waves, i.e., coupling between optical phonons and photons. The propagating length of SPhP can be much longer than the mean free path (MFP) of phonons at room and high temperatures, greater than 1 mm when the film thickness is less than 100 nm¹¹⁻¹³. In principle, these propagating surface waves

can contribute to heat conduction of the solid, especially in nanostructures where the volumetric heat conduction by phonons and electrons is relatively smaller. Unlike thermal radiation by photons, SPhP waves can carry high energy flux along the solid surface, i.e., the solid acts as a thermal waveguide, akin to an optical fiber carrying light signals. Despite the early theoretical predictions^{12, 13} and their pronounced role in radiation heat transfer¹⁴⁻¹⁶, observing heat conduction by SPhP in solids has been elusive due to its relatively small contribution to thermal conductance compared to classical heat carriers such as phonons and electrons. In fact, this new mechanism of heat conduction mediated by SPhP has been suggested in a few recent experiments^{17, 18}. However, the experimental work has not observed an increase in absolute thermal conductivity compared to the classical phonon heat conduction of the corresponding solids, but rather relied on the temperature dependence of the total thermal conductivity, which remains lower than that of the bulk phonon thermal conductivity. The uncharted regime of polaritonic heat conduction is exciting but has not been unambiguously realized in prior work.

1.2 Dispersion relation and Propagation length of SPhP

Silica (SiO_2) has been chosen to be the polar material to investigate polaritonic heat conduction for two reasons. First, it's a polar dielectric material, surface polaritons can be excited on the vacuum and silica surface. More importantly, silica has low and constant phonon thermal conductivity due to its small mean free path. The constant phonon thermal conductivity makes it easier to compare the phonon conductance to the total conductance of silica ribbon even though the thickness of silica ribbon is only tens of nanometers. On the other way, the small phonon conductance of silica ribbon could relatively increase the ratio of SPhP thermal conductance to the total conductance.

As a polar material, SiO_2 exhibits a positive or negative dielectric constant at different wavelengths due to the presence of optical phonons, which can show either dielectric or metallic behaviour. Previous studies have shown that SiO_2 waveguide can support SPhP modes in both metallic and dielectric regions even beyond the optical phonon frequency range^{13, 19, 20}. The modes in the dielectric region are also called Zenneck modes and optical guided modes. Here we performed mode analysis on representative SiO_2 NRs with width of 10 μm and thicknesses of 50, 500, 1000 nm to obtain the propagation property of SPhP modes by using a finite element method (FEM) based commercial software (COMSOL Multiphysics). The solved dispersion relation and propagation length are shown in Figure 1-1 and Figure 1-2, from which we can see that two modes are supported on SiO_2 NRs. The SiO_2 NRs have rectangular cross-sections with width of 10 μm and thicknesses of 50, 500, and 1000 nm. The solid and dash curves correspond to the quasi-TM and quasi-TE modes, respectively. The insets in Figure 1-2 show the $|\mathbf{E}|$ field distributions of two representative modes. The gray area marks the metallic region, and the light green area marks the region with refractive index less than 1 where no valid propagation mode is supported. In general,

rectangular waveguides support hybrid quasi-TM (solid curve) and quasi-TE (dash curve) modes with the dominant polarization components along the thickness or width direction, respectively. Both the two modes have dispersion close to the light line, except for the quasi-TE mode in the metallic range. The propagation length increases drastically with reduced waveguide thickness, because a larger portion of the mode volume is in the vacuum with zero loss. In the case of a 50 nm thick NR, the propagation length is greater than 1 cm, significantly larger than the MFP of phonons. This long propagation length is the main contributor to the high and ballistic SPhP thermal conductance in prior studies^{12, 13}.

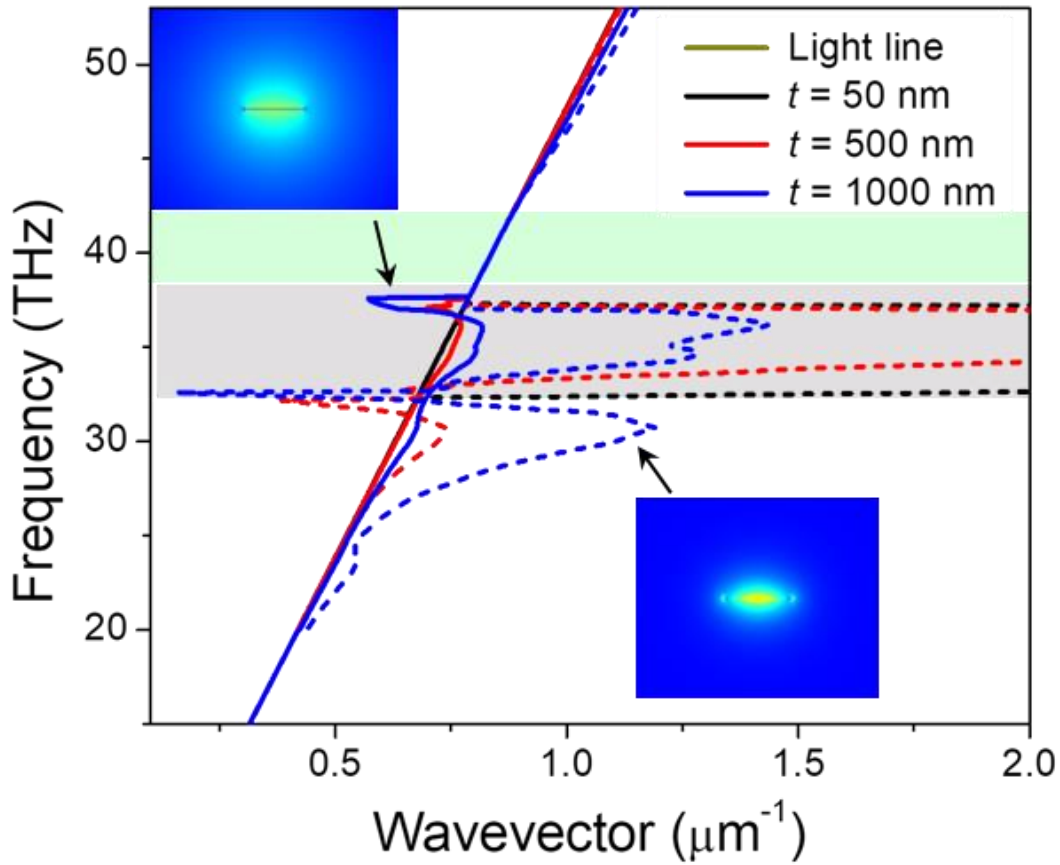


Figure 1-1: Dispersion relation of SPhP modes supported on SiO₂ NRs.

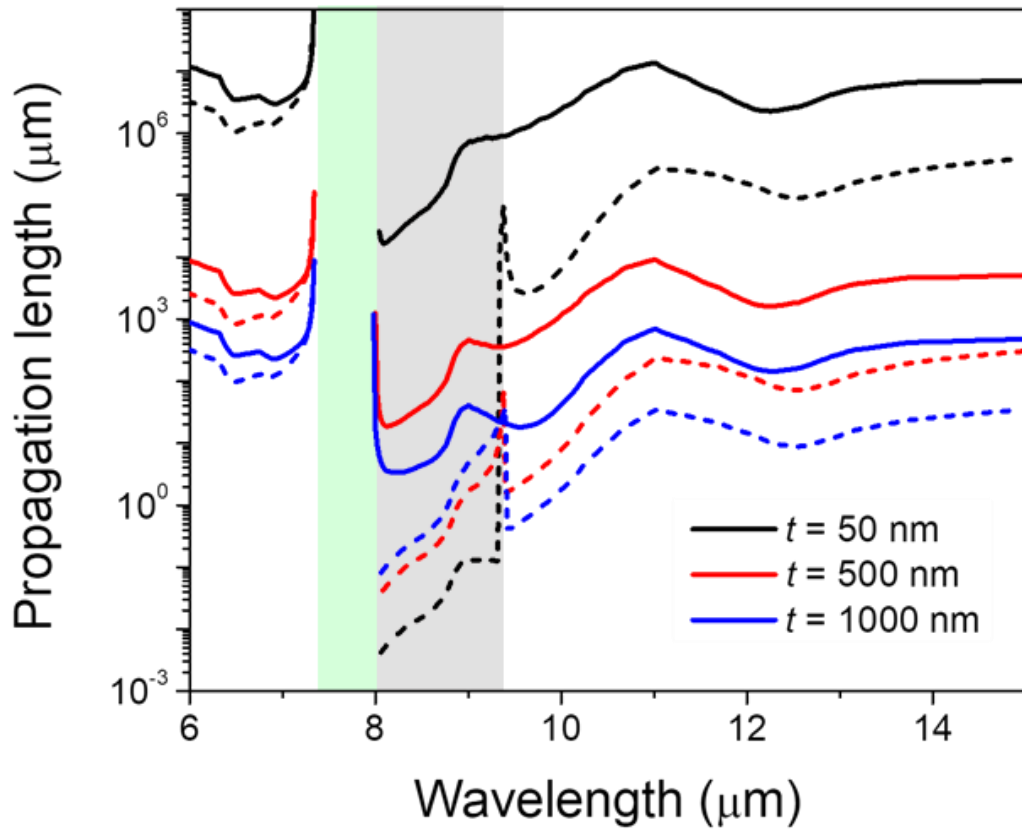


Figure 1-2: Propagation length of SPhP modes supported on SiO_2 NRs.

1.3 SPhP Thermal Conductance

Prior theoretical study has shown that the thermal conductance contributed by SPhP can be described as ¹³:

$$G_{SPhP} = \frac{1}{2\pi} \sum_{n=1}^N \int_{\omega_n^{min}}^{\omega_n^{max}} \hbar \omega \frac{\partial f_{\omega}(T)}{\partial T} \tau_n(\omega) \eta_n(\omega) d\omega \quad (1.1)$$

where N is the number of modes, ω_n^{min} and ω_n^{max} stand for the lowest and highest frequencies of each mode. $f_{\omega}(T)$ is the Bose-Einstein distribution function and T is the environmental temperature, τ_n is the transmission probability, and η_n is the absorption efficiency by the reservoir. Here in our case, we take $N = 2$ for the two modes (quasi-TM and quasi-TE), and $\tau_n = 1$ because the propagation length is much longer than the physical size (ballistic). However, the absorption efficiency η_n highly depends on the specific geometry and material properties, and computational complexity makes it difficult to make a quantitative calculation, considering the nanometer scale NR features and over 100 μm calculation domain size. Nevertheless, we can still use some physical principles to obtain its qualitative dependence trend and thus demonstrate the contributions of SPhP modes. The absorption efficiency η_n is proportional to the coupling efficiency of the propagation wave from the SiO_2 NR to the sensing beam, which depends on the mode profile matching between the two structures. For a SiO_2 NR, when the physical size is much smaller than the wavelength, the mode size (MS) is inversely proportional to the cross-section area (A) of the NR, i.e. $MS \propto 1/A$ ¹⁹. By substituting this into the thermal conductance equation above, we can obtain that $G_{SPhP} \propto A$ until it approaches a maximum value due to the saturation of the absorption efficiency.

We use the Landauer formula to analyze the SPhP thermal conductance (G_{SPhP}). Consider a rectangular SiO₂ NR waveguide with width of W , thickness of t , length of L , and temperature of T_h and T_s at each end, the heat flux Q along this NR is given by the Landauer formula ²¹:

$$Q = \sum_{n=1}^N \int_0^{k_n^{max}} \frac{1}{2\pi} \hbar \omega V [f_\omega(T_h) - f_\omega(T_s)] \tau_n(k) \eta_n(k) dk \quad (1.2)$$

where k , ω and $V = \partial\omega/\partial k$, are the wave vector, angular frequency, group velocity of the energy carriers propagating along the nanowire. Consider the energy carriers of SPhP in our case, k is the wave vector of SPhP. N is the number of SPhP modes supported by the SiO₂ NR. $f_\omega(T)$ is the Bose-Einstein distribution function, τ_n is the transmission probability of each mode and η_n is the corresponding absorption coefficient.

Considering that the temperature difference of temperature $\Delta T = T_h - T_c \ll (T_h + T_s)/2$, the term $f_\omega(T_h) - f_\omega(T_s)$ reduces to $f_\omega(T_h) - f_\omega(T_s) = \Delta T \partial f_\omega(T)/\partial T$. Then the SPhP thermal conductance can be expressed from $G = Q/\Delta T$ as:

$$G_{SPhP} = \frac{1}{2\pi} \sum_{n=1}^N \int_{\omega_n^{min}}^{\omega_n^{max}} \hbar \omega \frac{\partial f_\omega(T)}{\partial T} \tau_n(\omega) \eta_n(\omega) d\omega \quad (1.3)$$

where ω_n^{min} and ω_n^{max} stand for the lowest and highest frequencies of each mode. The value of ω_n^{min} and ω_n^{max} are considered as the lower and upper frequency limit of optical phonon of the materials. For example, 7.6 Trad/s and 258 Trad/s are used for SiO₂ in literatures²². In experiments like our system, the heating and sensing beam with Pt and Fe₃O₄ are included, which

will contribute to the mode excitations and absorption and thus contribute to thermal conductance. Considering that both Pt and Fe₃O₄ are lossy at a broadband frequency covering the whole range of Bose-Einstein distribution at our interested temperature, we can simply assume $\omega_n^{min} = 0$, $\omega_n^{max} = \infty$. Similar thermal excitation beyond the optical phonon range was already reported.²⁰ If considering the ideal case of $\omega_n^{min} = 0$, $\omega_n^{max} = \infty$, $\tau_n = 1$, and $\eta_n = 1$, then $G_{SPHP} = N \cdot G_0$, where $G_0 = \pi^2 k_B^2 T / 3h$ is known as the quantum of thermal conductance.

The thermal conductivity $k = G \cdot L/A$ is then given by:

$$k_{SPHP} = \frac{L}{2\pi A} \sum_{n=1}^N \int_{\omega_n^{min}}^{\omega_n^{max}} \hbar \omega \frac{\partial f_\omega(T)}{\partial T} \tau_n(\omega) \eta_n(\omega) d\omega \quad (1.4)$$

where $A = tW$ is the area of the cross-section of the NR.

In order to get the thermal conductivity, we first studied the characteristics of the propagation modes in the SiO₂ NR, including the dispersion relation, propagation length and also the mode profile. Here for our purpose, numerical simulations using the mode analysis module in a finite element method based commercial software (COMSOL Multiphysics) were conducted. The SiO₂ waveguide is modeled as a rectangular shape with an exemplary width of $W = 10 \mu\text{m}$, thickness $t = 50 \text{ nm}$ with the surrounding medium as vacuum. Fig. S8 shows the solved wave vector and mode profile of quasi-TM and quasi-TE mode. Both quasi-TM and quasi-TE modes show wave vectors very close to the vacuum wave vector k_0 , leading to small confinement and long propagation length. An exception is the quasi-TE mode in the metallic region (gray region in Figure 1-3). This is because, for quasi-TE mode, the electric field along the direction parallel to the SiO₂ NR exhibits a symmetric distribution. When the permittivity of SiO₂ is shown as metallic, the electric field is

highly confined within the metal, resulting in a short SPhP wavelength, a short decay length into the surrounding medium, and a smaller propagation length, due to enhancement of Ohmic losses. The wave vector is discontinuous within the wavelength range of 7.2 μm to 8.3 μm (green region in Figure 1-3), which is due to the fact that the refractive index ($n + ik$) of SiO_2 is less than 1. As a result, the calculated wave vector is also less than k_0 , which is physically invalid. Because if $k < k_0$, the fields outside the SiO_2 NR would be radiative in nature and would imply that the system is continually radiating energy out to infinity without a source.

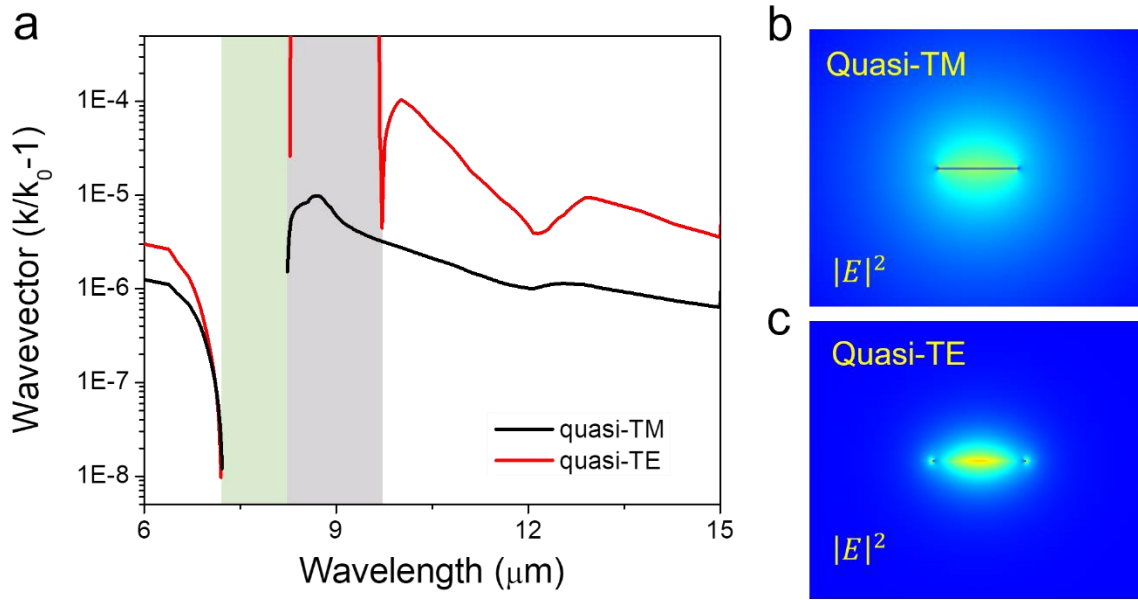


Figure 1-3: Wave vector and mode profile of quasi-TM and quasi-TE modes. (a) Numerical calculated wave vector of quasi-TM and quasi-TE modes of SiO_2 NR with 50 nm in thickness and 10 μm in width. The gray area marks the metallic regime of SiO_2 and the light green area marks the region with $n + ik < 1$ where no mode is supported. (b) and (c) The electric field distribution ($|E|^2$) of each mode at $\lambda = 10 \mu\text{m}$.

In order to gain a better understanding of how the waves propagate from the SiO_2 NR to the sensing beam and gradually get absorbed, we also conducted mode analysis on the sensing beam as shown in Figure 1-4. The thickness of Pt, Fe_3O_4 and SiO_2 are 110 nm, 350 nm, and 21 nm

respectively. The result shows that as the Fe_3O_4 thickness increases to over 300 nm, the propagation length of the waves greatly reduces to $< 50 \mu\text{m}$. In the experiment, we used 350 nm thick Fe_3O_4 , which resulted in a short SPhP propagation length and consequently enhanced the absorption coefficient of the SPhP by the reservoirs (the η_n term in Eq. 1.3). Of course, the final efficiency η_n is also depended on how much energy is coupled to the sensing beam, i.e., coupling efficiency.

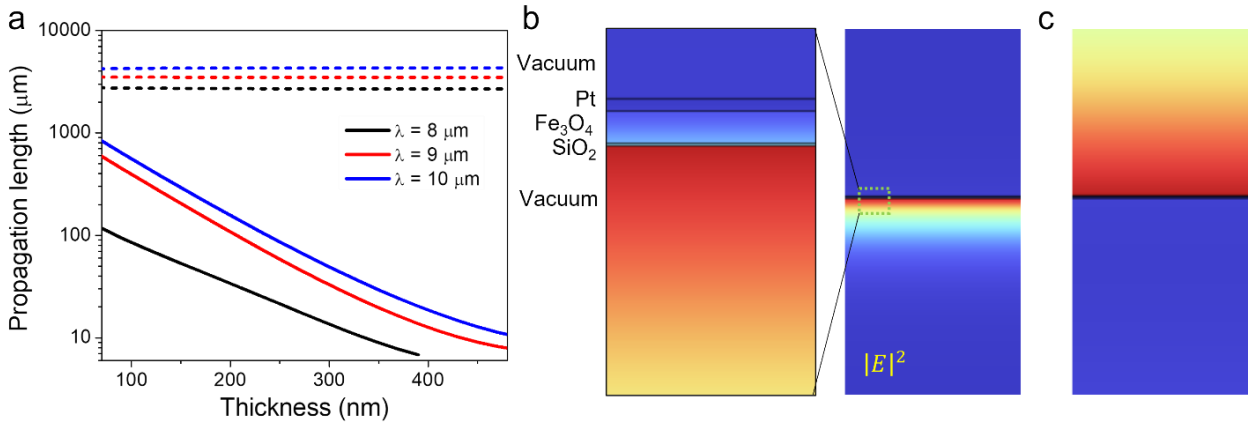


Figure 1-4: Propagation wave on the sensing beam. (a) Propagation length of two supported modes (solid and dash curve) as a function of Fe_3O_4 thickness. (b) and (c) The corresponding electric field ($|E|^2$) distributions.

The equation derived from the previous analysis reveals that G_{SPhP} of the SiO_2 NR is dependent on the transmission probability τ_n and corresponding absorption coefficient η_n of each SPhP mode. We calculated the propagation length (L_{SPhP}) of quasi-TM and quasi-TE mode through numerical mode analysis, from which we can obtain the transmission probability as:

$$\tau_n(\omega) = \exp\left(-\frac{L}{L_{\text{SPhP},n}(\omega)}\right) \quad (1.5)$$

The absorption efficiency η_n , however, highly depends on the specific geometry and material properties. Computational complexity makes it difficult to be estimated accurately,

especially considering that the feature size is only a few tens of nanometers while the whole device size is over a hundred micrometers. By assuming 100% absorption in the thermal reservoirs ($\eta_n = 1$), we can calculate the upper bound value of SPhP contributed thermal conductance G_{SPhP} . The thermal conductance and conductivity with considering the contributions of these two SPhP modes (quasi-TM and quasi-TE) are shown in Figure 1-5. It can be seen that for a narrow ribbon of $W = 2 \mu\text{m}$, G_{SPhP} is linearly dependent on the temperature because of the one-dimensional transport behaviour when $W < \lambda$. The two curves in Figure 1-5(a) overlap because the propagation lengths of the SPhP modes are long so that the SPhP contributions make no difference for nanoribbons with lengths of $50 \mu\text{m}$ and $100 \mu\text{m}$. The corresponding conductivity values contributed by SPhP modes are shown in Figure 1-5(b).

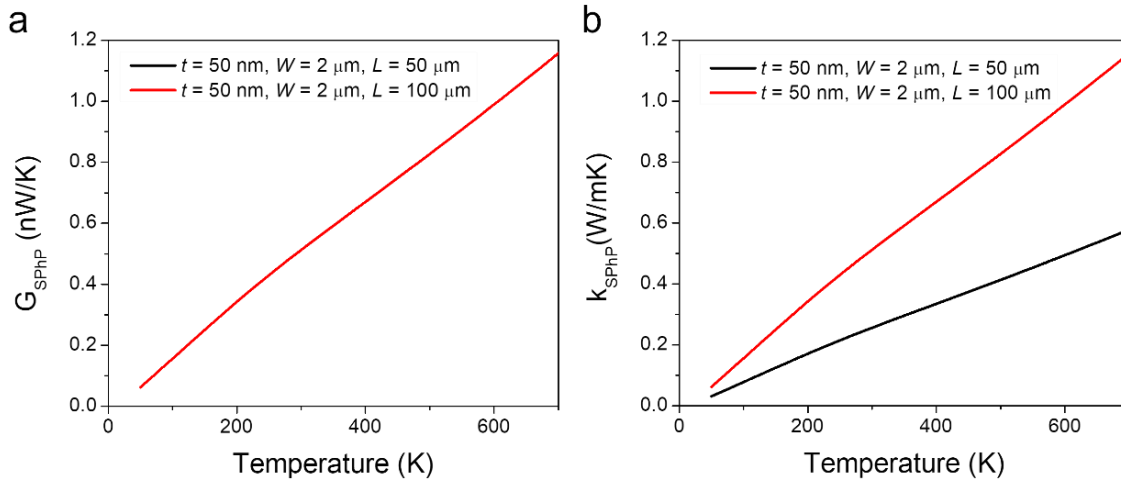


Figure 1-5: SPhP contributed thermal conductance and conductivity. (a) SPhP contributed thermal conductance for nanoribbons of $t = 50 \text{ nm}$, $W = 2 \mu\text{m}$, $L = 50 \mu\text{m}$ (black) and $t = 50 \text{ nm}$, $W = 2 \mu\text{m}$, $L = 100 \mu\text{m}$ (red). The black curve overlaps with the red curve. (b), The corresponding thermal conductivity contributed by SPhP.

1.4 SPhP waveguide and absorber design

In order to measure the SPhP contributed thermal conductance, we designed the device with a suspended SiO_2 nanoribbon waveguide as shown in Figure 1-6. The device consists of a heating and a sensing beam, representing the hot and cold thermal reservoirs, and the NR waveguide bridging the two. Figure 1-6 showing the heat conduction by SPhP and phonon in the waveguide between the hot and cold reservoirs, radiation loss from the waveguide, and direct background radiation between the two reservoirs. Each of these heat transfer pathways was measured and analyzed in this work to extract heat conduction mediated by SPhP in the waveguide.

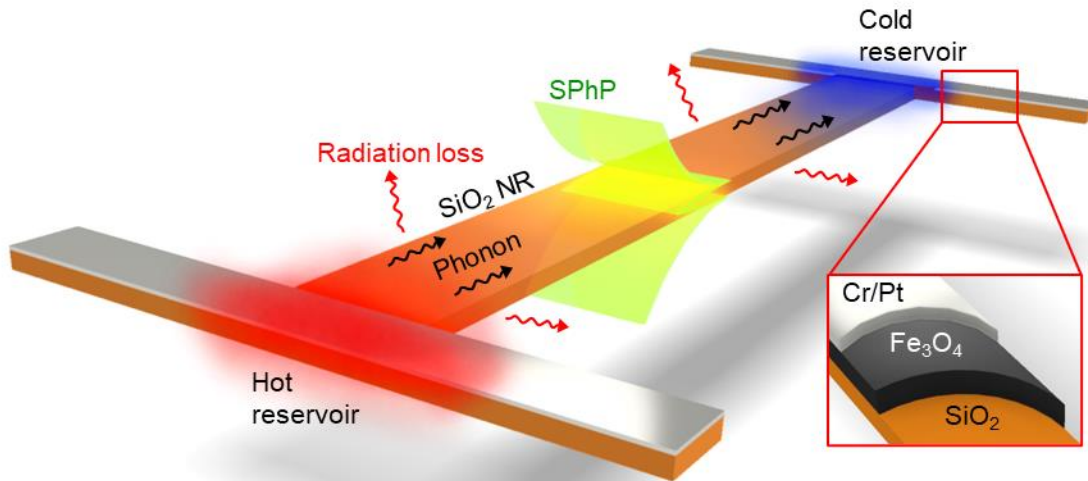


Figure 1-6: Schematic of heat conduction measurement of a SiO_2 NR waveguide device

There is a Fe_3O_4 layer between Pt and SiO_2 as an absorber to enhanced the absorption of SPhP. As shown in Figure 1-2, the propagation length of SPhP is very long, if there is no additional absorber in the sensing beam, the SPhP will escape into the vacuum through sensing beam. The black oxide greatly reduces the propagation length of the wave by about two orders of magnitude

due to its lossy nature (Figure 1-7), thus enhancing the absorption efficiency. The thermal reservoir supports two propagation modes and here we focus on the mode which is primarily attributed to the conversion between SPhP and heat. The thickness of SiO₂, Pt and Fe₃O₄ are set to 44 nm, 110 nm and 350 nm, as in the experiments. The refractive indices are taken from literature²³⁻²⁵.

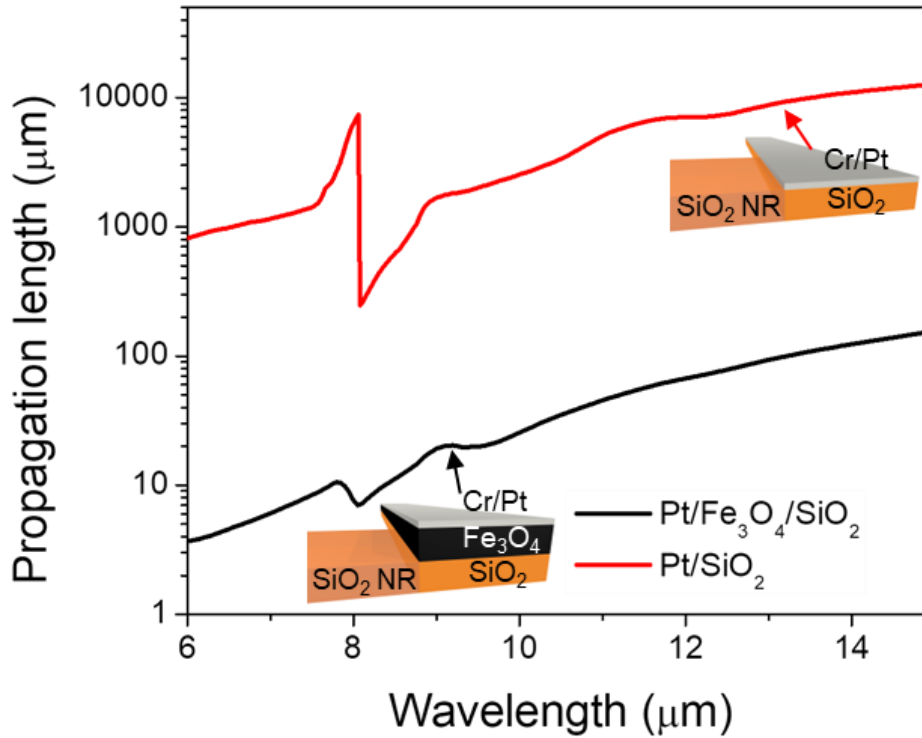


Figure 1-7: Propagation length of SPhP along the thermal reservoir.

The SiO₂ in the beams and layers are fabricated from the same 100 nm-thick thermal oxide layer on a Si wafer and thus have monolithic junctions without thermal contact resistance. The final NR thickness is reduced to 13 to 44 nm via controlled etching using buffered HF etchant and the slow parasitic etching by XeF₂. The beams are covered by ~110 nm thick Pt used for joule heating and thermometry. The beams and the NRs are suspended ~70 μm away from the substrate to avoid major SPhP leakage and to enable high-resolution heat conduction measurement (~10

pW K⁻¹) using a modulated heating technique and a noise-cancelling bridge scheme, as demonstrated in our earlier work²⁶. The SEM images of a representative SiO₂ NR device are shown in Figure 1-8. The thickness of the NRs after etching was determined from the frequency dependent thermal transport measurements at room or low temperatures that yielded heat capacity of the NR^{27, 28}, which was used to determine the exact cross-section area of the NRs. This approach was further validated by atomic force microscopy (AFM) thickness measurement of selective NRs cut and transferred to a flat substrate.

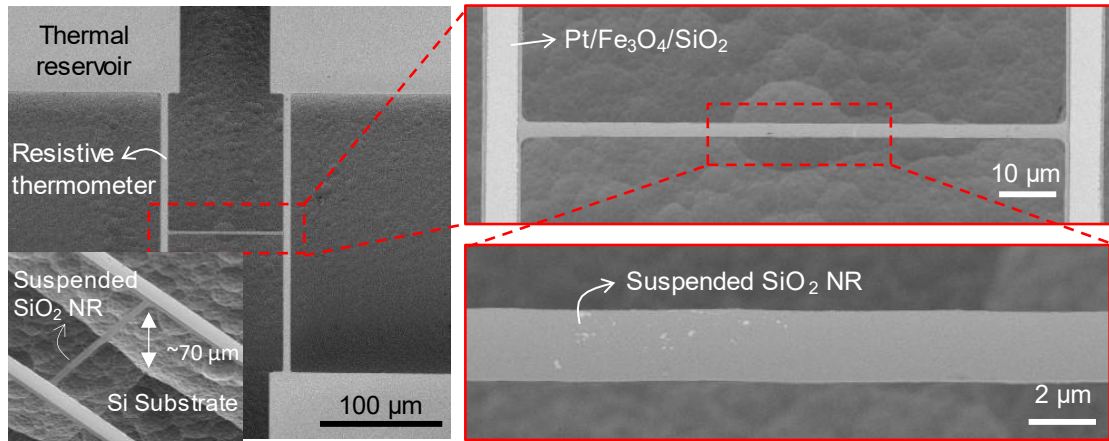


Figure 1-8: SEM images of a representative SiO₂ NR device.

1.5 Mode size for absorption efficiency

The mode size can have significant implications for various aspects of waveguide performance, such as coupling efficiency, propagation loss, and susceptibility to environmental influences. Unlike cylindrical or square waveguides, the mode distribution of the SiO₂ NR is not isotropic. As shown in Figure 1-9, the decay of the field intensity is faster in the vertical direction of the NR compared to the horizontal direction for a NR with $W > t$. One advantage of this design is that even though the overall mode volume is large, the mode size in the vertical direction can still be relatively small, thereby reducing the leakage to the substrate and improving the coupling efficiency to the sensing beam (reservoir). Here we define the mode size d as the distance from the interface where the field intensity is reduced to $1/e$ of the value at the solid surface. The calculated mode sizes in the vertical direction of SiO₂ NR are shown in Figure 1-9.

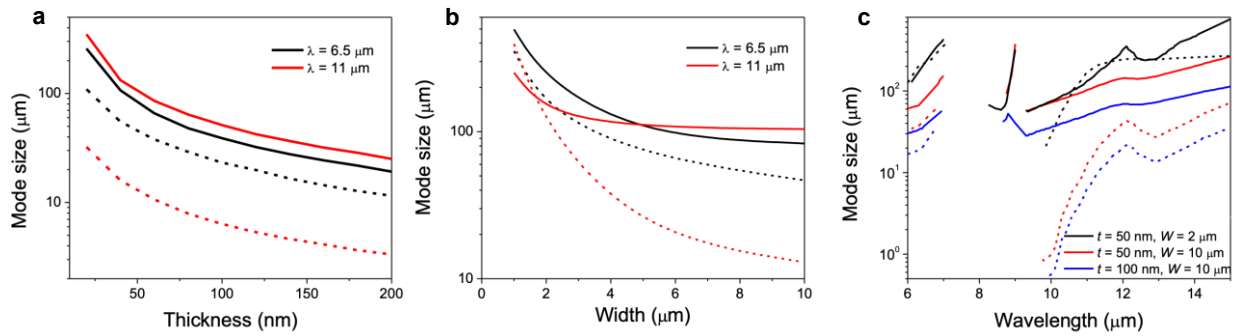


Figure 1-9: SPhP mode volume of SiO₂ NR with different dimensions. a, SPhP mode size of NR with 10 μm width and different thickness. b, SPhP mode size of NR with 50 nm thickness and different width. c, Dependence of SPhP mode size on wavelength (solid curve: quasi-TE mode, dash curve: quasi-TM mode). Inset: SEM image showing the gap between suspended SiO₂ NR and Si substrate.

The overall absorption efficiency depends on the leakage during propagation, coupling efficiency from the SiO₂ NR to the sensing beam, and how much of this energy is eventually absorbed as heat. The SiO₂ NRs support two propagation modes as quasi-TM mode and quasi-TE

mode. The sensing beam also supports two modes, one with a long propagation length and a large mode size, the other with a short propagation length and a small mode size (see Figure 1-4). Each of the two modes on the SiO₂ NR can be coupled to either one of the two modes on the sensing beam, i.e., four possible coupling pathways, as shown as A, B, C and D in Figure 1-10. The total coupling efficiency from quasi-TM mode and quasi-TE mode are $\eta_{quasi-TM} = \eta_A + \eta_B$ and $\eta_{quasi-TE} = \eta_C + \eta_D$. The terms η_A and η_C correspond to the couplings to the short propagation mode on sensing beam and end up with high absorption and high coupling efficiency when the mode size on SiO₂ NR is small. The terms η_B and η_D correspond to the couplings to the long propagation mode on the sensing beam and contribute less to the thermal conductance due to low absorption efficiency. We can neglect the contributions from η_B and η_D and simply use η_A and η_C to represent the contributions from quasi-TM and quasi-TE modes to the thermal conduction (marked as the red arrows in the Figure 1-10), i.e., $\eta_{quasi-TM} \approx \eta_A$ and $\eta_{quasi-TE} \approx \eta_C$. Please note that, from the coupling efficiency point of view, these four possible couplings have different coupling efficiencies depending on the mode similarity coefficient. For example, the SiO₂ NR with a large cross section has a smaller mode size and is more likely to couple to the mode on sensing beam with a small mode size, i.e., the couplings corresponding to the red arrows in Figure 1-10. Considering that after we added a lossy Fe₃O₄ layer on the heating and sensing beams to enhance the absorption efficiency, the propagation length on the sensing beam reduced to a few micrometers to tens of micrometers, we assume that all the energy coupled to the short propagation mode on sensing beam is eventually absorbed. The coupling efficiency can be calculated with the mode profile by using coupled mode theory as^{29, 30}:

$$\eta = \frac{\omega \epsilon_0 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (n_1^2 - n_2^2) \mathbf{E}_1^* \cdot \mathbf{E}_2 dx dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} n_z \cdot (\mathbf{E}_1^* \times \mathbf{H}_1 + \mathbf{E}_1 \times \mathbf{H}_1^*) dx dy} \quad (1.6)$$

where $\mathbf{E}_1(x, y)$, $\mathbf{E}_2(x, y)$, and $\mathbf{H}_1(x, y)$ are electric and magnetic fields in modes of waveguide 1 (SiO₂ NR) and waveguide 2 (sensing beam). $n_1(x, y)$ express the cross-sectional refractive index distribution in the case that both waveguides exist (SiO₂ NR and sensing beam), $n_2(x, y)$ is for the case that only the second waveguide (sensing beam) exists. ω , ϵ_0 , and n_z are the angular frequency of the light wave, the permittivity of vacuum, and the unit vector along the propagation direction z .

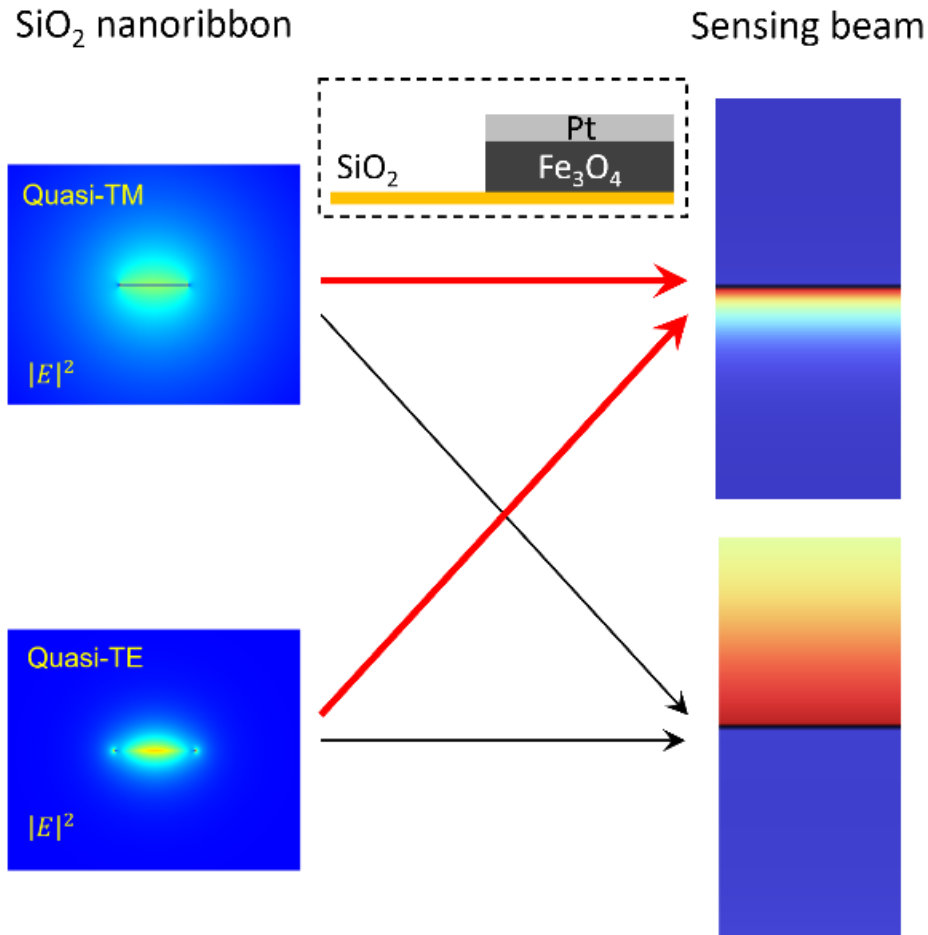


Figure 1-10: Possible mode couplings from the SiO₂ NR to the sensing beam. Each of the two modes on the SiO₂ nanoribbons can be coupled to either one of the two modes on the sensing beam, i.e., four possible coupling pathways which are marked as A, B, C and D, respectively. The red line arrows mark the two couplings that make the dominant contribution to the thermal conductance. The inset in the dash line box shows the cross section of our structure.

To obtain a qualitative dependence, we can use a semi-analytic method, namely, the effective index method, to get the mode profile on SiO₂ NR. By this method, a rectangular waveguide problem is transformed into a 1D effective waveguide problem. For our case of SiO₂ NR with thickness t and width W , we first solve the effective index n_{eff} of a SiO₂ slab with thickness of t , then use this n_{eff} for the second slab waveguide with width W to get the mode index. The solution for a general slab waveguide gives the mode size (MS) as^{30, 31}:

$$MS(\omega) \propto \frac{1}{\tanh\left(\frac{1}{2}k_0 t \sqrt{\epsilon_m(\omega) - \epsilon_d(\omega)}\right)} \quad (1.7)$$

where ϵ_m and ϵ_d are the permittivity of the waveguide core and surrounding medium. For our case of SiO₂ NR, we can have the mode size as:

$$MS_{NR}(\omega) \propto \frac{1}{\tanh(tW/C(\omega))} \quad (1.8)$$

where C is a parameter related to frequency and material property. The hyperbolic tangent function ($\tanh$) means that the mode size approach to the unity when the cross-section tW increase, assuming that the mode profiles on SiO₂ NR and the mode profile on sensing beam are perfectly matched at this condition. Combining equation 1.6 and equation 1.8 with $E(x, y) = E_0 e^{-\frac{y}{2MS_{NR}}}$, and simplifying, we can express the coupling efficiency as:

$$\eta_n(\omega) \approx \tanh(tW/C(\omega)) \quad (1.9)$$

The parameter C originated from the optical material property, which is frequency dependent. However, the spectral dependence of the mode size is weak outside the Reststrahlen band. For SiO_2 , the material property could vary dramatically within the Reststrahlen band but changes slowly with wavelength outside the Reststrahlen band, so does the mode size as shown in Figure 1-6. The modes on the SiO_2 NRs are supported with a frequency range much broader than the Reststrahlen band, so the average mode size does not change strongly with the wavelength, especially at a high temperature. For example, at the temperature of 550 K, the corresponding thermal emission peak is about $5.27\text{ }\mu\text{m}$ which is already away from the Reststrahlen band.

Acknowledgements

Chapter 1, in full, is a reprint of the materials as it appears in "Low-dimensional Heat Conduction in Surface Phonon Polariton Waveguide." Yu Pei, Li Chen, Wonjae Jeon, Zhaowei Liu, Renkun Chen. Nature Communications 14, no. 1 (2023): 8242.

Chapter 2 HEAT CONDUCTION IN SURFACE PHONON POLARITON WAVEGUIDE

2.1 Introduction

We designed the device that used to measure heat conductance through surface phonon polariton depending on the properties of SPhP as discussed in chapter 1. SiO_2 has been chosen for the polar dielectric material as SPhP waveguide. To clearly differentiate the SPhP contribution from phonons, the cross-section of the waveguide has to be considerably reduced. This leads to greatly enhanced SPhP propagation length, which is highly desirable, but also drastically enlarged SPhP mode size which introduces two additional major concerns. First, the waveguide must be suspended far away from any bulky solids to avoid significant SPhP wave leakage. Second, the large mode size usually makes the coupling between the miniature waveguide and the thermal reservoirs much less efficient.

As mentioned earlier, the longer propagation length in a thinner NR is accompanied by a bigger mode size, as a larger portion of the wave is in the vacuum. For the NR with width of 10 μm and thickness of 50 nm, the mode size at the wavelength of 6 μm is $\sim 60 \mu\text{m}$ for quasi-TM mode and $\sim 30 \mu\text{m}$ for quasi-TE mode. The large mode size poses two challenges for the observation of SPhP heat conduction in a NR waveguide: (i) the SPhP can be leaked to the substrate if the NR is not sufficiently separated from it; and (ii) the absorption of the wave with a large mode size by the thin reservoirs is very low without a proper design. By etching the Si underneath the NRs, we suspended the NRs from the Si substrate by at least $\sim 70 \mu\text{m}$ to minimize the SPhP leakage. We then enhanced the absorption of SPhP by embedding a lossy dielectric layer of black oxide (Fe_3O_4) on the thermal reservoirs. The black oxide greatly reduces the propagation

length of the wave by about two orders of magnitude due to its lossy nature, thus enhancing the absorption efficiency.

We realize that all the prior modeling and experiment works were only focused on the waveguide itself, such as the materials and geometries of nanowires and thin films, without considering the interaction of SPhP with the surrounding environment and reservoirs. However, to experimentally observe the polaritonic heat conduction, the aforementioned two concerns are crucial but have yet to be carefully addressed. In this work, through the rational design of the waveguide cross-section and its coupling to the reservoirs using an efficient absorber, we observe an increased thermal conductivity in nanoribbons (NRs) of SiO₂, by as much as 34% over its well-known phonon thermal conductivity limit. For samples with relatively small mode size which means leakage of the wave to the substrate during propagation is negligible, the thermal transport is shown to be ballistic over 100 μm length, that is, near constant thermal conductance with different lengths. Our results unambiguously demonstrate an enhanced effective thermal conductivity due to SPhP and the extraordinary characteristics compared to the traditional heat conduction carried by phonons and electrons, thus opening an entirely new regime for thermal transport.

2.2 SiO₂ nanoribbons waveguide device fabrication

SiO₂ NRs were fabricated from a 100-nm thick thermally grown SiO₂ layer on a Si wafer. The Fe₃O₄/Pt beams were deposited and patterned by sputtering and liftoff. The SiO₂ NRs and the SiO₂ underneath the beams were defined by photolithography and reactive ion etching (RIE). The Si substrate outside of the NR and beam regions was etched using deep RIE. The thickness of the SiO₂ NRs was then controllably reduced by etching in a buffered oxide etchant. Finally, the NRs and the beams were suspended from the substrate using dry XeF₂ etching. There is a small but non-negligible etching of SiO₂ by XeF₂. The thickness of the obtained SiO₂ NR was determined from both AFM imaging and frequency dependent thermal transport measurements, which yielded the heat capacity and hence the thickness of the NR sample^{27, 28}.

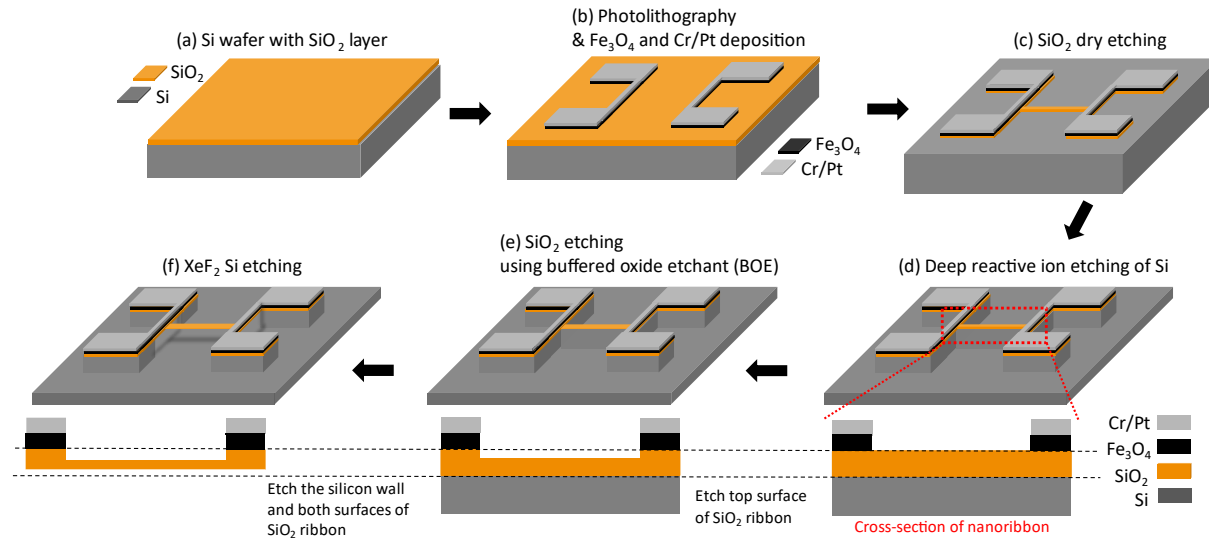


Figure 2-1: SiO₂ nanoribbons waveguide device fabrication process.

Figure 2-1 shows the detailed fabrication process of SiO₂ nanoribbons waveguide device. (a) The fabrication of NRs starts with a silicon wafer having a 100 nm wet thermal oxide layer on top. (b) A layer of photoresist (NR9-3000PY) is spin-coated onto the wafer. Then, the photolithography (Heidelberg MLA150) is used to pattern the Fe₃O₄ and electrodes layer. After

hard baking and photoresist development, the wafer is deposited with Fe_3O_4 (350 nm), Cr (5 nm), and Pt (110 nm) in sequence using sputtering (Denton Discovery 18 Sputter System). At last, the wafer is soaked in Resist Remover RR4 to do lift-off. (c) Photoresist is used as an etching mask to define the SiO_2 NRs and cover the electrodes. The SiO_2 dry etching process (Oxford Plasmalab P80, CHF_3 and Ar gas) etches other parts of the SiO_2 on the Si wafer. (d) Another lithography step provides an etching mask with a slightly larger area than the NR and electrodes, followed by Si deep reactive ion etching (Oxford Plasmalab P100 RIE/ICP, SF_6 gas), which creates a step between SiO_2 NRs and Si substrate. Resist Remover RR4 and O_2 plasma are used to remove photoresist and clean the photoresist residues. (e) The sample is placed in buffered oxide etchant (BOE) to get thinner SiO_2 NRs. This process only etches the top surface of SiO_2 NRs. The thickness of the SiO_2 NRs can be controlled by adjusting the etching time. (f) The sample is etched by XeF_2 (Xactix XeF_2 Etcher) to release the device and make suspended structures. XeF_2 possesses high selectivity between Si and SiO_2 ($> 1000:1$). XeF_2 etches the Si wall under the NRs, resulting in suspended SiO_2 NRs. During this process, however, XeF_2 also etches SiO_2 NR slightly. The exact thickness of the suspended SiO_2 NRs is determined from frequency-dependent thermal transport measurement on the NRs, which yields heat capacity (and cross-section area) of the NR.

The original SiO_2 layer thickness is 100 nm from the thermal oxide layer of the Si wafers. The thickness of the NRs after the buffered oxide etchant (BOE, containing buffered HF) etching process can be measured using a surface profiler (DektakXT). We denote this thickness as t_0 . Note that this thickness is further reduced slightly to the final thickness (t) of the suspended NRs due to the XeF_2 etching, which has a very low but non-negligible etching rate on SiO_2 . As shown in Figure 2-2, the NR thickness after a 30s BOE etching process for the sample of $L = 49 \mu\text{m}$, W

$= 9.9 \mu\text{m}$, $t = 44 \text{ nm}$ is around 62 nm , i.e., $t_0 = 62 \text{ nm}$. The chip has a Pt marker on top of SiO_2 as shown in Figure 2-2(d), which was used to measure the reduction of the top surface SiO_2 thickness (δ_t) during the XeF_2 etching process by measuring the thickness difference before and after the XeF_2 etching. For the sample of $L = 49 \mu\text{m}$, $W = 9.9 \mu\text{m}$, $t = 44 \text{ nm}$, we found $\delta_t = 15 \text{ nm}$. For the SiO_2 NRs during the fabrication steps of XeF_2 etching (from Figure 2-1 (e) to (f)), initially only the top surface of SiO_2 NR was etched by XeF_2 and then both of the top and bottom surfaces were etched by XeF_2 after the NR has been suspended. Therefore, the suspended NR thickness will be between $t_0 - \delta_t$ and $t_0 - 2\delta_t$ depending on sample size and etching cycles. For the sample with $L = 49 \mu\text{m}$, $W = 9.9 \mu\text{m}$, $t = 44 \text{ nm}$, the final NR thickness (t) is expected to be between $32 - 47 \text{ nm}$ (i.e., between $(62 - 30) \text{ nm}$ and $(62 - 15) \text{ nm}$). The actual thickness ($t = 44 \text{ nm}$) obtained from the frequency-dependent measurement is within this expected range.

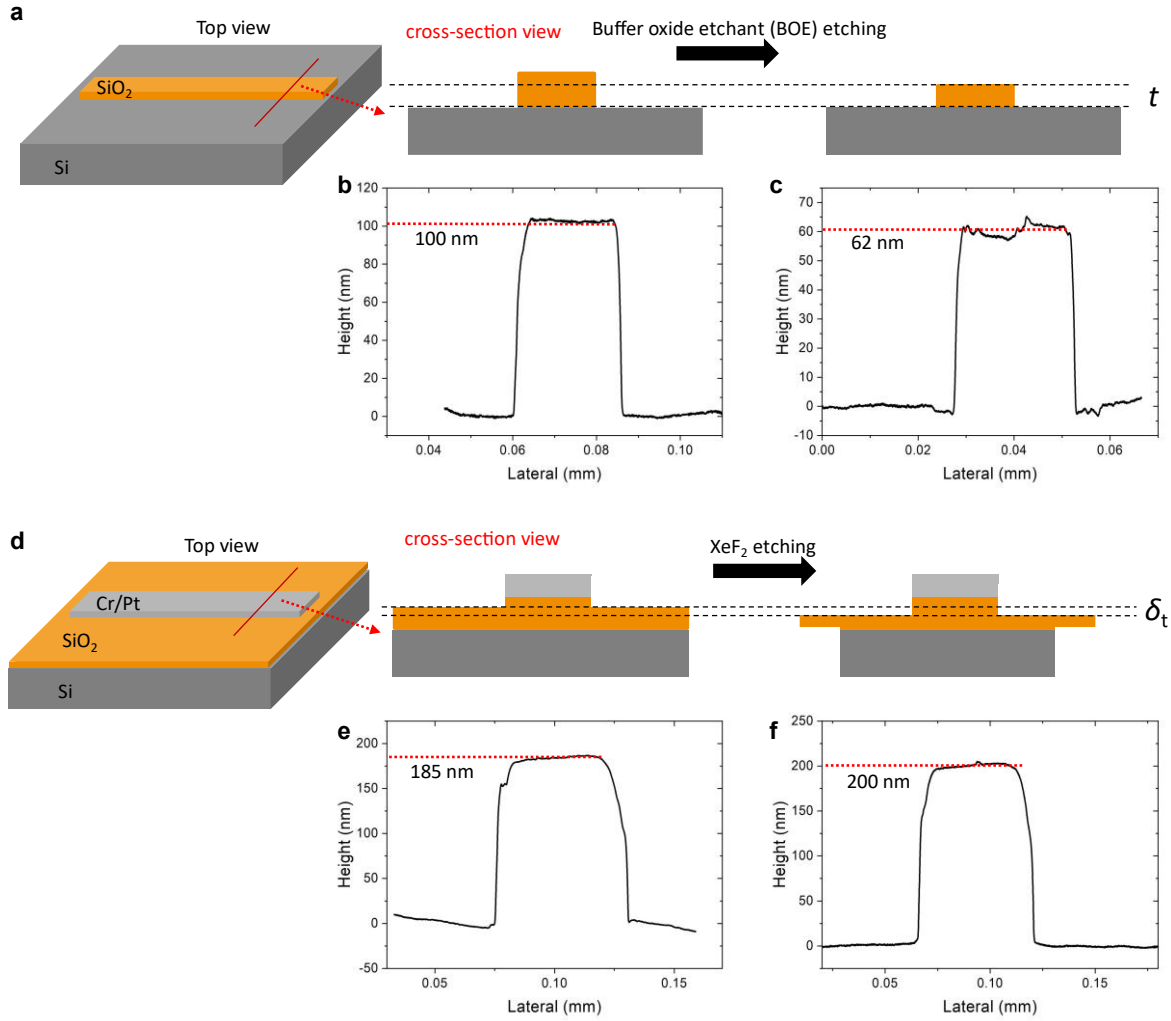


Figure 2-2: SiO₂ NR thickness measurement. (a) Schematic of SiO₂ NR thickness reducing after BOE etching, the red line is the surface profiler scan route. We denote the thickness after the BOE etching as t_0 . (b)(c) Surface profile measurement results for the sample of $L = 49 \mu\text{m}$, $W = 9.9 \mu\text{m}$, $t = 44 \text{ nm}$ before and after BOE etching. The thickness is reduced from the original thermal oxide layer thickness of 100 nm to 62 nm. (d) Schematic of Pt marker on SiO₂. (e)(f) Surface profile measurement results for the sample before and after XeF₂ etching, showing the 15 nm etching (δ_t) of the SiO₂ layer by XeF₂. This is a very small but non-negligible etching of SiO₂ considering that the Si is etched by more than 10 μm . For the SiO₂ NR, the thickness reduction due to the XeF₂ etching is expected to be between δ_t and $2\delta_t$ because the NR is suspended during the etching process, after which the bottom surface of the NR is also etched.

The Fe₃O₄ absorber in our sample was deposited by RF sputtering using a Fe₃O₄ target.

From the SEM image (Figure 2-3), its surface is porous and sparse. The color of the film on clear glass slides is dark red instead of the black color of Fe₃O₄. We measured the electric resistance

of the Fe_3O_4 film using a 4-point probe method. The deposited Fe_3O_4 film electric resistance is around $24.4 \, \Omega \cdot \text{cm}$, which is larger than pure Fe_3O_4 ($\sim 5 \times 10^{-4} \, \Omega \cdot \text{cm}$)³² and smaller than pure Fe_2O_3 ($\sim 3 \times 10^4 \, \Omega \cdot \text{cm}$)³³. We can assume that the composition of our film is a mixture of both, i.e., $(\text{FeO})_x (\text{Fe}_2\text{O}_3)_{1-x}$. This is likely caused by the residual oxygen in the sputter vacuum chamber.

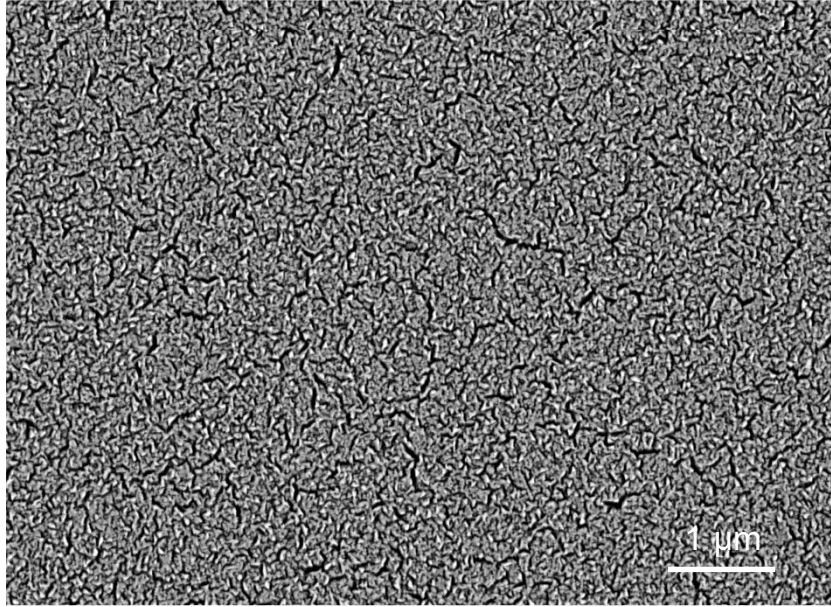


Figure 2-3: SEM image of sputter deposited Fe_3O_4 film.

The Fabricated NRs have thickness (t), width (W), and length (L) in the range of 20-50 nm, 1-10 μm , and 50-400 μm , respectively. Figure 2-4 shows the scanning electron microscopy (SEM) images of the devices.

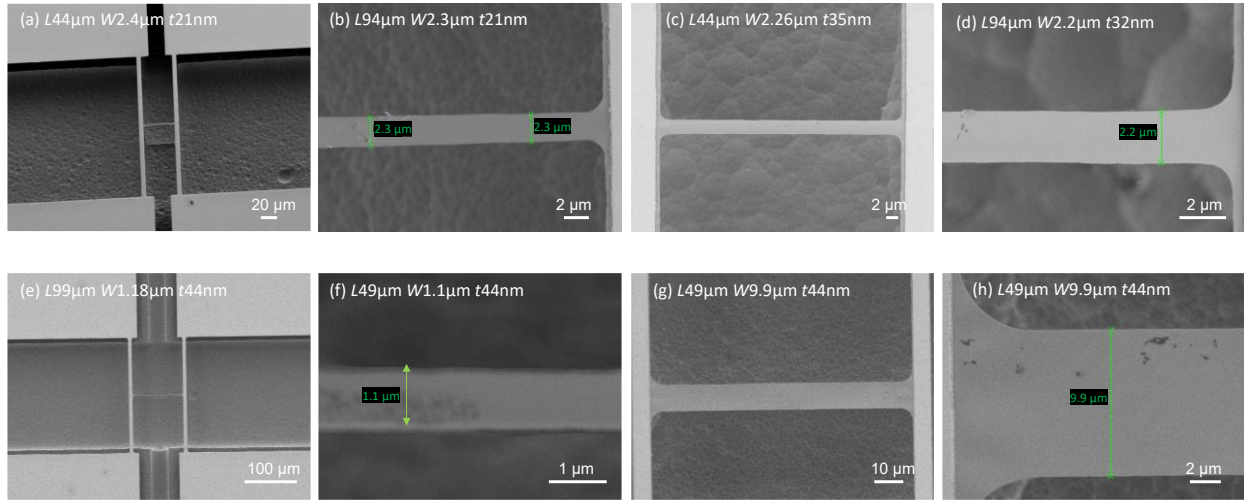


Figure 2-4: SEM images of SiO₂ NR with different widths and lengths. (a) $L = 44 \mu\text{m}$, $W = 2.4 \mu\text{m}$, $t = 21 \text{ nm}$. (b) $L = 94 \mu\text{m}$, $W = 2.3 \mu\text{m}$, $t = 21 \text{ nm}$. (c) $L = 44 \mu\text{m}$, $W = 2.26 \mu\text{m}$, $t = 35 \text{ nm}$. (d) $L = 94 \mu\text{m}$, $W = 2.2 \mu\text{m}$, $t = 32 \text{ nm}$. (e) $L = 99 \mu\text{m}$, $W = 1.18 \mu\text{m}$, $t = 44 \text{ nm}$. (f) $L = 49 \mu\text{m}$, $W = 1.1 \mu\text{m}$, $t = 44 \text{ nm}$. (g) $L = 49 \mu\text{m}$, $W = 9.9 \mu\text{m}$, $t = 44 \text{ nm}$. (h) $L = 49 \mu\text{m}$, $W = 9.9 \mu\text{m}$, $t = 44 \text{ nm}$.

2.3 Thermal conductivity measurement

We employed high-resolution heat conduction measurement ($\sim 10 \text{ pW K}^{-1}$) using a modulated heating technique and a noise-cancelling bridge scheme, as demonstrated in our earlier work ²⁶. The Pt layers on the two $\text{SiO}_2/\text{Fe}_3\text{O}_4/\text{Pt}$ beams were used for joule heating on the heating beam and for thermometry on both beams. An AC voltage ($V_{1\omega}$) at a modulated frequency ω was applied to the heating beam. 3ω voltage of the heating beam was measured to determine the temperature rise and the thermal conductance of the beam. The sensing beam forms a Wheatstone bridge with a pairing beam of the similar resistance inside the same cryogenic vacuum chamber, along with two external resistors. A small DC current was applied to the bridge and 2ω voltage was measured from the bridge, which was used to determine the temperature rise on the sensing beam and ultimately the thermal conductance of the SiO_2 NR. A low frequency (e.g., $\sim 0.5 \text{ Hz}$) was chosen to ensure that the thermal penetration length was longer than the NRs and the beams. The modulated heating and the Wheatstone bridge were used to greatly suppress the effects of the $1/f$ noise and environmental temperature fluctuation.

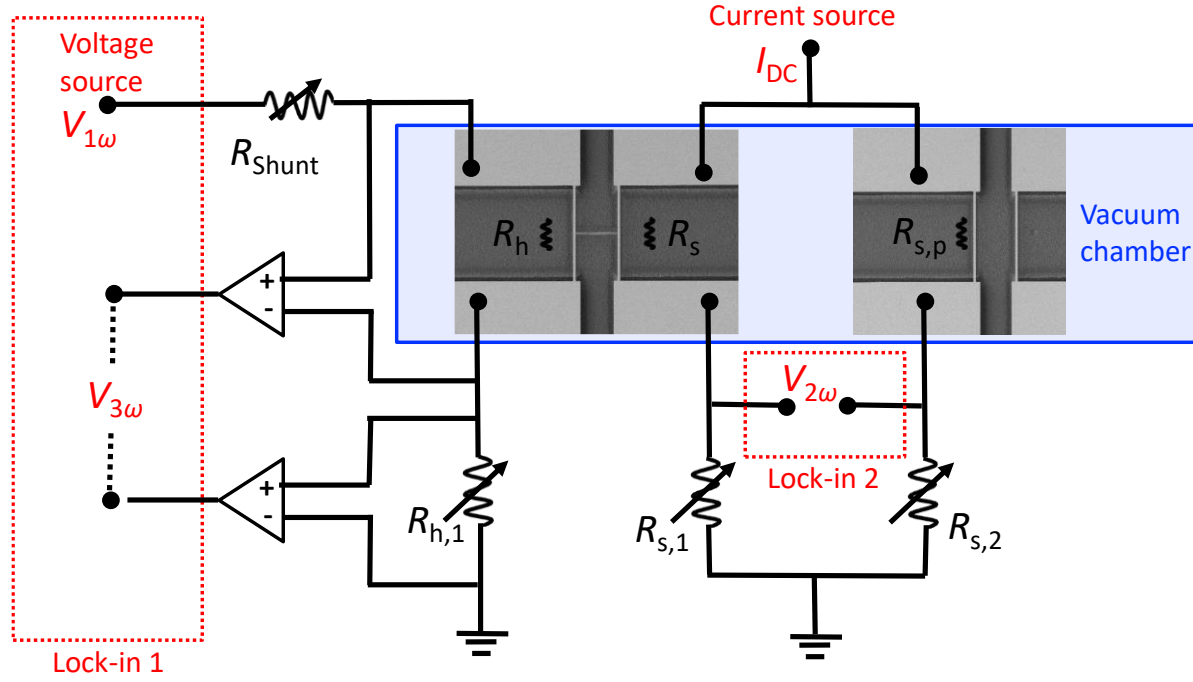


Figure 2-5: Schematic of the thermal conductivity measurement platform.

The SiO₂ NR thermal conductivity measurement platform (as shown in Figure 2-5) is based on the AC heating and lock-in thermometry scheme. Its thermal conductance resolution can reach the order of 10s pW/K^{34, 35}. An AC voltage ($V_{1\omega}$) at a modulated frequency ω is applied on one of the SiO₂/Pt beams (denoted as the heating beam, R_h). The frequency is set at 0.4847 Hz so that the heat penetration depth is much longer than the NR length. The joule heating created a second harmonic temperature rise in the heating beam and consequently a third harmonic voltage signal ($V_{h,3\omega}$) due to the Pt beam resistance change ($(\Delta R_{h,2\omega})$). A lock-in amplifier (Stanford Research SR830) collects the $V_{3\omega}$ signal which can be used to calculate the temperature rise (ΔT_h) in the center of the heating beam (Equation 2.1). Part of the heat on the heating beam, denoted as Q_s , will transfer to the other beam (sensing beam, R_s) through the SiO₂ NR which yields a second harmonic temperature rise in the sensing beam (ΔT_s). A beam of another sample on the same chip is served as the pair resistor ($R_{s,p}$) and forms a Wheatstone bridge scheme together with R_s , R_1 , and

R_2 . This on-chip Wheatstone bridge circuit could effectively reject common mode noise and thus improve the measurement sensitivity³⁵. A small direct current (I_{DC}) is applied to the bridge circuit and another lock-in amplifier is used to measure the 2nd harmonic bridge voltage ($V_{s,2\omega}$). Then the temperature rise in the middle of the sensing beam (ΔT_s) can be calculated using Equation 2.2³⁴.

$$\Delta T_h = 3 \frac{V_{h,3\omega}}{I_\omega} \left(\frac{dR_h}{dT} \right)^{-1} \quad (2.1)$$

$$\Delta T_s = 2\sqrt{2} \frac{V_{s,2\omega}(R_s + R_{s,p} + R_1 + R_2)}{I_{DC}R_2} \left(\frac{dR_s}{dT} \right)^{-1} \quad (2.2)$$

where I_ω is the current flowing in the heating beam, $\frac{dR_h}{dT}$ and $\frac{dR_s}{dT}$ are the temperature coefficient of resistance (TCR) of the heating and sensing beams, respectively.

The heat flux from the heating to the sensing beam (Q_s) is the same as heat transfer from the middle of the sensing beam to the substrate. Thus, the apparent thermal conductance of the SiO₂ NR (G_a) can be determined by:

$$G_a(\Delta T_h - \Delta T_s) = Q_s = G_b \Delta T_s \quad (2.3)$$

$$G_a = \frac{G_b \Delta T_s}{(\Delta T_h - \Delta T_s)} \cong G_b \frac{\Delta T_s}{\Delta T_h} \quad (2.4)$$

where G_b is the thermal conductance of sensing beam. ΔT_s is several orders of magnitude smaller than ΔT_h , so $\Delta T_h - \Delta T_s$ can be approximated as ΔT_h in Equation 2.4.

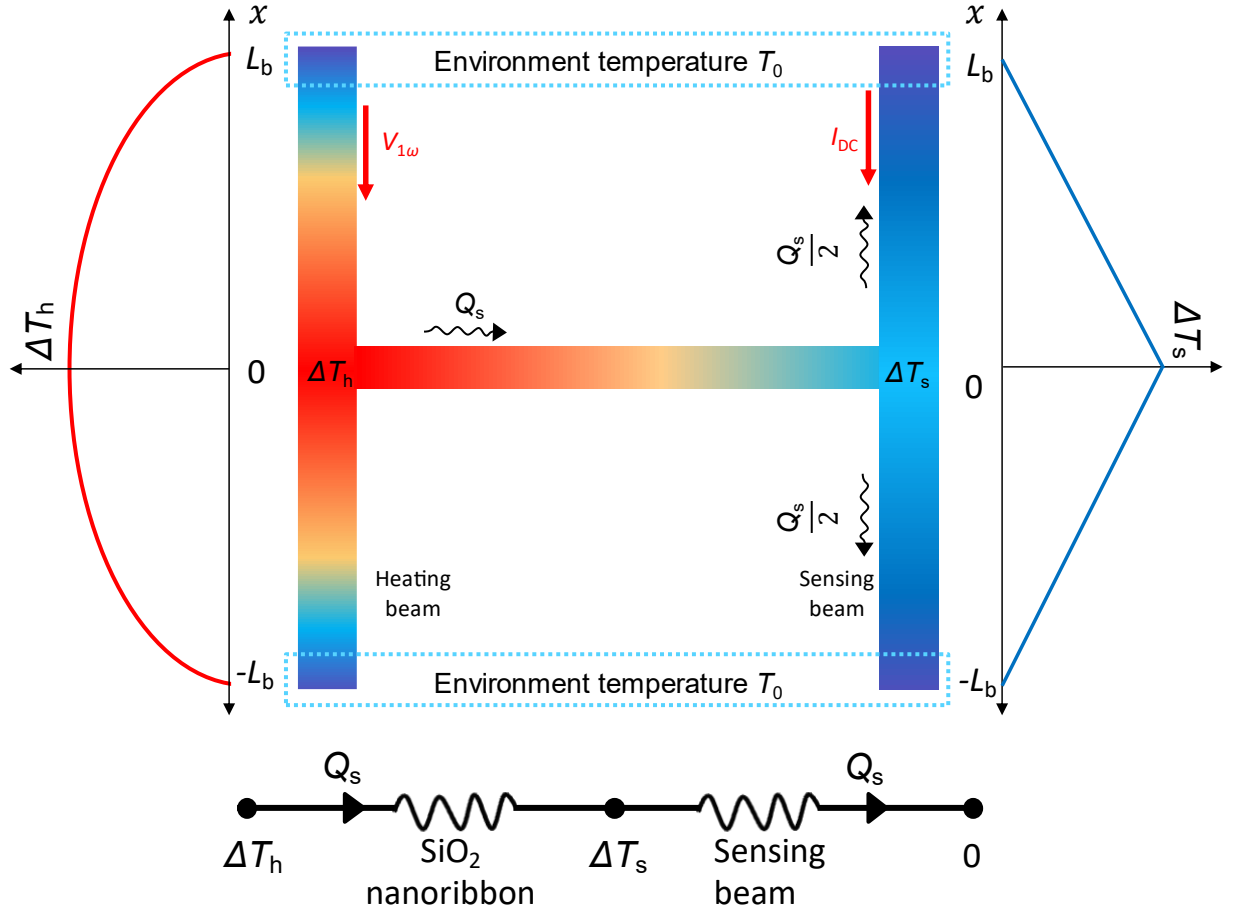


Figure 2-6: Temperature distribution on the measurement device, including the left heating and right sensing beams and the NR bridging the two.

Figure 2-6 shows the temperature distribution on the sample. For both the heating and the sensing beams, the ends of the beams have the same temperature as the Si substrate. The temperature rise distribution along the heating beam due to the Joule heating can be written as follows ³⁴

$$\Delta T_h(x) = -\frac{q_h}{2k_b}x^2 + \frac{q_h}{2k_b}L_b^2 \quad (2.5)$$

where q_h is the internal heat source per unit volume due to the Joule heating, $q_h = \frac{I_h^2 R_h}{2L_b S_b}$,

I_h is the root-mean-squared (RMS) value of the current on the heating beam, R_h is the heating

beam resistance, L_b is the half beam length, S_b is the beam cross-section area, k_b is the thermal conductivity of the beam. The highest temperature is in the middle of the heating beam:

$\Delta T_h|_{x=0} = \frac{q_h}{2k_b} L_b^2$. As for the sensing beam, the temperature distribution is linear since there is only heat conduction from the middle of the beam to the end.

In the thermal conductivity measurements, we applied different AC voltages on the heating beam, which give different heating power $Q_h = I_h^2 R_h$. Figure 2-7 shows the measured ΔT_h and ΔT_s with different Q_h at 300 K and 550 K. We use linear fitting to get slopes of $\Delta T_h/Q_h$ and $\Delta T_s/Q_h$ and use the ratio of the slope to yield $\frac{\Delta T_s}{\Delta T_h}$, which is used to determine the thermal conductance of the NRs (as shown in Equation 2.4).

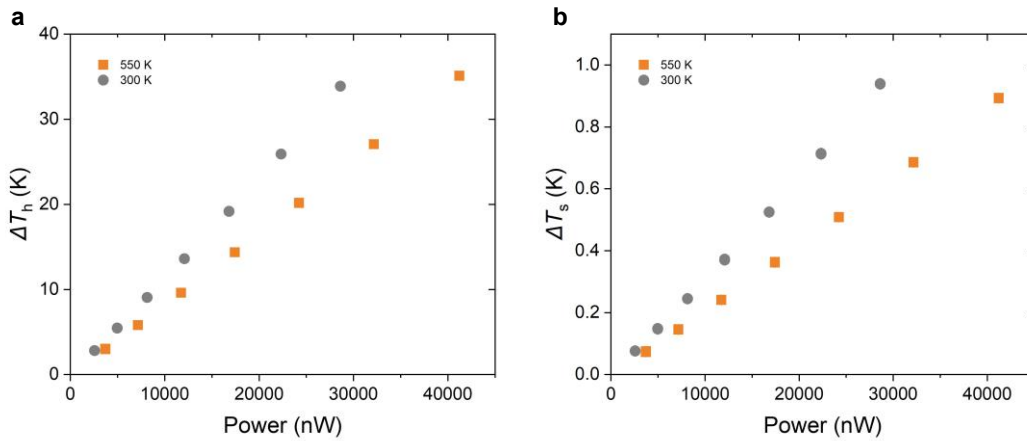


Figure 2-7: Heating and sensing beam temperature rise (ΔT_h , ΔT_s) versus input power. (a) ΔT_h and (b) ΔT_s with different Q_h at 300 K and 550 K for the NR sample with $L = 49 \mu\text{m}$, $W = 9.9 \mu\text{m}$, and $t = 44 \text{ nm}$.

In order to accurately determine the thickness of SiO_2 NR, we also did frequency dependent measurements for our samples. By modulating the AC heating current frequency, the thermal penetration depth (L_p) will also be changed. In the low-frequency regime, L_p is longer than the NR length (L), which is the frequency range we used in our NR thermal conductivity measurement.

As frequency increases, the L_p will be decreasing. This is the frequency regime we can use to determine the heat capacity (or thermal diffusivity) of the NR sample.

For both the NR and the sensing beams, we can use the following equation to analyze the heat transfer:

$$\frac{\partial \Delta T(x,t)}{\partial t} = \alpha \frac{\partial^2 \Delta T(x)}{\partial x^2} \quad (2.6)$$

where α is the thermal diffusivity. At angular frequency ω , by setting $\Delta T(x,t) = \Delta T(x)e^{j\omega t}$, Equation 2.6 can be written as

$$j\omega \Delta T(x)e^{j\omega t} = \alpha \frac{d^2 \Delta T(x)}{dx^2} e^{j\omega t} \quad (2.7)$$

The general solution for Equation 2.7 is

$$\Delta T_i(x) = C'_i \cosh(a_i x) + C''_i \sinh(a_i x) \quad (2.8)$$

where $a^2 = \frac{j\omega}{\alpha}$. C'_i and C''_i are constants and the subscripts $i = 1, 2$ are for the sensing beam and the NR, respectively. By applying the corresponding boundary conditions for the beam and the NR, the relation between frequency and temperature rise ratio at the two ends of the NR can be written as³⁵

$$\frac{\Delta T_s}{\Delta T_h} = \frac{1}{\frac{k_1 A_1 a_1 \sinh(a_2 L_2)}{k_2 A_2 a_2 \tanh(a_1 L_1)} + \cosh(a_2 L_2)} \quad (2.9)$$

where k, A, L are the thermal conductivity, cross-section area and length for the NR and the beam respectively.

In this equation, the only unknown parameter is $A_2 = (W_2 t_2)$. As the width of NR (W_2) can be measured, the thickness of NR (t_2) can be obtained by fitting Equation 2.9 to the measured data. Figure 2-7(a) shows the thickness fitting result for a SiO₂ NR, where the experimental data is the

measured temperature rise ratio between the sensing and heating side at different frequencies and the solid fitting curves are calculation results using Equation 2.9 by assuming different NR thicknesses. This result shows that $t_2 = 47$ nm yields the best fitting.

To confirm this thickness, we did atomic force microscopy (AFM) imaging on the same NR. We transferred the NR to a polydimethylsiloxane (PDMS) substrate by buckling the sample on the substrate and applying pressure. The NR thickness was then measured by using an AFM and the result is shown in Figure 2-7(b), with an inset image of the NR scanned by AFM. Both thickness fitting and AFM measurement show the NR thickness is around 47 nm. Additionally, the thermal conductivity of SiO₂ NR calculated using this dimension matches well with bulk SiO₂ value at low temperature, where the role of SPhP heat conduction is negligible.

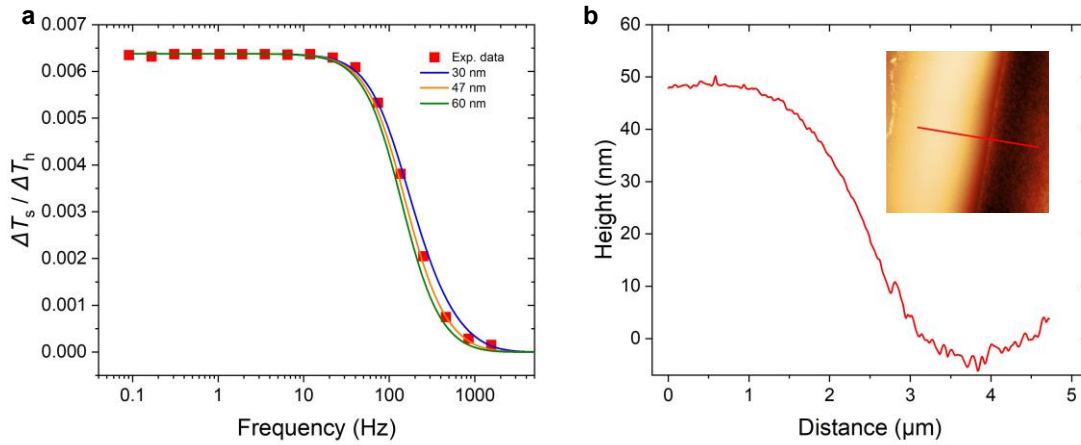


Figure 2-8: Combined thermal transport and tomographic measurements to determine NR thickness. (a) SiO₂ NR thickness fitting result through frequency-dependent temperature rise measurement. (b) Atomic Force Microscopy (AFM) thickness measurement result of the same NR; inset is an AFM image of the SiO₂ NR and the red line is the scan route.

2.3 Measured apparent thermal conductivity of SiO₂ NRs

We the measured apparent thermal conductivity of NR samples with various thicknesses and widths and at two different lengths ($L = \sim 50$ and ~ 100 μm) within the temperature range of 100 to 550 K. Figure 2-9 shows that for the samples without the black oxide absorber, the measured thermal conductivity closely follows the bulk phonon thermal conductivity of SiO₂ for the entire temperature range regardless of the NR geometry ($t = 13$ and 21 nm). This suggests that the heat carried by SPhP in the NRs cannot be absorbed efficiently in the thermal reservoirs to contribute to the measured thermal conductivity. On the other hand, the measured thermal conductivity of NRs with similar geometries but with black oxide absorbers show enhanced thermal conductivity over the phonon limit. This is consistent with the expectation for polaritonic heat conduction.

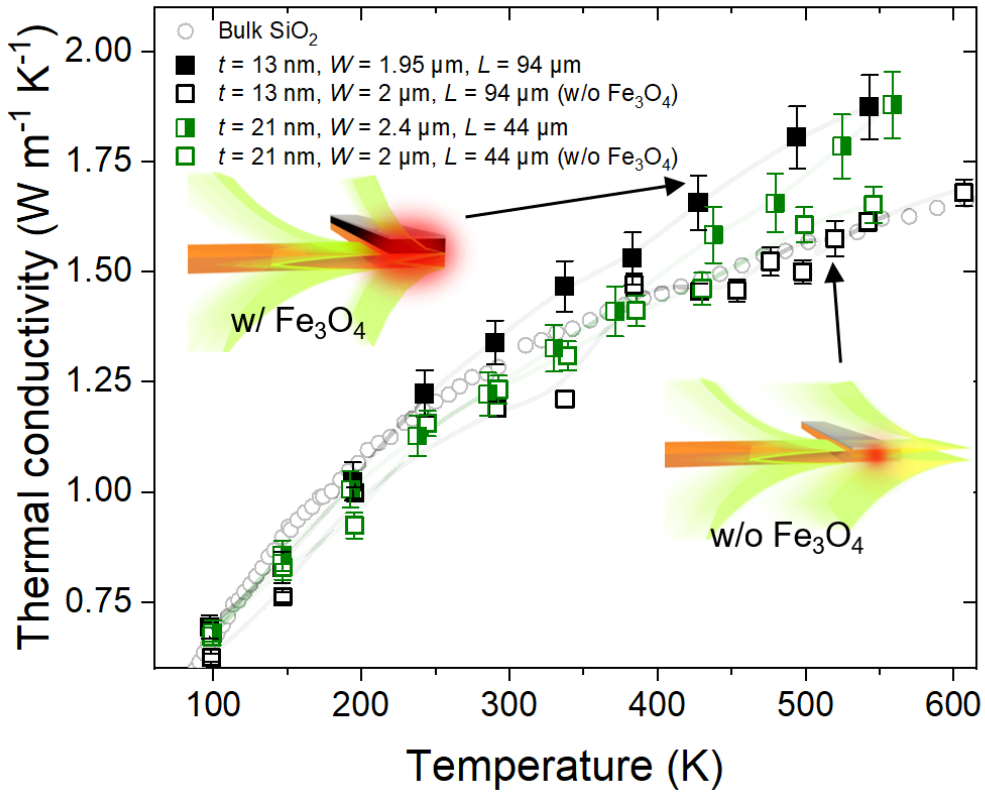


Figure 2-9: Comparison of thermal conductivity of samples with and without the Fe₃O₄ absorber.

Figures 2-10 and 2-11 show similarly enhanced thermal conductivity of NR samples with black oxide absorbers, with $t \sim 20$ nm & $W \sim 1$ -2 μ m (Figures 2-10) and $t \sim 16$ -50 nm & $W \sim 1$ -10 μ m (Figure 2-11). The empty circles in all the figures are the bulk thermal conductivity value of amorphous SiO₂ taken from³⁶. Error bars in all figures are determined by the standard deviations from the conductance measurements and NR's dimension determination, following previously published protocols.^{35, 37} Conductance measurement error originates from the linear regression fitting applied to the temperature rise versus power plots (Figure 2-7). NR dimension determination error arises due to non-uniform width of NRs.

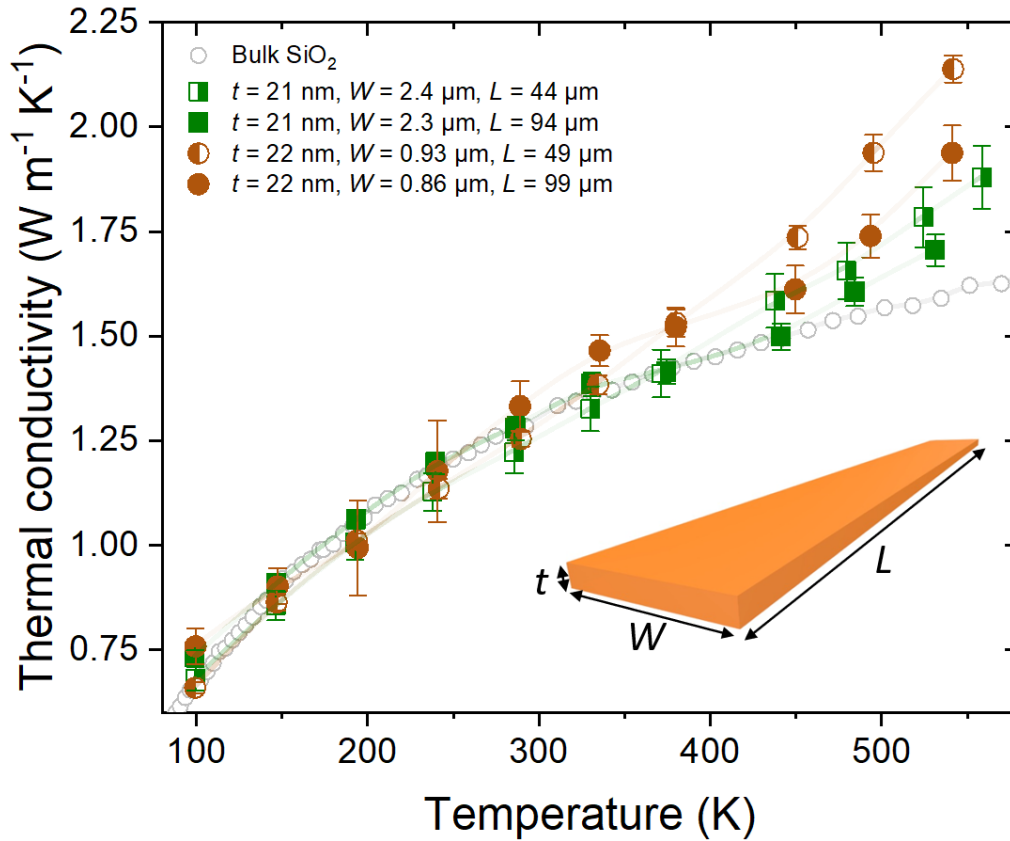


Figure 2-10: The measured apparent thermal conductivity of NR samples with $t = 21$ -22 nm.

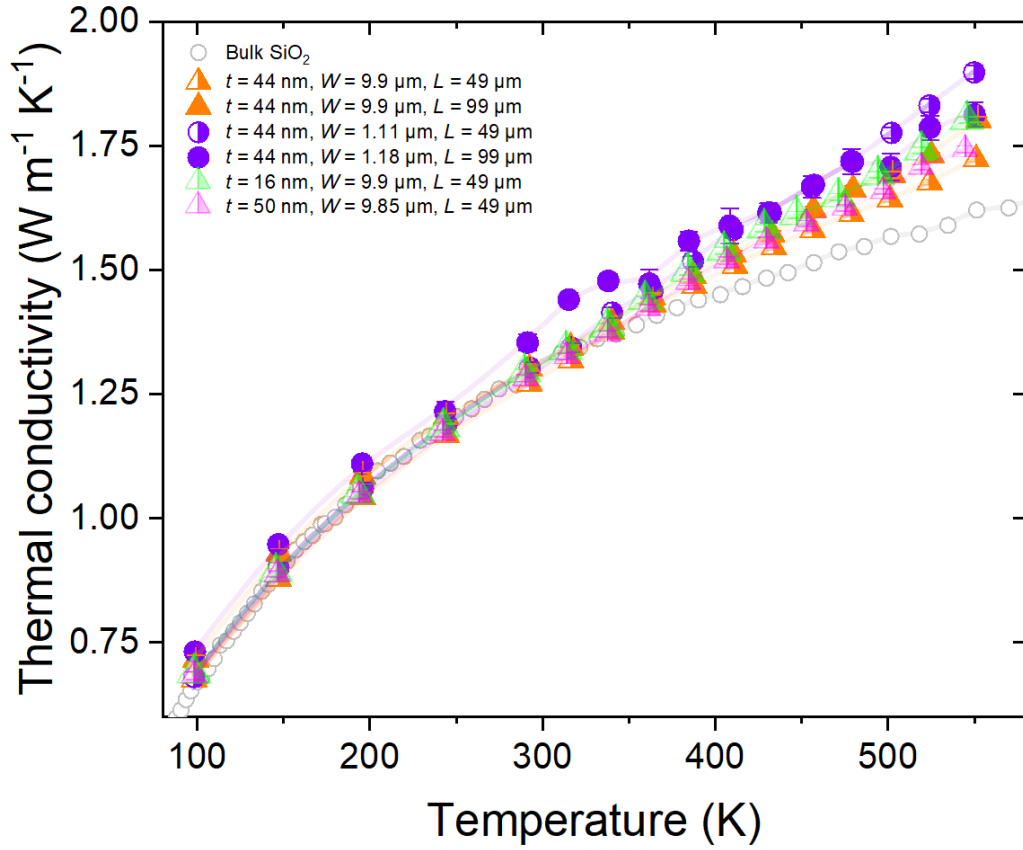


Figure 2-11: The measured apparent thermal conductivity of NR samples with W around 1 and 10 μm .

For all the NR samples with black absorbers, this increase in thermal conductivity is larger at higher temperatures, consistent with the trend expected for heat conduction mediated by SPhP. The highest value is $2.14 \text{ W m}^{-1} \text{ K}^{-1}$ at 550 K (or 34% higher than bulk SiO_2 thermal conductivity) for the sample of $t = 22 \text{ nm}$, $W = 0.93 \mu\text{m}$, and $L = 49 \mu\text{m}$. This work provides a clear experimental observation of enhanced thermal conductivity contributed by SPhP through rational design of absorbers.

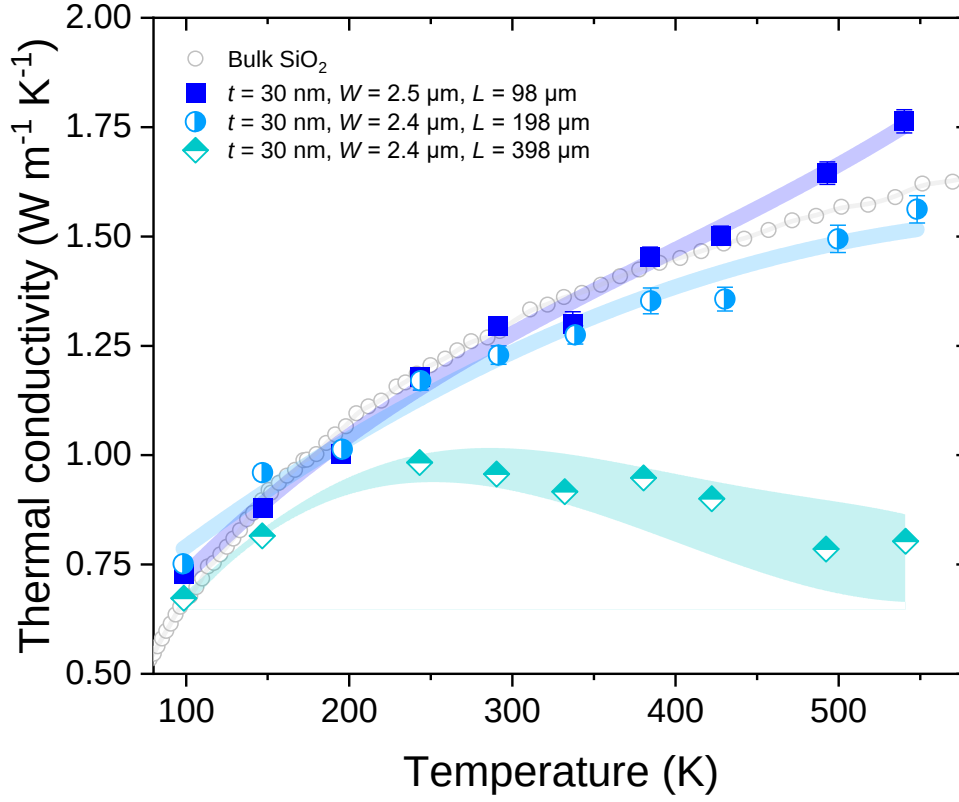


Figure 2-12: Apparent thermal conductivity of NR samples with similar width and thickness and different lengths, showing the radiation heat loss on long samples.

We also measured apparent thermal conductivity of NR samples with similar width and thickness and different lengths, longer sample ($L = 398 \mu\text{m}$) shows the radiation heat loss on long samples (Figure 2-12). The radiation heat loss from the NR is analyzed along with the phonon heat conduction in the ribbon, manifested as progressively reduced apparent thermal conductivity on the ribbons with the same thickness but larger length. This “thermal fin” effect is due to the relatively larger radiation heat loss compared to heat conduction in a longer ribbon and has also been observed by us on SiO₂ NRs with larger thickness ($\sim 100 \text{ nm}$) without the black absorber design³⁵.

2.4 Extracting the SPhP conductance

In order to determine the contribution of the propagating SPhP to thermal conductance, it is necessary to eliminate the effects of other factors, such as the phonon thermal conductance of SiO₂ NR, background conductance, and radiation heat loss, from the measured apparent thermal conductance. First, the temperature distribution on the NR was obtained using the thermal fin model, and the radiation heat loss (Q_{loss}) was calculated by integrating the heat dissipation over the entire length of the NR (Section 2.4.1). Next, we calculated the heat flux conducted by phonon (Q_{ph}) using the NR geometry and the bulk phonon thermal conductivity value of SiO₂³⁶. The effective thermal conductance of phonon with the radiation heat loss was then calculated as:

$$G_{ph+loss} = \frac{Q_{ph}-Q_{loss}}{\Delta T_h - \Delta T_s} \quad (2.10)$$

where ΔT_h and ΔT_s are the experimentally measured temperature rises of the heating and sensing sides respectively. Additionally, the background thermal conductance (G_{bg}) was determined by measuring the thermal conductance of a blank device without SiO₂ NR between the heating and sensing beam (Section 2.4.2). Consequently, the SPhP thermal conductance is extracted as:

$$G_{SPhP} = G_{Apparent} - G_{ph+loss} - G_{bg} \quad (2.11)$$

2.4.1 Radiation heat loss from NR

The radiation heat loss from NR can be calculated using fin model. During the measurement, the whole chamber environment including the Si substrate is carefully controlled at the same environmental temperature T , which varied from 300 K to about 550 K in this study. Therefore, we can consider the ribbon is being surrounded by an enclosure at the same temperature

(T). Since the ribbon is much smaller than the surrounding objects, include the vacuum chamber wall and the Si substrate, we can assume the surrounding enclosure as a blackbody, regardless of the actual optical properties or emissivity of the surrounding materials. Radiative heat transfer flux between two gray surfaces is³⁸:

$$\dot{Q}_{12} = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \frac{A_1(1-\varepsilon_2)}{A_2 \varepsilon_2}} \quad (2.12)$$

where A and ε are the surface area and emissivity respectively, σ is the Stefan–Boltzmann constant. Subscripts 1 and 2 means the objects 1 and 2. In our case of a very small nanoribbon (object 1) surrounded by a much larger enclosure (object 2), $F_{12} = 1$, and $\frac{A_1}{A_2} \cong 0$. The emissivity of nanoribbon ε_1 is very small. Therefore, the above equation is reduced to:

$$\dot{Q}_{12} = \varepsilon_1 A_1 \sigma (T_1^4 - T_2^4) \quad (2.13)$$

We can see that the radiative flux only depends on the emissivity of object 1 (i.e., nanoribbon in our case) and is independent of the properties of the enclosure (either the vacuum chamber wall or the Si substrate).

As mentioned earlier, $T_2 = T$ (enclosure or environmental temperature), $T_1 = T + \Delta T$ where $\Delta T \ll T$ (Note: ΔT is between ΔT_h and ΔT_s), so the radiative heat transfer coefficient (h_r) can be written as:

$$h_r = \frac{\varepsilon_1 A_1 \sigma (T_1^4 - T_2^4)}{T_1 - T_2} \cong 4\varepsilon_1 \sigma T^3 \quad (2.14)$$

Where ε_1 is the NR emissivity, which is obtained from the simulation for different NR thicknesses. The radiation heat loss from the NR is calculated based on a thermal fin model. The steady state heat conduction equation along the NR can be written as:

$$kA \frac{d^2 \Delta T}{dx^2} - h_r P \Delta T = 0 \quad (2.15)$$

where k is the NR thermal conductivity, A is the cross-section area of the NR and P is the perimeter of the NR cross section.

By setting $\beta^2 = \frac{h_r P}{Ak}$, the Equation 2.15 can be written as:

$$\frac{d^2 \Delta T}{dx^2} = \beta^2 \Delta T \quad (2.16)$$

The general solution for Equation 2.14 is

$$\Delta T = C_1 \sinh(\beta x) + C_2 \cosh(\beta x) \quad (2.17)$$

After applying the boundary condition

$$\Delta T|_{x=0} = \Delta T_h \quad (2.18)$$

$$\Delta T|_{x=L} = \Delta T_s \quad (2.19)$$

where L is the NR length, we can get the temperature distribution along the NR as follows:

$$\Delta T(x) = \left(\Delta T_s - \frac{\Delta T_h \cosh(\beta L)}{\sinh(\beta L)} L \right) \sinh(\beta x) + \Delta T_h \cosh(\beta x) \quad (2.20)$$

The total radiation heat loss from the NR can be calculated by integrating the heat loss along the NR:

$$Q_{loss} = \int_0^L h_r P \Delta T(x) dx \quad (2.21)$$

To obtain the surface emissivity of the SiO₂ NR, we performed full-wave simulations by using the commercial software COMSOL Multiphysics. The SiO₂ NR was set to be infinitely long using periodic boundary conditions at two ends and surrounded by vacuum with a perfect matching layer (PML) as the boundary condition to ensure accuracy. The incident light was modeled as a plane wave with a certain angle of incidence (α, θ) (Figure 2-13).

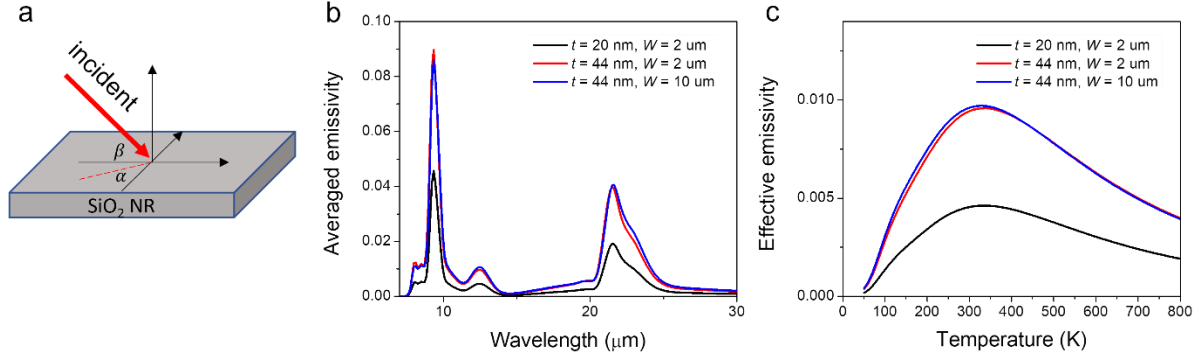


Figure 2-13: Simulation result for the emissivity of the thin SiO₂ NRs. (a) Schematic of the simulated structure calculating the absorption of incident light from varies directions by the SiO₂ NR. (b) Directionally averaged emissivity vs. wavelength for NRs with different thicknesses and widths. (c) Total effective emissivity vs. temperature.

The absorption cross-section was calculated as:

$$\sigma_{abs}(\alpha, \theta, \lambda) = \frac{Q_{abs}(\alpha, \theta, \lambda)}{I_0} \quad (2.22)$$

Where Q is the total absorption obtained by integrating the Ohmic losses over the volume of SiO₂ NR, I_0 is the intensity of incident light, (α, θ) stands for the angle of incident, λ is the wavelength of incident light. Then, by using the Kirchhoff's law, the emissivity can be expressed as:

$$\epsilon(\alpha, \theta, \lambda) = \frac{\sigma_{abs}(\alpha, \theta, \lambda)}{S} \quad (2.23)$$

where S is the physical surface area. In simulations, we performed 200-300 different incident angles for each structure to obtain the averaged emissivity $\bar{\epsilon}(\lambda)$ (Figure 2-13(b)). The temperature dependent effective emissivity (Figure 2-13(c)) can be calculated as:

$$\epsilon(T) = \frac{\int BB(T, \lambda) \cdot \bar{\epsilon}(\lambda) d\lambda}{\int BB(T, \lambda) d\lambda} \quad (2.24)$$

where $BB(T, \lambda)$ is the black-body radiation based on Planck's law.

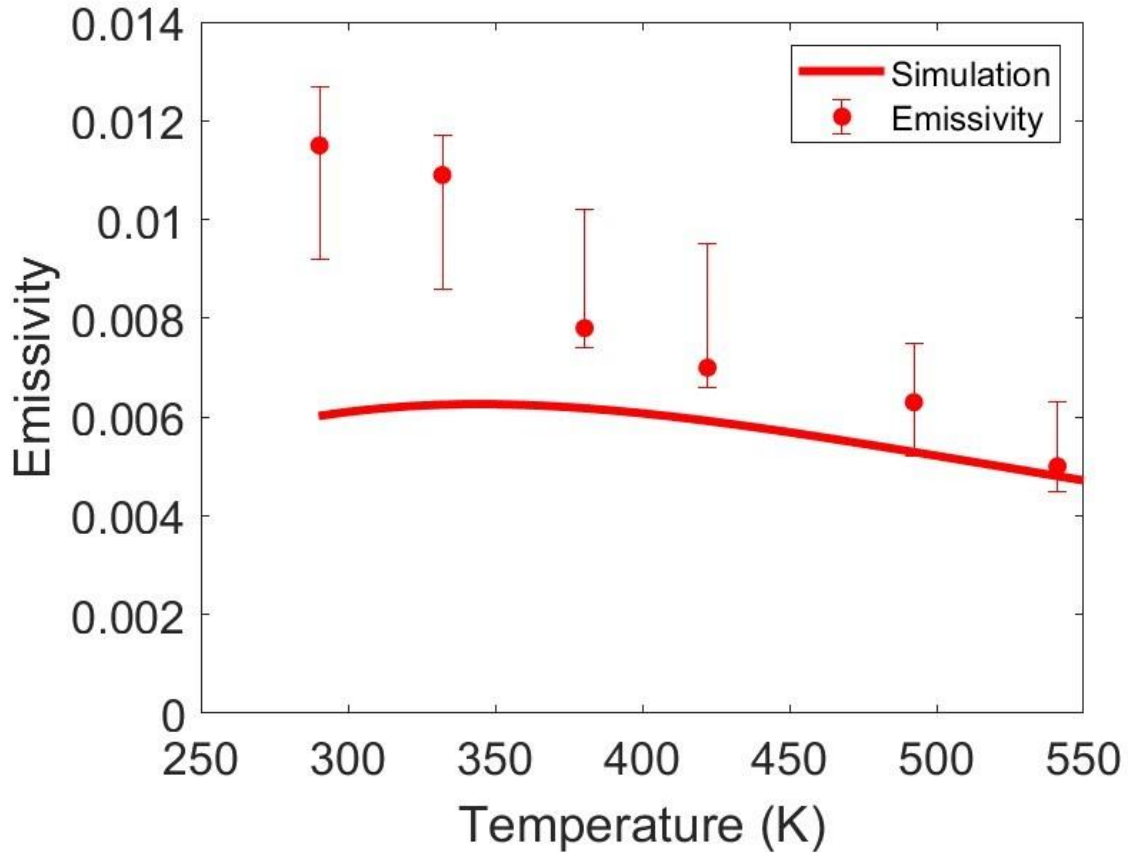


Figure 2-14: Comparison between the simulated results and the experimentally extracted emissivity from the 400 μm long NR sample (shown in Figure 2-12). The NR thickness is 30 nm. The error bars for emissivity are derived from the errors of the thermal conductivity in Figure 2-12.

Figure 2-14 shows a comparison between the simulated results and the experimentally extracted emissivity from the 400 μm long NR sample in Figure 2-12. The NR thickness is 30 nm in this case. The simulation result agrees well with the extracted value at high temperatures (> 350 K). At lower temperature, the simulation result underestimates the emissivity value. This is likely due to the more leakage of the SPhP waves to the substrate at lower temperatures. At lower temperatures, the peak thermal wavelength is longer and therefore the corresponding mode sizes

of the propagating modes are generally larger, leading to more leakage. This part of the energy loss is included in the experiments but is not accounted for in the simulation, since it is very challenging to handle such a large simulation domain.

2.4.2 Device background thermal conductance

In order to account for the device background conductance (G_{bg}) that comes from direct radiation heat transfer between the heating and sensing beams, we measured the conductance on devices without NR between the two beams. As can be seen from Figure 2-15(a), this background thermal conductance increases rapidly with temperature, and it is not neglectable at high temperature. This background thermal conductance is much larger than the beam-to-beam blackbody radiation thermal conductance (G_{BB}) as shown in the Figure 2-15(a), where G_{BB} is calculated using:

$$G_{BB} = 4\varepsilon\sigma A_{side}F_{12}\left(\frac{T_h+T_s}{2}\right)^3 \quad (2.25)$$

where $\varepsilon = 1$ was used to calculate the blackbody limit, A_{side} is the side wall surface area of the beam facing each other (which is the product of the thickness and the length of each beam), F_{12} is the view factor for the two parallel side walls of the beams (for the 44 μm gap, $F_{12} = 0.0045$, and for the 94 μm gap $F_{12} = 0.0018$). T_h and T_s are the temperature of the heating and sensing beam, respectively. The measured background conductance much higher over the blackbody limit is due to the directional thermal radiation mediated by SPhP in the thin SiO_2 beams, as studied by Reddy et al ¹⁵.

We also found that the background conductance decreased rapidly as the gap size increased. For the 400 μm gap, there was no measurable background signal at all. Instead of the linear relation between ΔT_s and heating power, we could only see noises in the ΔT_s measurement, as shown in Figure 2-15(b).

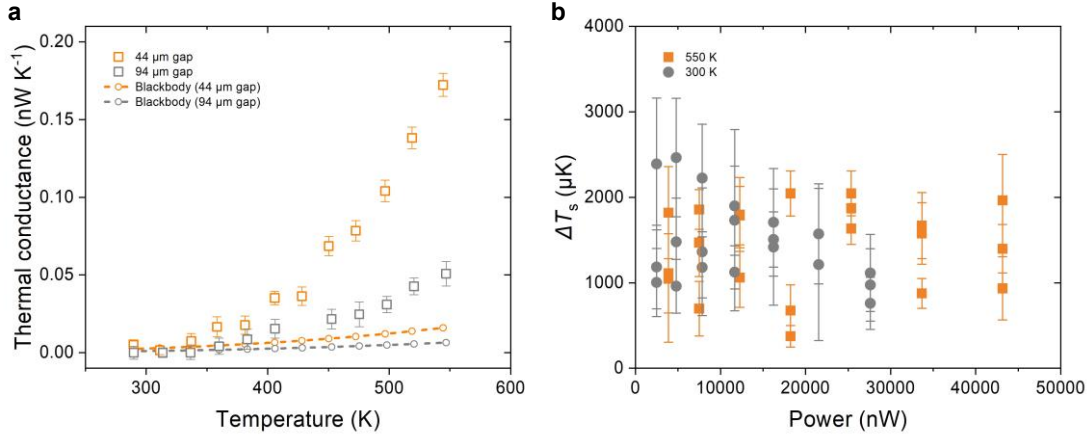


Figure 2-15: The background conductance for devices of different gaps. (a) Background thermal conductance for devices without a NR. (b) ΔT_s as a function of heating power for 400 μm gap device, showing only noise with this gap size, meaning no measurable background conductance.

In addition, the device background single as mentioned can be directly eliminated through the ‘canceling’ bridge circuit as shown in Figure 2-16. A blank pair device without a nanoribbon and a pair resistance $R_{h,2}$ have been added to the original measurement platform. An identical heating current (I_h) is applied to the heating sides (R_h and $R_{h,p}$) of both devices to create the same temperature rise in the two heating beams. Since the devices are almost identical and their background conductance values are approximately equal. The difference in the resistance changes on R_s and $R_{s,p}$ which corresponding to the temperature rises on the sensing sides of the two devices is directly measured using a Wheatstone bridge. Consequently, we can directly obtain the nanowire conductance from a single measurement based on this scheme.

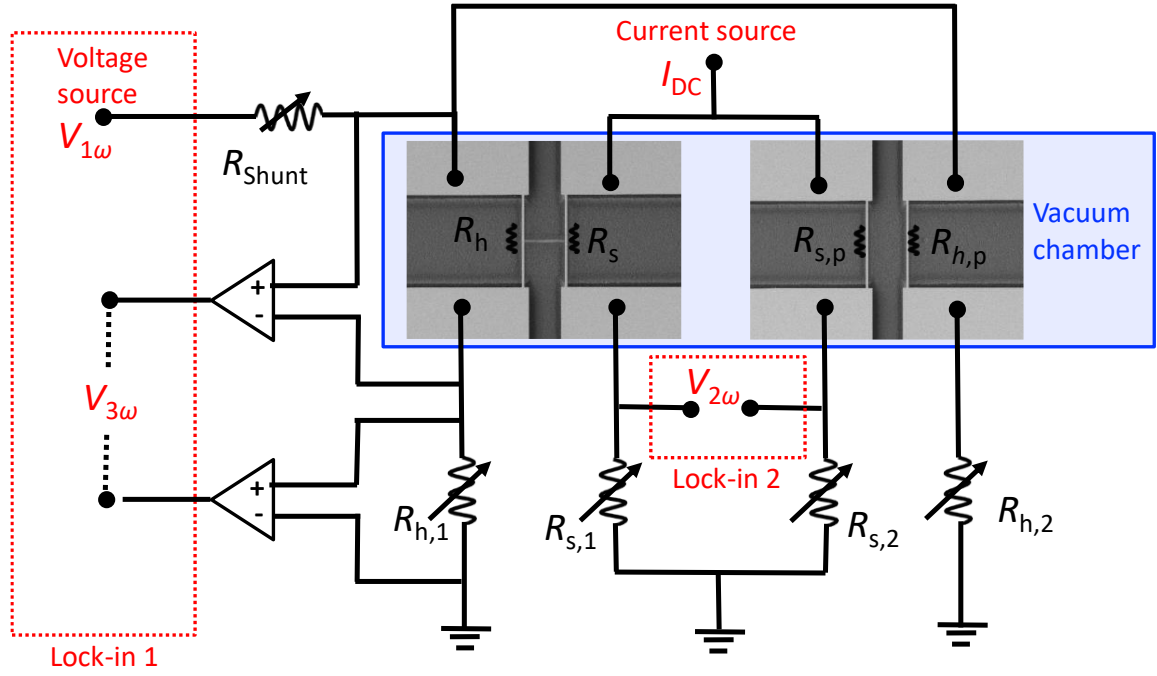


Figure 2-16: Schematic of the background signal canceling measurement platform.

A SiO₂ NR ($t = 54$ nm, $W = 9.98$ μ m, $L = 50$ μ m) has been measured with (Figure 2-16) and without (Figure 2-5) background canceling circuit, separately. From Figure 2-17, it can be seen that the apparent thermal conductivity still shows enhancement at high temperatures after removing the background signal. For the apparent thermal conductance measured with background signal canceling, SPhP thermal conductance is calculated by

$$G_{SPhP} = G_{Apparent} - G_{ph+loss} \quad (2.26)$$

While for another measurement method, the SPhP thermal conductance is extracted as:

$$G_{SPhP} = G_{Apparent} - G_{ph+loss} - G_{bg} \quad (2.27)$$

Figure 2-17 shows the comparison of G_{SPhP} of the same sample with different measurement methods. Either removing the background signal directly in the measurement or

subtracting the background signal during data processing, the calculated G_{SPhP} were similar which validates our approach to removing background signal.

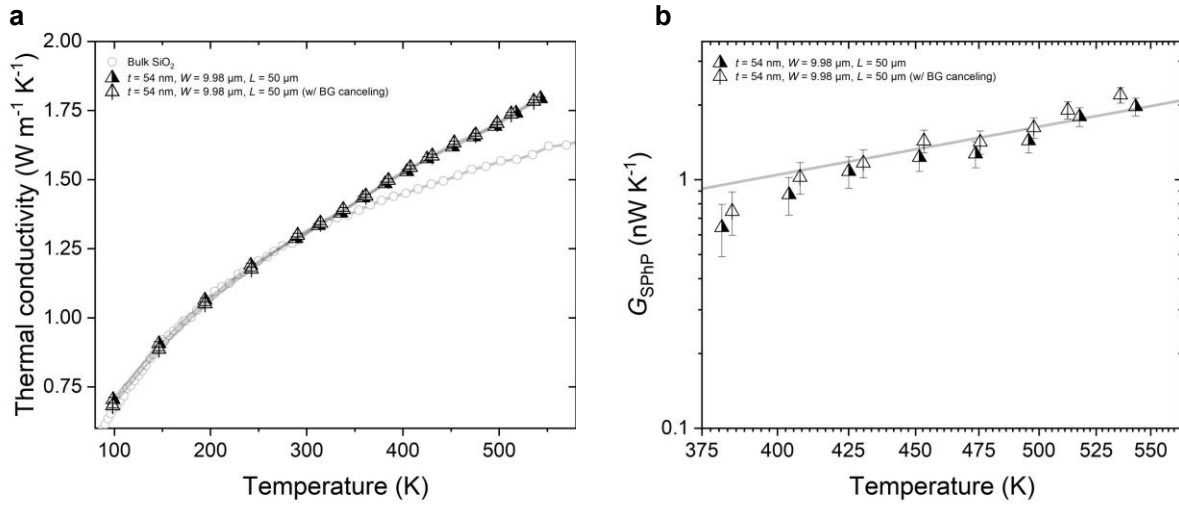


Figure 2-17: Background signal canceling measurement results. (a) The apparent thermal conductivity and (b) the calculated SPhP thermal conductance of the SiO₂ NR measured with and without BG canceling circuit, separately.

2.5 SPhP thermal conductance of the SiO₂ NRs

We then extracted thermal conductance mediated by SPhP (G_{SPhP}) by analyzing and subtracting other components contributing to the measured total apparent thermal conductivity: (i) Phonon thermal conductance (G_{ph}) through the NRs, (ii) Radiation heat loss from the NR to the ambient, (iii) Direct background thermal conductance (G_{bg}) from the hot to cold thermal reservoirs via thermal radiation. The phonon contribution is calculated using the well-known thermal conductivity of amorphous SiO₂ ³⁶ and the NR geometry. The phonon thermal conductivity of amorphous SiO₂ slowly increases with temperature above 300 K and is independent of nanostructure size even down to 7.7 nm thickness as studied by us previously (SI in Ref. ³⁹), due to the short effective MFP of non-propagating diffusion (~ 1 nm) in amorphous SiO₂ ⁴⁰. The radiation heat loss from the NR is analyzed along with the phonon heat conduction in the ribbon, manifested as progressively reduced apparent thermal conductivity on the ribbons with the same thickness but larger length (Figure 2-12). This “thermal fin” effect is due to the relatively larger radiation heat loss compared to heat conduction in a longer ribbon and has also been observed by us on SiO₂ NRs with larger thickness (~ 100 nm) without the black absorber design ³⁵. Following the same procedure in our prior work ³⁵, we extract the emissivity (ϵ) of the SiO₂ NR by comparing the measured apparent thermal conductivity to the bulk value in the 400- μ m-long NR. The extracted ϵ value at different temperatures for the 400 μ m long sample is shown in Figure 2-14: ϵ ranges from 0.012 to 0.005 when temperature increases from 300 to 500 K. The coloured area in Figure 2-12 corresponds to the range of the extracted ϵ value. This ϵ is considerably lower than the bulk value of SiO₂ (~ 0.9) and that of thicker NRs studied earlier (~ 0.1 for $t = 100$ and $W = 11.5$ μ m ³⁵) due to the much smaller thickness. To obtain ϵ of NRs with different geometries (e.g., $t = 22$ nm and 44 nm in Figures 2-10 and 2-11), we also modeled ϵ using full-wave simulations with

COMSOL Multiphysics (see Section 2.4.1). The modeled ε for the 30-nm-thick NR agrees well with the measured value shown in Figure 2-14. We then used the model ε to estimate the radiation heat loss from the NRs.

The third component, G_{bg} is determined by measuring a blank device without a NR between the heating and sensing beams, as shown in Supplementary Fig. S16. The background conductance originates from radiation heat exchange between the two beams, as manifested by its rapid increase with temperature and exponential decrease with larger distance between the beams. The measured G_{bg} at 550 K is significantly greater than the blackbody limit with the consideration of the view factor between the beams (see Section 2.4.2). This is caused by the directional thermal radiation mediated by SPhP in the SiO₂ beams, as observed by Reddy et al ¹⁵.

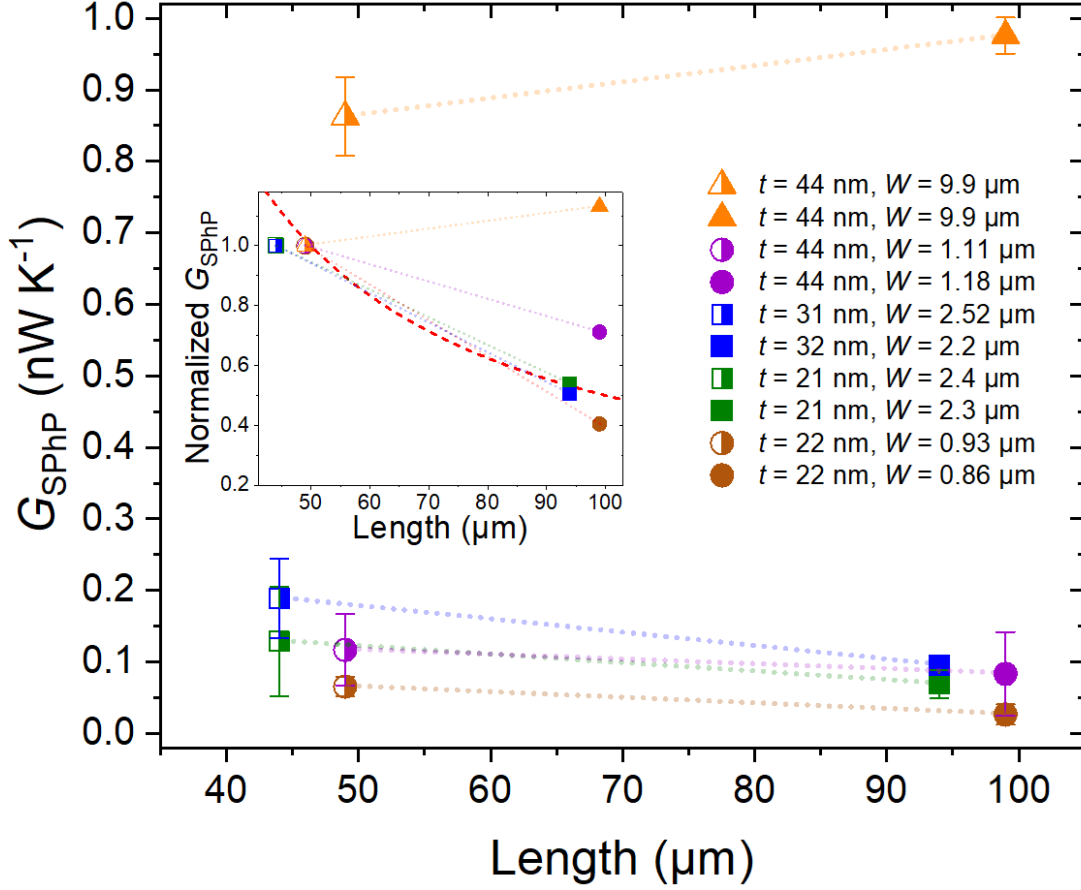


Figure 2-18: Length-dependence of SPhP thermal conductance (G_{SPhP}) of the SiO₂ NRs at 550 K. Inset: normalized G_{SPhP} with the value of ~50 μm long samples.

The extracted SPhP conductance is shown in Fig. 3. Fig. 3a shows G_{SPhP} of each sample at ~550 K as a function of the sample length. We find that for the sample with the larger thickness and width ($W = 9.9$ μm and $t = 44$ nm), G_{SPhP} remains nearly constant over a wide length range of 49 μm to 99 μm, demonstrating the ballistic heat conduction behaviour by SPhP. The ballistic transport regime over 50 μm at high temperature is expected for SPhP due to its larger wavelength and long propagation length (Figure 1-7) and is remarkable when compared to traditional heat carriers such as phonons that typically have MFP $< \sim 1$ μm at room temperature⁴¹⁻⁴³. On the other

hand, the samples with smaller width and thickness show a reduction in G_{SPhP} in longer NRs (Figure 2-18 inset). This reduction is not due to diffusive thermal transport. Rather, the larger mode size of the SPhP waves in thinner and narrower NRs results in stronger leakage of the wave to the substrate and consequently less efficient coupling to the thermal reservoirs. This can be clearly seen from the SPhP waveguiding mode profile along the thickness direction of two NR samples with different thickness and width, as depicted in Figure 2-19. The absolute value of electric field intensity for blue line is much smaller than black one. The intensity is normalized with their maximum value in the figure for better comparison. The thinner and narrower the NR, the larger the mode size, leading to SPhP energy leakage to the substrate and difficult to coupling to reservoir. As mentioned earlier, the majority of the mode volume of the SPhP wave is in vacuum. The mode size of SPhP increases rapidly with decreasing ribbon width and thickness (see Section 1.5). For the NR with $\sim 1 \mu\text{m}$ width and 21 nm thickness, the mode size is around $400 \mu\text{m}$, which is much larger than the gap between the SiO_2 NR and the Si substrate ($\sim 70 \mu\text{m}$), resulting in significant energy leak to the substrate before reaching the sensing reservoir. As the thickness and width of the SiO_2 NR increase, the SPhP mode is increasingly confined to the vicinity of the NR (mode size $\sim 40 \mu\text{m}$ when $W = 9.9 \mu\text{m}$ and $t = 44 \text{ nm}$), resulting in negligible leakage to the substrate during the propagation along the NR. It can be seen from Figure 3c that the SPhP contributed thermal conductance of 16 nm thick sample ($\sim 0.5 \text{ nW/K}$ at 550K) is lower than 50 nm one ($\sim 0.8 \text{ nW/K}$) due to the large loss. The two samples have similar width and length, but the 16 nm one has much smaller thickness, its thermal conductivity is higher (Figure 2-11) due to the normalization to their cross sections: $k = \frac{G \cdot L}{W \cdot t}$.

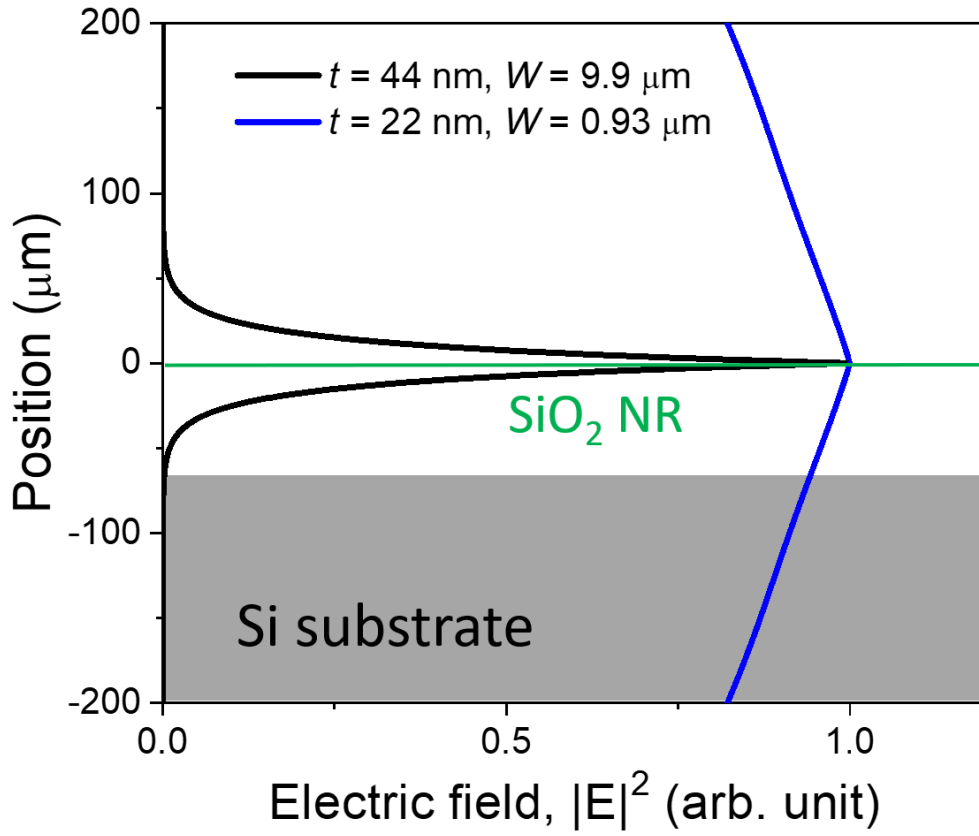


Figure 2-19: Simulated mode profile of the SiO₂ NR waveguide quasi-TM mode at the wavelength of 10 μm in the thickness direction for two samples: $t = 22\text{ nm}$ and $W = 0.93\text{ }\mu\text{m}$ (blue) and $t = 44\text{ nm}$ and $W = 9.9\text{ }\mu\text{m}$ (black).

The large wavelength of SPhP makes it possible to observe the low-dimensional heat conduction behaviour with SPhP that are otherwise only accessible in exotic phononic or electronic heat conduction systems, such as atomic and molecular structures and sub-Kelvin phononic waveguide. For NRs with thickness and width smaller than the wavelength ($\sim 5\text{ }\mu\text{m}$ at 550 K), the transport should be one dimensional. Similarly, for NRs with thickness smaller than the wavelength but width comparable to the wavelength, the transport is close to two-dimensional.

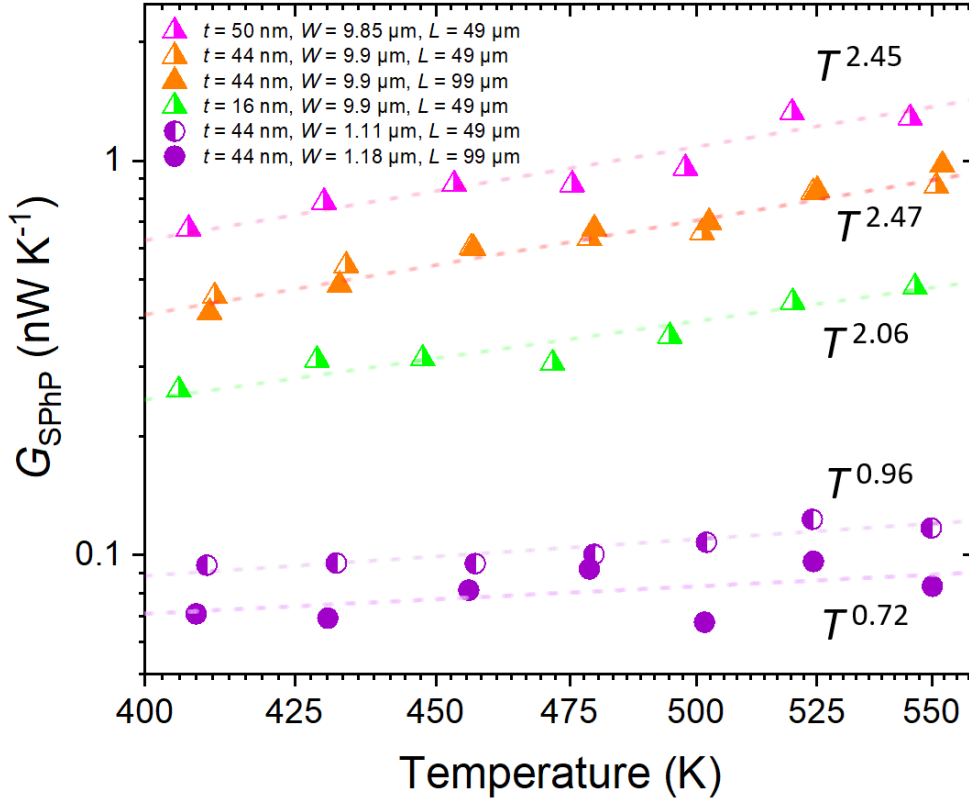


Figure 2-20: Temperature-dependent G_{SPhP} of the SiO₂ NRs with different thickness and different widths of ~ 1 and ~ 10 μm , showing close to T and T^2 dependence respectively. The apparent thermal conductivity of these samples is shown in Figure 2-11.

We fit the measured G_{SPhP} as a power law function of temperature ($G_{SPhP} \sim T^\alpha$), and find that α is close to 1 and 2 for the ~ 1 μm and ~ 10 μm wide samples, respectively within the temperature range of 400-550 K. (Figure 2-20). This is consistent with the theoretical prediction of 1D and 2D G_{SPhP} in narrow and wide SPhP waveguide respectively^{13, 44}. However, the exponents α deviate from 1 or 2. This is due to the fact that the observed G_{SPhP} is still only a fraction of the respective theoretical 1D and 2D limits. For example, G_{SPhP} of the ~ 1 μm wide samples is about 10% of the theoretical 1D limit. The deviations from the theoretical limit are

caused by the losses of SPhP waves, either leaked into the substrate during propagating or scattered into free space when coupling into the cold reservoir. Both loss mechanisms depend on the mode sizes of the waves: the larger the mode size, the bigger the losses. The mode size mainly depends on the cross section of the sample and it is larger for samples with smaller cross sections. That is the reason for the lower G_{SPhP} in the $\sim 1 \mu\text{m}$ wide samples. For a specific sample, the mode size could also change with the temperature. This is mainly because the mode size depends on the wavelength, and the peak thermal wavelength of the emission spectrum depends on the temperature. However, for a narrow temperature range such as from 400 to 550 K, the peak thermal wavelength does not change dramatically. Furthermore, the spectral dependence of the mode size is also quite weak for the case considered here. For SiO_2 , the material property varies dramatically within the Reststrahlen band but changes slowly with wavelength outside the Reststrahlen band²³, so does the mode size. The modes on the SiO_2 NRs are supported with frequency range much broader than the Reststrahlen band, so the average mode size does not change a lot with temperature especially at relatively high temperatures. That means the percentage of measured G_{SPhP} relative to the theoretical value is almost the same, so the measured G_{SPhP} also show similar T dependence as the theoretical prediction within the narrow temperature range studied.

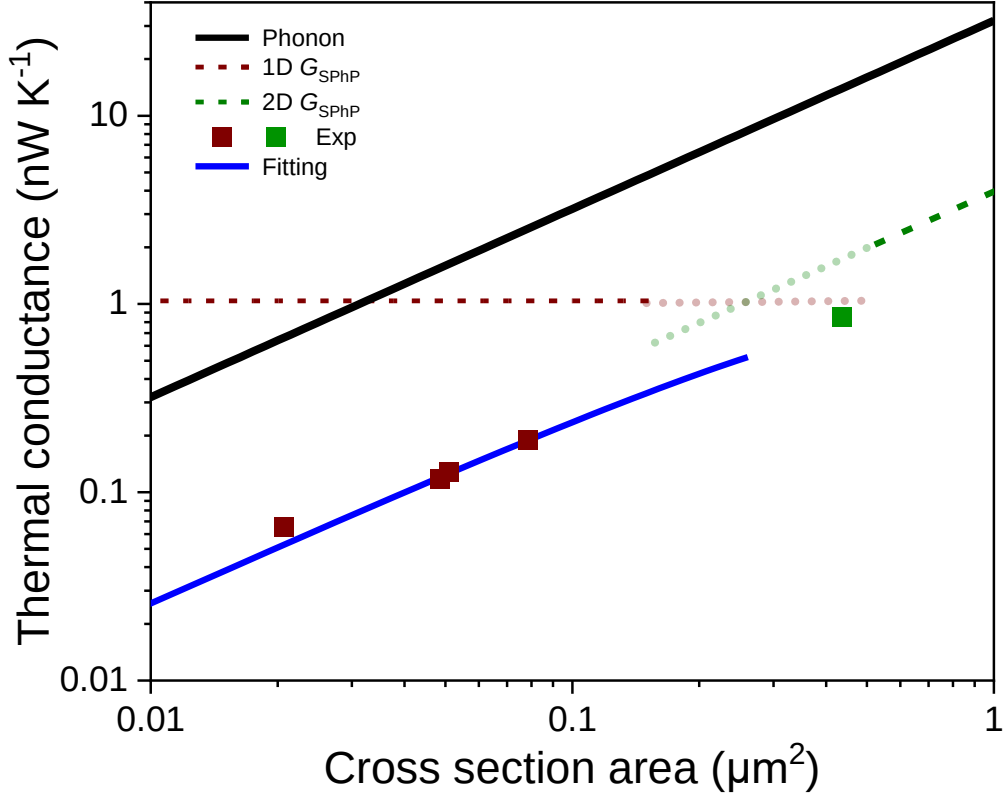


Figure 2-21: Dependence of G_{SPhP} on the NR cross-section area compared to the calculated phonon thermal conductance of 50-μm-long NRs (solid black line) and the 1D and 2D quantum limits of G_{SPhP} (red and green dashed lines) in the small and large cross-section area regimes respectively. The experiment data corresponding to the ~ 50-μm-long NRs in Fig. 3a. Red dots for samples with small cross section (1D), green dot for sample with larger width (2D).

In an SPhP waveguide, when the wavelength of SPhP is larger than the characteristic sizes of samples along two or one directions and with perfect transmission and absorption coefficient (i.e., $\tau_n = 1$ & $\eta_n = 1$ in Eq. 1), 1D and 2D quantum limits of thermal conductance can be achieved^{13, 44}. The 1D quantum limit of G_{SPhP} is proportional to T and is only dependent on physical constants¹³. The 2D limit is proportional to T^2 and the ratio G_{SPhP}/W only depends on physical constants²⁷. In Figure 2-21 we plot G_{SPhP} at 550 K as a function of the cross-section area

of the NRs ($A = tW$) and compare it to the 1D and 2D quantum thermal conductance limit. The thickness and width dependence are shown in Figure 2-22.

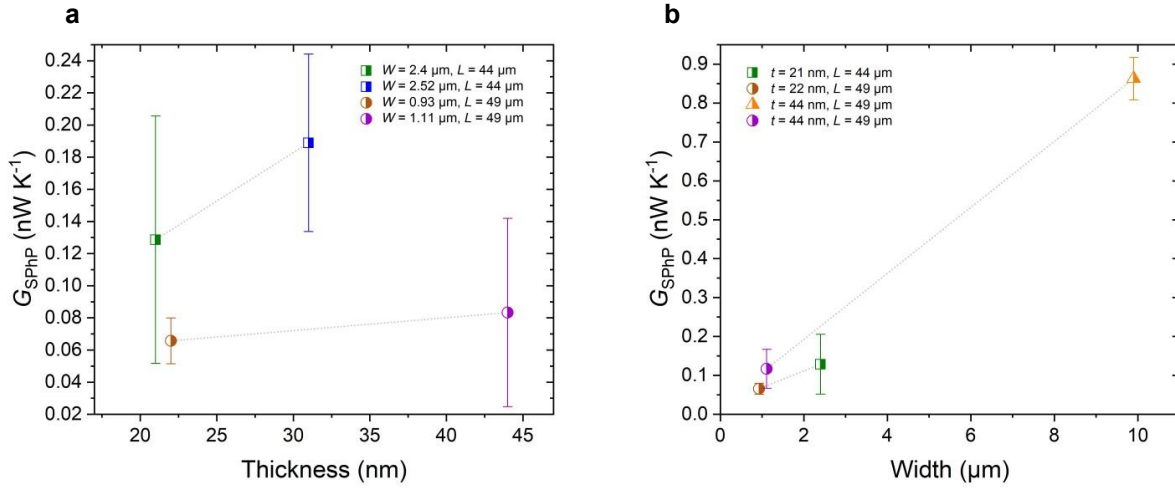


Figure 2-22: Thickness and width-dependence of SPhP thermal conductance. (a) Thickness, and (b) width-dependence of SPhP thermal conductance of SiO₂ NRs.

We observed that G_{SPhP} is still lower than the quantum limits due to the non-ideal absorption to the reservoirs. We also found that G_{SPhP} increases with a larger cross-section area due to the smaller mode size, less energy leakage, and better absorption. We fit the experimental data using a simplified relation to account for the non-ideal absorption coefficient, $\eta_n \approx \tanh(A/C_{eff})$, shown as the blue curve in Figure 2-21. We used $\eta_n = \tanh(A/C_{eff})$ to fit the data for our 1D samples (red data points in Figure 2-21), where $A = tW$ is the cross section and C_{eff} is an effective parameter after considering the frequency dependence. The trend aligns well when a single value of $C_{eff} = 0.45 \mu m^2$ is used. The fitted value of C_{eff} for our experiment data can be treated as an average scaling factor of the mode size for the four samples under the temperature of 550K. A single fitting parameter C_{eff} can fit all the experimental data, showing the validity of our physical picture. This result suggests that one could realize the quantum limit of

thermal conductance at room and high temperatures if the absorption coefficient can be enhanced to near unity, for instance, by using more optimized absorber materials and geometry.

The observed G_{SPhP} is still lower than the phonon limit (see Figure 2-21). However, as the phonon conductance follows the Fourier's law, namely, proportional to the cross-section area and inversely proportional to the length, one can potentially realize a regime where G_{SPhP} is much larger than the phonon limit if the absorption coefficient can be optimized to near the unity. For the SiO₂ NRs with the 50-100 μm length studied here, this regime can be achieved when the cross-section area is less than 0.03 μm^2 (i.e., the regime above the black curve and below the red curve in Figure 2-21). For samples with larger cross-section area (such as the wide ribbons), one could also maintain high G_{SPhP} but lower phonon conductance in NRs with nanoscale porosity in it, or with very long NRs due to the ballistic nature of SPhP, provided that the mode size is substantially smaller than the gap between the NR and the substrate. Finally, hyperbolic metamaterial with high-density metal-dielectric interfaces⁴⁵ is also a promising system to observe high G_{SPhP} as each interface can support SPhP modes.

2.6 Conclusion

In summary, we have experimentally realized enhanced thermal conductivity mediated by SPhP in a polar dielectric (SiO_2) nanoribbon waveguide, which represents an entirely new heat conduction regime that has been pursued for nearly two decades. The new regime shows combined characteristics of text-book heat conduction (high energy flux) and thermal radiation (ballistic and large wavelength). We identified the key factors that are crucial for the measurement of heat flux carried by SPhP but have been overlooked in prior theoretical predictions and experimental attempts: optimal mode size surrounding the waveguide and efficient absorption of the wave by the thermal reservoirs. We then carefully designed our NR waveguide geometry and the absorbers in the reservoirs to realize an overall thermal conductivity greater than the well-known phonon limit in amorphous SiO_2 . Due to the large wavelength of SPhP, the SPhP thermal conductance shows 1D and 2D temperature dependence in narrow and wide NRs respectively even at room and high temperatures. For the sample that has little leakage of SPhP to the substrate, we showed length-independent, ballistic thermal conductance. This work paves the way for observing low-dimensional heat conduction phenomena mediated by SPhP waves and could lead to the realization of quantum thermal conductance at high temperature as well as high SPhP thermal conductance over the phonon limit, and thus could have broad implications in fields such as microelectronics and nanophononics⁴⁶.

Acknowledgements

Chapter 2, in full, is a reprint of the materials as it appears in "Low-dimensional Heat Conduction in Surface Phonon Polariton Waveguide." Yu Pei, Li Chen, Wonjae Jeon, Zhaowei Liu, Renkun Chen. Nature Communications 14, no. 1 (2023): 8242.

3.1 Introduction

Thermophotovoltaic (TPV) systems convert heat to electricity via photons and they commonly consist of three parts (a heat source, an emitter and a photovoltaic cell). The heat source of TPV usually higher than 1000K. The concentrated solar heat, waste heat from industries, heat from fuel combustion or nuclear processes can all be harnessed using TPV system. According to the Stefan-Boltzmann law and Wien's displacement law, higher temperature radiated higher power density and the lower light flux peak wavelength. Since only the photon with the energy higher than the bandgap energy of the PV cell can be absorbed and converted into electricity eventually, a lower band gap PV cell can greatly improve efficiency. Indium gallium arsenide antimonide (InGaAsSb), gallium antimonide (GaSb), and Indium gallium arsenide (InGaAs) are typical low band gap PV cells, the wavelength λ_{Eg} corresponding their band gap energy are 2.2 μm , 1.85 μm and 1.68 μm . Even if the temperature is as high as 1800 K, the peak wavelength of black body radiation is around 1.6 μm . Which mean there are a lot of Out-of-band photons' energy will be wasted, also, those energy will heat up the PV cell and decreased the efficiency of the TPV system.

With the development of micro/nanofabrication technologies people are enable to tailor the NIR radiative spectrum. A selective emitter with narrowband thermal emission near the PV cell band gap corresponding wavelength and a high emissivity can greatly improve the efficiency of the TPV system. The selective thermophotovoltaic (TPV) emitters have three common types: Multilayer stacks, Photonic crystal (PC) structures, and Metamaterial array.

The multilayer stacks are the simple way to get a selective TPV emitter⁴⁷⁻⁴⁹. Good optical performance can be got by varying the thickness of alternating metal and dielectric layers. High melting point metals, such as Tungsten (W, 3422°C), Tantalum (Ta, 3020 °C), and platinum (Pt, 1768°C) are the frequent choice for high-temperature emitters. There are also some refractory

dielectric materials, aluminum oxide (Al_2O_3 , 2072°C), Hafnium oxide (HfO_2 , 2758°C), and Ytterbium oxide (Yb_2O_3 , 2355°C) commonly used as a protective layer in TPV emitters. The highest working temperature for that kind of TPV emitter is 1400°C reported by Manohar Chirumamilla et al⁴⁸. They used six bilayers of W and HfO_2 as the emitter structure which means the interfaces are is very big. HfO_2 grain grows with temperature increase and eventually will penetrate at the interface leads to local ruptures of the W thin-film. Also, tungsten is easily oxide by the O_2 diffusion from the outer atmosphere through the HfO_2 layers. This limits their emitter can only work in a high vacuum environment (3×10^{-5} mbar).

Another typical TPV emitter is Photonic crystals (PhC) structure⁵⁰⁻⁵², such as rods or cavities in a substrate. Kehang Cui et al show a long-term high-temperature stability of their W-CNT PhC emitter (negligible degradation of optical properties after annealing for 168 hours at 1273 K in He flow environment)⁵¹. But the high density nanopatterned vertically aligned carbon nanotubes (VACNTs) are hard to grow⁵³ and the atomic layer deposition (ALD) of Al_2O_3 and W is high cost⁵⁴.

Metamaterial array is one promising class of TPV emitter recently⁵⁵⁻⁵⁷. Metamaterial are artificial novel structures with periodic subwavelength patterns. By control the shape, geometry, size, orientation and arrangement of the structures, metamaterial can achieve electromagnetic property that cannot be found in Natural materials. Metamaterial have a lot of applications such as negative refractive index material, invisibility cloaks, perfect lenses and perfect absorber. However, those materials which can sustain high temperature (such as W, Ta, Pt) either do not have suitable optical property or their optical properties will shift from room temperature to high temperature. Chang C et al fabricated an emitter with different diameter W nano disks on Al_2O_3 spacer and bottom W-ground plane⁵⁶. (By adding a HfO_2 protective layer, their emitter can

maintain thermal stability up to 1200°C.) W is a good refractory material but it is not a very good plasmonic material, so they do not realize very good narrowband thermal emission.

Table 3-1 summarized the performance of representative selective thermal emitters, the highest working temperature is 1673K, but the working time is only 6 hours even in high vacuum. All of those work cannot realize long working hours at high temperature in atmosphere.

Table 3-1: Performance of representative selective thermal emitters

Type	Description	Working temperature	Working environment	Working time	Reference
Multilayer stacks	Si/SiO ₂ /W/Si/W Multi layer	1200K	Not mentioned	24h	Zhang W, et al. 2021
	W-HfO ₂ layered metamaterial	1673K	Vacuum	6h	Chirumamilla M, et al. 2019
	W/ Al ₂ O ₃ layers	1473K	Vacuum	3h	Kim J H, et al. 2019
Photonic crystal (PhC) structures	Si rods on MgO substrate	1338K	Vacuum		Suemitsu M, et al. 2019
	Tungsten-carbon nanotube (W-CNT) PhC	1273K	He flows	168h	Cui K, et al. 2018
	HfO ₂ coated W inverse colloidal 3D PhC	1273K	Ar flow	12h	Arpin K A, et al. 2013
	W 2D cavity array	1200K	Vacuum	10h	Yeng Y X, et al. 2012
Metamaterial array	Pt array on Al ₂ O ₃ /Pt	1273K	Ar	2h	Woolf D N, et al. 2018
	HfO ₂ -coated W nanodisks on the Al ₂ O ₃ /W layers	1473K	Vacuum	12h	Chang C, et al. 2018
	TiN square loop on SiO ₂ space on TiN	1073K	Vacuum	8h	Li W, et al. 2014

In this paper, we use aluminum as the metamaterial since its one of the best plasmonic material, even in the molten state, so it can outperform all the existing solid-state high-temperature plasmonic materials. Aluminum also has ultralow vapor pressure up to 1700°C. Therefore, it is inherently stable with a proper sealing layer. Aluminum oxide shows dielectric properties can be used to construct the metamaterial and its stable in oxidizing atmospheres. Most importantly, Al and Al_2O_3 will not react at high temperature.

3.2 Proposed structure and simulation

There are two main problems for the previous works. First, there are reactions between dielectric, metal, and oxygen at very high temperatures, which produce compounds that affect optical properties or produce gas cause cavities. Second, there will be thermal stress due to different volume expansions for different materials, causing deformation and voids.

The materials we used in Our design are Al and Al_2O_3 , they have the following advantages. First, they are thermodynamically stable even at high temperatures since Al_2O_3 is the only oxide form for Al. Besides, Al is a good plasmonic material to do metamaterial design. Compare to high temperature refractive materials like tungsten and chrome, Al has more negative real part permittivity. Most importantly, we have special design of porous Al to eliminate the thermal stress after Al melts at the melting point.

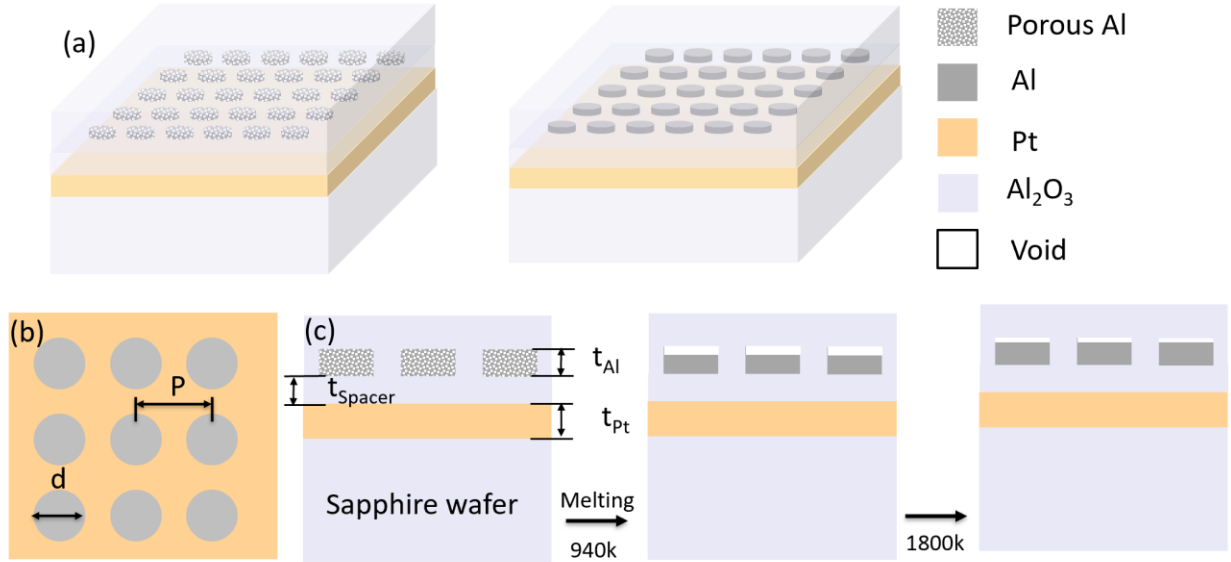


Figure 3-1: Structure of emitter (a) Molten Meta-Material emitter design (b) top view (c) side view of emitter as fabricated, at 940K, and at 1800K.

Our emitter design is a metal-dielectric-metal structure as shown in Figure 3-1. A 100nm Pt layer was deposited on a crystalline sapphire (Al_2O_3) wafer as a mirror to eliminate transmission of the structure. Porous Al disk array resonators is on top of the 150nm-thick Al_2O_3 spacer. Additionally, there is a 300nm top Al_2O_3 layer to encapsulate the Al array. Pt and Al_2O_3 have well matched coefficients of thermal expansion from room temperature to 1500K⁵⁸. Considering the different volume thermal expansion coefficients of Al and Al_2O_3 and aluminum volume change during the solid-to-liquid phase transition, the volume expansion of Al and Al_2O_3 to be about 30% and 3%, respectively, from 300K to 1800K.

As you can see, at 940K, the porous Al will melt and become solid Al, the volume of Al decreased, and this void could compensate the volume expansion difference at much higher temperature. When the porous Al has larger than 30% porosity it can eliminate the thermal stress even at 1800K.

Plasmonic metamaterials which combine subwavelength metallic elements with dielectric structures have been long utilized for the control of thermal emission spectrum. To illustrate how our MMM concept can achieve an efficient narrow-band thermal emission, we performed preliminary simulations by using a commercial software COMSOL Multiphysics. We controlled the plasmonic response of the MMM structure by varying five independent parameters: Al nanodisk thickness (h), diameter (d), period (p), top coated Al_2O_3 thickness (t), and distance to the bottom Al mirror (g). Figure 3-2 shows the calculated results of two example MMM structures. Narrowband absorptance (emittance) peaks are centered at $\lambda = 1.6 \mu\text{m}$ were obtained, well-aligned with the center wavelength of blackbody radiation at $T = 1800\text{K}$. A quality factor of ~ 16 and maximum emittance of 60% were observed for MMM structure without bottom mirror, where (h ,

$d, p, t) = (100 \text{ nm}, 290 \text{ nm}, 890 \text{ nm}, 200 \text{ nm})$. A quality factor of ~ 5.6 and maximum emittance $>98\%$ were observed for $(h, d, p, t, g) = (100 \text{ nm}, 290 \text{ nm}, 940 \text{ nm}, 300 \text{ nm}, 275 \text{ nm})$ when a bottom mirror was added. These narrowband response peaks were induced by the dipolar plasmon resonance excitation on Al nano-disks, enhanced by the periodic feature and the bottom mirror. This result clearly demonstrates the effectiveness of utilizing the MMM to tailor thermal emission spectrum solely by geometries.

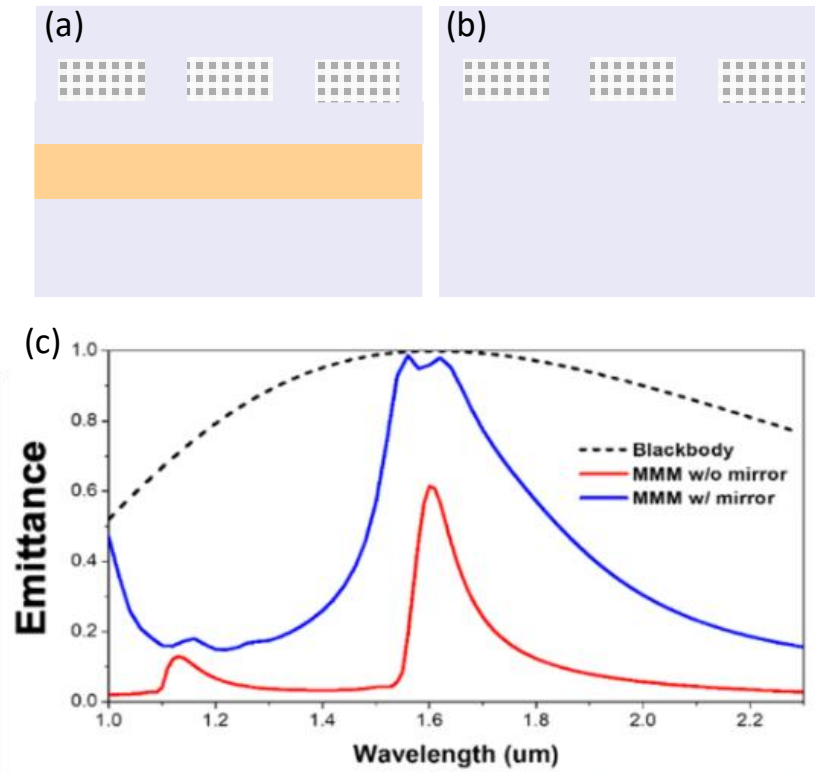


Figure 3-2: Side view of MMM with (a) and without (b) bottom mirror. Simulation result of MMM emitter emittance at 1800K. (c) Black dash curve is the normalized blackbody emission.

3.3 Mid-infrared selective MMM emitter

In order to quickly verify the feasibility of our design, we use photolithography made micro size periodic Al dots sample, with a bigger period ($3\mu\text{m}$) and diameter ($1.7\mu\text{m}$) the resonance peak wavelength also increased to mid-infrared reign ($\sim 6.8\mu\text{m}$), which can be easily measured by commercial FTIR machine. Figure 3-3 shows the Mid-infrared selective MMM emitter spectrum from COMSOL simulation.

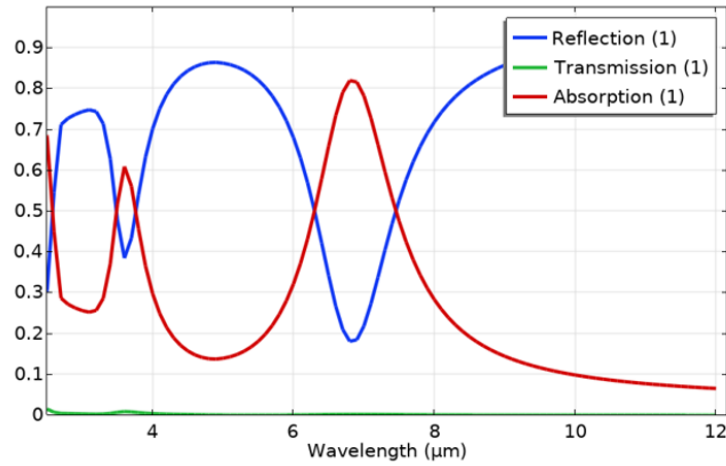


Figure 3-3: Mid-infrared selective MMM emitter spectrum.

Mid-infrared emitter fabrication process is illustrated in Figure 3-4. First, we deposited Pt mirror and Al_2O_3 spacer on sapphire wafer using sputter. Then, Al and Cu composite disk has been deposited using E-beam evaporator by photon lithography and liftoff. After copper etchant wet etching, we can get porous Al disk. Last, a Al_2O_3 encapsulation layer deposited on top to prevent Al oxidation and deformation.

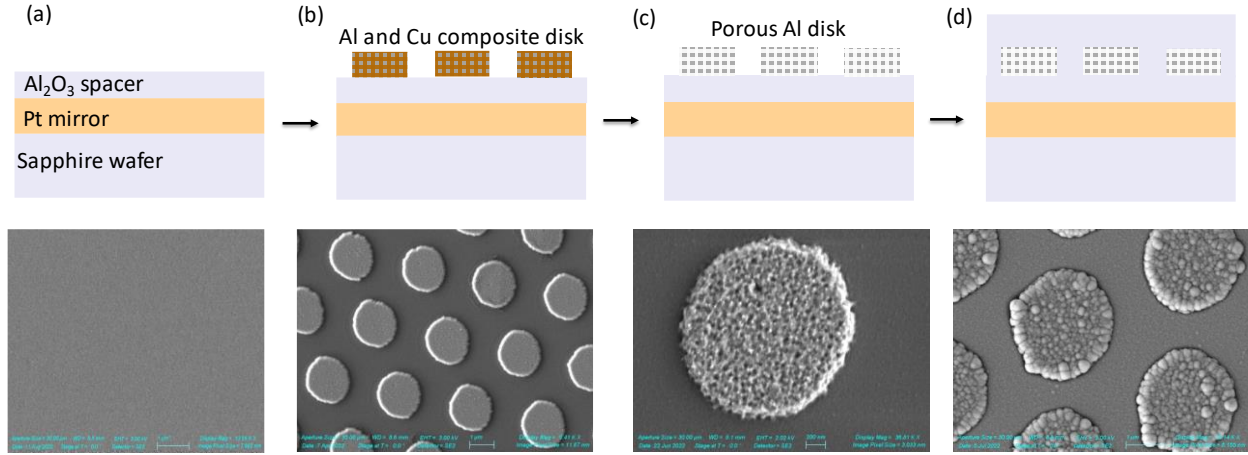


Figure 3-4: (a) Pt mirror and Al_2O_3 spacer on sapphire wafer. (b) Al and Cu composite disks on substrate. (c) Porous Al disk by copper etchant wet etching. (d) Al_2O_3 encapsulation layer.

Solid Al and porous Al disks sample are being fabricated separately to do the control experiment. We did test for the stability of emitter at high temperature. All of the samples are annealed at 1073K for 20 minutes in vacuum ($\sim 5 \times 10^{-5}$ Torr). Before annealing the samples are similar and after annealing there are obvious difference. From the SEM images in Figure 3-5, the Al_2O_3 layer on top solid Al disks sample has shown many crakes, while for porous Al disks, there are almost no crakes. This validated our design that porous Al could release the thermal expansion stress difference at high temperature.

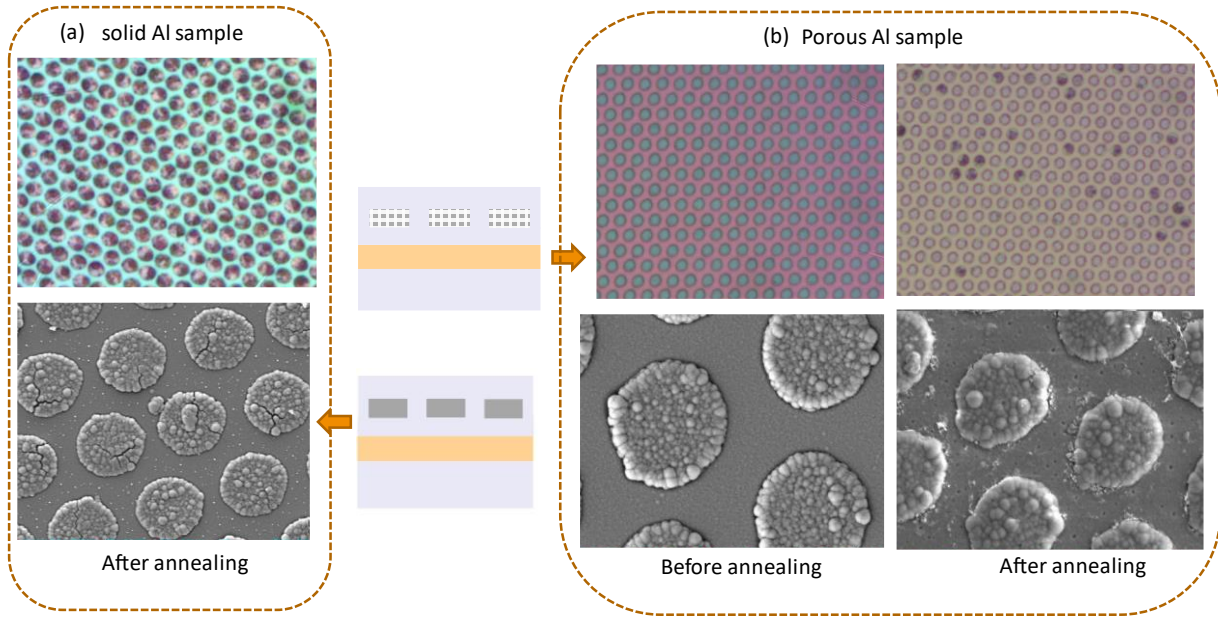


Figure 3-5: Stability test at high temperature for (a) solid Al disks sample and (b) porous Al disks sample.

We measured the reflectance spectrum for the emitters before and after annealing using FTIR. As shown in Figure 3-6, for both solid and porous Al disks sample, they all shown good resonance peak before annealing. The peak wavelength is consisting with the simulation result in Figure 3-3. After annealing, for the solid Al disks sample, the resonance peak is gone, which is the dash black line. As for the porous Al disks sample, there is still a resonance peak, but the peak wavelength shifted a little, which may because the deformation of Al disk after melting and re-solidification and Al disk partially oxidation.

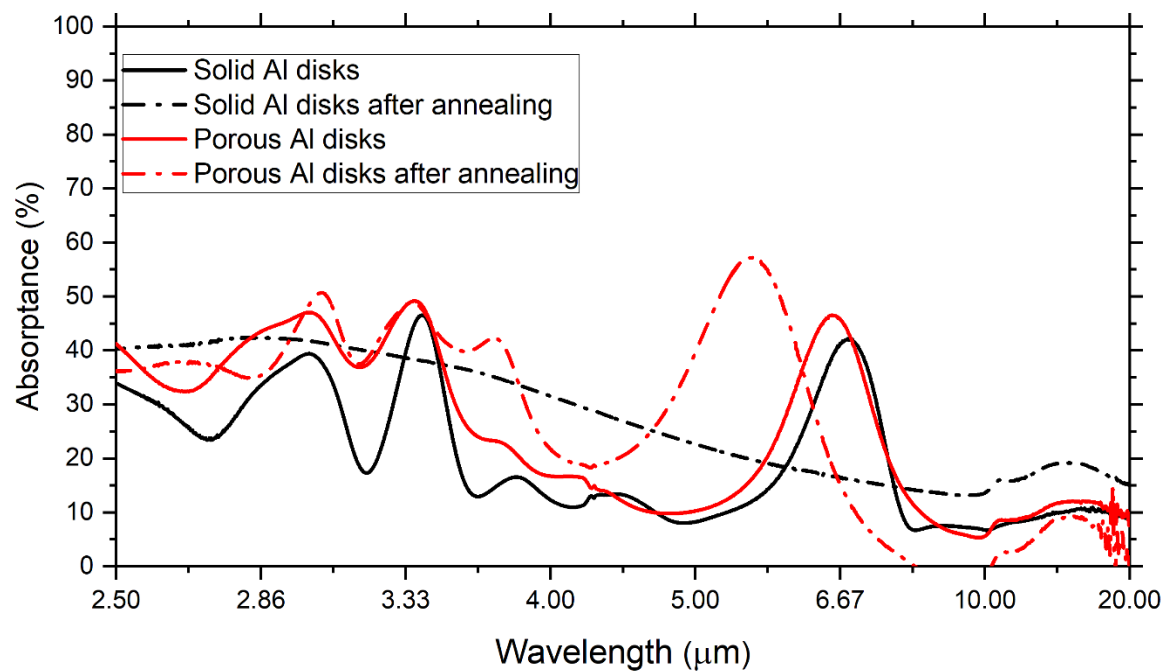


Figure 3-6: Absorptance spectrum for the emitters before and after annealing.

3.4 Near-infrared selective MMM emitter

By apply nanosphere colloidal lithography, nanoscale Al disks can be fabricated and we can get Near-infrared selective MMM emitter. The nanosphere we used for colloidal lithography is non-functionalized polystyrene (PS) particles from Alpha Nanotech Inc. The emitter fabrication process is illustrated in Figure 3-7.

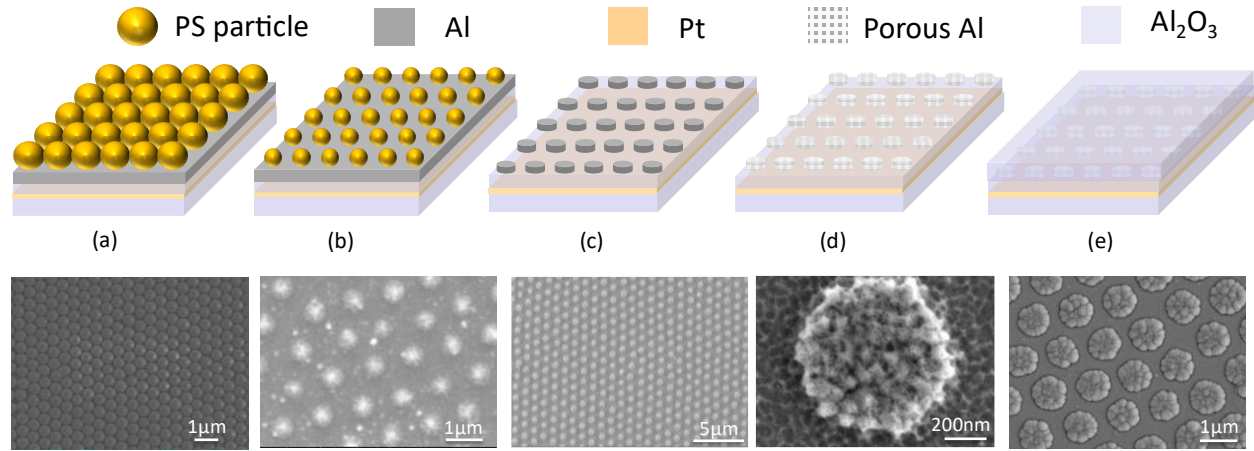


Figure 3-7: (a) Self-assembled monolayer of PS spheres in close-packed hexagonal array. (b) PS spheres after the RIE process with oxygen plasma. (c) Al disks array after RIE of the Al and removal of the PS mask. (d) Porous Al disks after Al etching using Cr etchant. (e) Device with Al_2O_3 encapsulation to prevent Al oxidation.

First, we prepared a substrate with Al layer Al_2O_3 spacer and Pt mirror on top of sapphire wafer. Then the substrate was placed in a container filled with water. A PS particle sphere and IPA mixture solution (ratio 1:1) were injected to the surface of water. After a Self-assembled monolayer of PS spheres in close-packed hexagonal array formed, the substrate can be taken out, we can get a sample as shown in Figure 3-7(a). After that, a dry etching with oxygen plasma were did to etching the PS particle to designed Al disk diameter. Using those PS particles as etching mask to do Al etching and remove PS particle after etching, we can get the Al disks as shown in Figure 3-7(c). Cr etchant is used to etch the solid Al disk to porous Al. Last, an Al_2O_3 layer were deposited on top to protect Al.

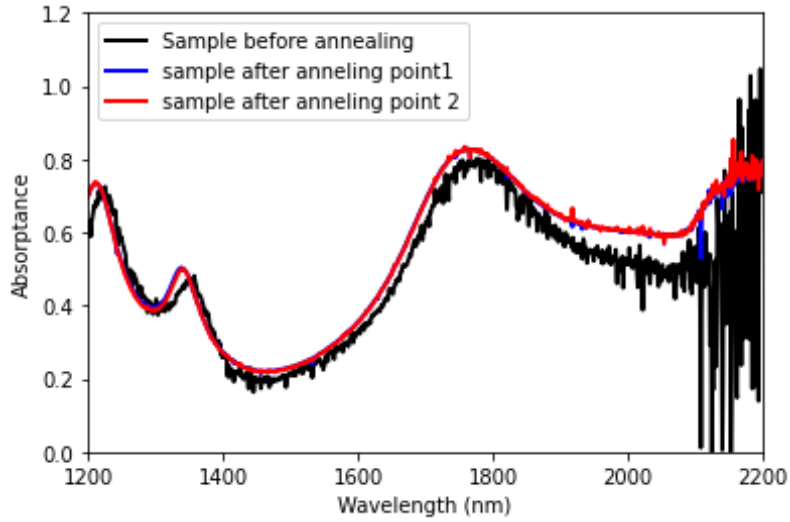


Figure 3-8: Absorbance spectrum for the Near-infrared emitters before and after annealing.

We did similar high temperature stability test for the Near-infrared selective MMM emitter at 1037K and in vacuum condition ($\sim 1 \times 10^{-4}$ Torr). The sample absorbance spectrum almost does not change before and after annealing, which is a good sign that MMM emitter solved the main two problems (reaction between dielectric and metal and thermal stress due to different volume expansion) in the previous work. However, if anneal the emitter at higher temperature and non-vacuum environment, the sample will fail because of the Al disks oxidation. The deposited few hundred nanometers Al_2O_3 excupation layer is amorphous Al_2O_3 , the oxygen could go through the voids between Al_2O_3 grains. Alpha phase Al_2O_3 is an excellent oxygen barrier at high temperature, with one of the lowest oxygen diffusivities at 1800K ($\sim 10^{-20} \text{ m}^2/\text{s}$ in α - Al_2O_3). Hence, bond a sapphire wafer to the top of MMM emitter is a promising way to protect Al in emitter^{59, 60}.

Acknowledgements

Chapter 3, in part is currently being prepared for submission for publication of the material. “High-Temperature Molten Meta-Material Based Selective Thermophotovoltaic Emitter”. Yu Pei, Li Chen, Jie Hu, Renkun Chen, and Zhaowei Liu. The dissertation author was the primary researcher and author of this material.

REFERENCES

1. Feng, T.; Pati, B.; Chung, K. M.; Pei, Y.; Chen, R., Ceramic-to-metal bonding using rare-earth containing Sn–Bi solder. *Journal of Materials Science: Materials in Electronics* **2024**, 35 (6), 369.
2. Pei, Y.; Zhong, H.; Wang, M.; Zhang, P.; Zhao, Y., Effect of contact pressure on the performance of carbon nanotube arrays thermal interface material. *Nanomaterials* **2018**, 8 (9), 732.
3. Zhong, H.; Pei, Y.; Hu, Z.; Zhang, P.; Guo, J.; Gong, X.; Zhao, Y., A study of the heat transfer properties of CIP doped magnetorheological elastomers. *Smart Materials and Structures* **2019**, 28 (2), 025027.
4. Zhang, Z.; Passlack, M.; Pitner, G.; Kuo, C.-H.; Ueda, S. T.; Huang, J.; Kashyap, H.; Wang, V.; Spiegelman, J.; Lam, K.-T., Sub-nanometer interfacial oxides on highly oriented pyrolytic graphite and carbon nanotubes enabled by lateral oxide growth. *ACS Applied Materials & Interfaces* **2022**, 14 (9), 11873-11882.
5. Schwab, K.; Henriksen, E. A.; Worlock, J. M.; Roukes, M. L., Measurement of the quantum of thermal conductance. *Nature* **2000**, 404 (6781), 974-977.
6. Jezouin, S.; Parmentier, F. D.; Anthore, A.; Gennser, U.; Cavanna, A.; Jin, Y.; Pierre, F., Quantum Limit of Heat Flow Across a Single Electronic Channel. *Science* **2013**, 342 (6158), 601-604.
7. Cui, L. J.; Jeong, W.; Hur, S.; Matt, M.; Klockner, J. C.; Pauly, F.; Nielaba, P.; Cuevas, J. C.; Meyhofer, E.; Reddy, P., Quantized thermal transport in single-atom junctions. *Science* **2017**, 355 (6330), 1192-1195.
8. Cui, L. J.; Hur, S.; Akbar, Z. A.; Klockner, J. C.; Jeong, W.; Pauly, F.; Jang, S. Y.; Reddy, P.; Meyhofer, E., Thermal conductance of single-molecule junctions. *Nature* **2019**, 572 (7771), 628-+.
9. Yang, L.; Tao, Y.; Zhu, Y. L.; Akter, M.; Wang, K.; Pan, Z. L.; Zhao, Y.; Zhang, Q.; Xu, Y. Q.; Chen, R. K.; Xu, T. T.; Chen, Y. F.; Mao, Z. Q.; Li, D. Y., Observation of superdiffusive phonon transport in aligned atomic chains. *Nature Nanotechnology* **2021**, 16 (7), 764-+.
10. Chang, C. W.; Okawa, D.; Majumdar, A.; Zettl, A., Solid-state thermal rectifier. *Science* **2006**, 314 (5802), 1121-1124.
11. Xu, X. F.; Pereira, L. F. C.; Wang, Y.; Wu, J.; Zhang, K. W.; Zhao, X. M.; Bae, S.; Bui, C. T.; Xie, R. G.; Thong, J. T. L.; Hong, B. H.; Loh, K. P.; Donadio, D.; Li, B. W.; Ozyilmaz, B., Length-dependent thermal conductivity in suspended single-layer graphene. *Nature Communications* **2014**, 5.
12. Chen, D. Z. A.; Narayanaswamy, A.; Chen, G., Surface phonon-polariton mediated thermal conductivity enhancement of amorphous thin films. *Physical Review B* **2005**, 72 (15).
13. Ordonez-Miranda, J.; Tranchant, L.; Kim, B.; Chalopin, Y.; Antoni, T.; Volz, S., Quantized Thermal Conductance of Nanowires at Room Temperature Due to Zenneck Surface-Phonon Polaritons. *Physical Review Letters* **2014**, 112 (5).
14. Kim, K.; Song, B.; Fernandez-Hurtado, V.; Lee, W.; Jeong, W. H.; Cui, L. J.; Thompson, D.; Feist, J.; Reid, M. T. H.; Garcia-Vidal, F. J.; Cuevas, J. C.; Meyhofer, E.; Reddy, P., Radiative heat transfer in the extreme near field. *Nature* **2015**, 528 (7582), 387-391.

15. Thompson, D.; Zhu, L. X.; Mittapally, R.; Sadat, S.; Xing, Z.; McArdle, P.; Qazilbash, M. M.; Reddy, P.; Meyhofer, E., Hundred-fold enhancement in far-field radiative heat transfer over the blackbody limit. *Nature* **2018**, *561* (7722), 216-+.
16. Shen, S.; Narayanaswamy, A.; Chen, G., Surface Phonon Polaritons Mediated Energy Transfer between Nanoscale Gaps. *Nano Letters* **2009**, *9* (8), 2909-2913.
17. Wu, Y.; Ordonez-Miranda, J.; Gluchko, S.; Anufriev, R.; Meneses, D. D.; Del Campo, L.; Volz, S.; Nomura, M., Enhanced thermal conduction by surface phonon-polaritons. *Science Advances* **2020**, *6* (40).
18. Wu, Y.; Ordonez-Miranda, J.; Jalabert, L.; Tachikawa, S.; Anufriev, R.; Fujita, H.; Volz, S.; Nomura, M., Observation of heat transport mediated by the propagation distance of surface phonon-polaritons over hundreds of micrometers. *Applied Physics Letters* **2022**, *121* (11).
19. Chang, D. E.; Sorensen, A. S.; Hemmer, P. R.; Lukin, M. D., Strong coupling of single emitters to surface plasmons. *Physical Review B* **2007**, *76* (3).
20. Gluchko, S.; Palpant, B.; Volz, S.; Braive, R.; Antoni, T., Thermal excitation of broadband and long-range surface waves on SiO₂ submicron films. *Applied Physics Letters* **2017**, *110* (26).
21. Landauer, R., Spatial Variation of Currents and Fields Due to Localized Scatterers in Metallic Conduction. *Ibm J Res Dev* **1957**, *1* (3), 223-231.
22. Tranchant, L.; Hamamura, S.; Ordonez-Miranda, J.; Yabuki, T.; Vega-Flick, A.; Cervantes-Alvarez, F.; Alvarado-Gil, J. J.; Volz, S.; Miyazaki, K., Two-dimensional phonon polariton heat transport. *Nano letters* **2019**, *19* (10), 6924-6930.
23. Ordonez-Miranda, J.; Tranchant, L.; Chalopin, Y.; Antoni, T.; Volz, S., Thermal conductivity of nano-layered systems due to surface phonon-polaritons. *Journal of Applied Physics* **2014**, *115* (5).
24. Rakic, A. D.; Djuricic, A. B.; Elazar, J. M.; Majewski, M. L., Optical properties of metallic films for vertical-cavity optoelectronic devices. *Applied Optics* **1998**, *37* (22), 5271-5283.
25. Querry, M. R. *Optical constants*; Missouri Univ-Kansas City: 1985.
26. Zheng, J. L.; Wingert, M. C.; Dechaumphai, E.; Chen, R. K., Sub-picowatt/kelvin resistive thermometry for probing nanoscale thermal transport. *Review of Scientific Instruments* **2013**, *84* (11).
27. Shin, S.; Chen, R., Plasmonically enhanced thermal radiation by means of surface phonon polaritons. *Physical Review Applied* **2020**, *14* (6), 064013.
28. Zheng, J.; Wingert, M. C.; Moon, J.; Chen, R., Simultaneous specific heat and thermal conductivity measurement of individual nanostructures. *Semiconductor Science and Technology* **2016**, *31* (8), 084005.
29. Yariv, A., Coupled-mode theory for guided-wave optics. *IEEE Journal of Quantum Electronics* **1973**, *9* (9), 919-933.
30. Okamoto, K., *Fundamentals of optical waveguides*. Elsevier: 2021.
31. Knox, R.; Toullos, P. In *Integrated circuits for the millimeter through optical frequency range*, Proc. Symp. Submillimeter Waves, Brooklyn, NY: 1970; pp 497-515.
32. Martinez, A. I.; Garcia-Lobato, M. A.; Perry, D. L., Study of the Properties of Iron Oxide Nanostructures. *Nanotechnol Sci Tech* **2009**, 183-194.

33. Saritaş, S.; Turgut, E.; Kundakci, M.; Gürbulak, B.; Yildirim, M., Compared with α -Fe₂O₃ and ZnXFe₃-XO₄ thin films grown by Chemical Spray Pyrolysis. *Int J Sens Netw Data Commun* **2017**, 6 (152), 2.
34. Wingert, M. C.; Chen, Z. C.; Kwon, S.; Xiang, J.; Chen, R., Ultra-sensitive thermal conductance measurement of one-dimensional nanostructures enhanced by differential bridge. *Review of Scientific Instruments* **2012**, 83 (2).
35. Shin, S. M.; Elzouka, M.; Prasher, R.; Chen, R. K., Far-field coherent thermal emission from polaritonic resonance in individual anisotropic nanoribbons. *Nature Communications* **2019**, 10.
36. Cahill, D. G., Thermal-Conductivity Measurement from 30-K to 750-K - the 3-Omega Method. *Review of Scientific Instruments* **1990**, 61 (2), 802-808.
37. Wingert, M. C.; Chen, Z. C.; Dechaumphai, E.; Moon, J.; Kim, J.-H.; Xiang, J.; Chen, R., Thermal conductivity of Ge and Ge-Si core-shell nanowires in the phonon confinement regime. *Nano letters* **2011**, 11 (12), 5507-5513.
38. Bergman, T. L.; Lavine, A. S.; Incropera, F. P.; DeWitt, D. P., *Introduction to heat transfer*. John Wiley & Sons: 2011.
39. Kwon, S.; Zheng, J. L.; Wingert, M. C.; Cui, S.; Chen, R. K., Unusually High and Anisotropic Thermal Conductivity in Amorphous Silicon Nanostructures. *Acs Nano* **2017**, 11 (3), 2470-2476.
40. Larkin, J. M.; McGaughey, A. J., Thermal conductivity accumulation in amorphous silica and amorphous silicon. *Physical Review B* **2014**, 89 (14), 144303.
41. Henry, A. S.; Chen, G., Spectral phonon transport properties of silicon based on molecular dynamics Simulations and lattice dynamics. *Journal of Computational and Theoretical Nanoscience* **2008**, 5 (2), 141-152.
42. Regner, K. T.; Sellan, D. P.; Su, Z.; Amon, C. H.; McGaughey, A. J.; Malen, J. A., Broadband phonon mean free path contributions to thermal conductivity measured using frequency domain thermoreflectance. *Nature communications* **2013**, 4 (1), 1640.
43. Yang, F.; Dames, C., Mean free path spectra as a tool to understand thermal conductivity in bulk and nanostructures. *Physical Review B* **2013**, 87 (3), 035437.
44. Guo, Y. Y.; Tachikawa, S.; Volz, S.; Nomura, M.; Ordonez-Miranda, J., Quantum of thermal conductance of nanofilms due to surface-phonon polaritons. *Physical Review B* **2021**, 104 (20).
45. Ferrari, L.; Wu, C. H.; Lepage, D.; Zhang, X.; Liu, Z. W., Hyperbolic metamaterials and their applications. *Prog Quant Electron* **2015**, 40, 1-40.
46. Pei, Y.; Chen, L.; Jeon, W.; Liu, Z.; Chen, R., Low-dimensional heat conduction in surface phonon polariton waveguide. *Nature Communications* **2023**, 14 (1), 8242.
47. Zhang, W.; Wang, B.; Zhao, C., Selective thermophotovoltaic emitter with aperiodic multilayer structures designed by machine learning. *ACS Applied Energy Materials* **2021**, 4 (2), 2004-2013.
48. Chirumamilla, M.; Krishnamurthy, G. V.; Knopp, K.; Krekeler, T.; Graf, M.; Jalas, D.; Ritter, M.; Störmer, M.; Petrov, A. Y.; Eich, M., Metamaterial emitter for thermophotovoltaics stable up to 1400 C. *Scientific reports* **2019**, 9 (1), 7241.
49. Kim, J. H.; Jung, S. M.; Shin, M. W., Thermal degradation of refractory layered metamaterial for thermophotovoltaic emitter under high vacuum condition. *Optics express* **2019**, 27 (3), 3039-3054.

50. Suemitsu, M.; Asano, T.; Inoue, T.; Noda, S., High-efficiency thermophotovoltaic system that employs an emitter based on a silicon rod-type photonic crystal. *ACS Photonics* **2019**, *7* (1), 80-87.
51. Cui, K.; Lemaire, P.; Zhao, H.; Savas, T.; Parsons, G.; Hart, A. J., Tungsten–carbon nanotube composite photonic crystals as thermally stable spectral-selective absorbers and emitters for thermophotovoltaics. *Advanced Energy Materials* **2018**, *8* (27), 1801471.
52. Arpin, K. A., *Three-dimensional metallic architectures for photonic and energy storage applications*. University of Illinois at Urbana-Champaign: 2012.
53. Pitner, G.; Safron, N.; Chao, T.-A.; Li, S.; Su, S.-K.; Zeevi, G.; Lin, Q.; Chiu, H.-Y.; Passlack, M.; Zhang, Z. In *Building high performance transistors on carbon nanotube channel*, 2023 IEEE Symposium on VLSI Technology and Circuits (VLSI Technology and Circuits), IEEE: 2023; pp 1-2.
54. Li, S.; Chao, T.-A.; Gilardi, C.; Safron, N.; Su, S.-K.; Zeevi, G.; Bechdolt, A. D.; Passlack, M.; Oberoi, A.; Lin, Q. In *High-performance and low parasitic capacitance CNT MOSFET: 1.2 mA/ μm at V_{DS} of 0.75 V by self-aligned doping in sub-20 nm spacer*, 2023 International Electron Devices Meeting (IEDM), IEEE: 2023; pp 1-4.
55. Woolf, D. N.; Kadlec, E. A.; Bethke, D.; Grine, A. D.; Nogan, J. J.; Cederberg, J. G.; Burckel, D. B.; Luk, T. S.; Shaner, E. A.; Hensley, J. M., High-efficiency thermophotovoltaic energy conversion enabled by a metamaterial selective emitter. *Optica* **2018**, *5* (2), 213-218.
56. Chang, C.-C.; Kort-Kamp, W. J.; Nogan, J.; Luk, T. S.; Azad, A. K.; Taylor, A. J.; Dalvit, D. A.; Sykora, M.; Chen, H.-T., High-temperature refractory metasurfaces for solar thermophotovoltaic energy harvesting. *Nano letters* **2018**, *18* (12), 7665-7673.
57. Li, W.; Guler, U.; Kinsey, N.; Naik, G. V.; Boltasseva, A.; Guan, J.; Shalae, V. M.; Kildishev, A. V., Refractory plasmonics with titanium nitride: broadband metamaterial absorber. *Adv. Mater* **2014**, *26* (47), 7959-7965.
58. Woolf, D.; Hensley, J.; Cederberg, J.; Bethke, D.; Grine, A.; Shaner, E., Heterogeneous metasurface for high temperature selective emission. *Applied Physics Letters* **2014**, *105* (8).
59. Niklaus, F.; Stemme, G.; Lu, J.-Q.; Gutmann, R., Adhesive wafer bonding. *Journal of applied physics* **2006**, *99* (3).
60. Li, W.; Liang, T.; Chen, Y.; Jia, P.; Xiong, J.; Hong, Y.; Lei, C.; Yao, Z.; Qi, L.; Liu, W., Interface characteristics of sapphire direct bonding for high-temperature applications. *Sensors* **2017**, *17* (9), 2080.