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Observation of heat transport mediated by the propagation distance of surface phonon-polaritons over hundreds micrometers

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Efficient heat dissipation in micro/nano electronics requires long-distance propagation of heat carriers operated above room temperature. However, thermal phonons—the primary heat carriers in dielectric nanomaterials—dissipate the thermal energy after just a few hundred nanometers. Theory predicts that the mean free path of surface phonon-polaritons (SPhPs) can be hundreds of micrometers, which may improve the overall dissipation of heat in nanomaterials. In this work, we experimentally demonstrate such long-distance heat transport by SPhPs. Using the 3ω technique, we measure the in-plane thermal conductivity of SiN nanomembranes for different heater-sensor distances, membrane thicknesses, and temperatures. We find that thin nanomembranes support heat transport by SPhPs, as evidenced by an increase in the thermal conductivity with temperature. Remarkably, the thermal conductivity measured 200 μm away from the heater is consistently higher than that measured 100 μm closer. This result suggests that heat conduction by SPhPs quasi-ballistically over at least hundreds of micrometers. Our findings pave the way for coherent heat manipulations above room temperature over macroscopic distances, which impacts the applications in thermal management and polaritonics.

Heat conduction in semiconductors is essentially governed by the mean free path of heat carriers. In nanomaterials of the size comparable to the mean free path, heat conduction can even happen ballistically^{1–3}, without dissipation of thermal energy, which could be used for cooling in microelectronics⁴. However, even in silicon membranes, the mean free path of phonons at room temperature is as short as 30 – 300 nm^{5, 6}, which only becomes shorter at higher temperatures⁷. Such a short propagation length makes it unfeasible to attain the ballistic regime in the micro-sized dielectric materials used in modern electronics. Therefore, heat carriers with a longer propagation length are desirable.

Over the past two decades, the propagation, detection, and energy transport of surface electromagnetic waves has attracted attention due to the predominance of surface effects over the volumetric ones in nanostructures with high surface-to-volume ratio⁸. Certain types of surface electromagnetic waves may even carry heat^{9–12} and thus improve the thermal performance and stability of nanoscale devices^{13–15}. One type of such waves is the surface phonon-polaritons (SPhPs)—evanescent surface waves generated by the coupling of photons with optical phonons^{16–21}. SPhPs can be excited with a monochromatic light source with given frequency, which correspond to the SPhP resonant frequency. It is reported that the SPhPs generated on SiC is excited and detected optically by using scattering-type near field optical microscopy (s-SNOM)²². Theoretical works predict that SPhPs can propagate along the surface of polar dielectric materials without dissipation for hundreds of micrometers^{23, 24}, which is orders of magnitude longer than the typical mean free path of phonons. Moreover, recent experiments demonstrated that in thin dielectric membranes, SPhPs can even carry heat at least as effi-

ciently as phonons^{25, 26}. However, the quasi-ballistically conduction remains to be experimentally demonstrated.

In this work, we aim to demonstrate that the heat transport via SPhPs depend on propagation distance over hundreds of micrometers. Our experiments compare the thermal conductivity of SiN membranes measured 100 and 200 μm away from the heater. The SPhPs in SiN film is expected to exist in the frequency range between 125 to 225 Trad/s^{25} . The intrinsic propagation length of SPhP depends on the sample's thickness and their spectra are shown in supplementary. The propagation length scales down as the thickness increase. Assuming that phonon transport in amorphous membranes is purely diffusive at these length scales²⁷, any difference in the measured thermal conductivity can only be explained by the presence of additional heat conduction channels. Thus, by conducting the measurements for different heater-sensor distances, membrane thicknesses, and temperatures, we demonstrate how heat conduction by SPhPs occurs in thin membranes and remains quasi-ballistic for hundreds of micrometers.

Samples of amorphous SiN membranes with thicknesses of 50, 100, and 200 nm were suspended in a $1 \times 1 \text{ mm}^2$ square windows on Si substrates, while thickness of 30 nm was suspended in a $0.5 \times 0.5 \text{ mm}^2$ square windows. The SiN membranes are commercially available from the NORCADA company and were suspended by back etching the silicon substrate. These high-stress ($\approx 250 \text{ MPa}$) membranes were flat (curvature radius of 4 m) to ensure an ideal measurement for the long-range SPhP propagation. Gold wires of 4 μm in width and 100 nm in height, serving the heater and the sensors. A layer of 10-nm-thick Cr was deposited between Au and SiN to enhance the adhesion.

To measure the in-plane thermal conductivity of SiN membranes, we used the 3ω method^{28, 29}. Figure 1(a) illustrates the 3ω setup with four probes coupled to a heating stage and placed in a vacuum chamber. To probe the thermal conductivity at different propagation distances, two sensor wires were

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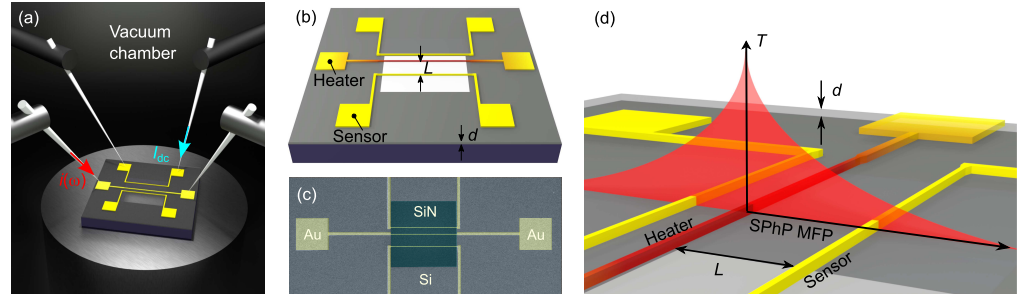


FIG. 1. Schemes of the 3ω experimental setup and the SiN sample. (a) Illustration of the SiN sample in a vacuum chamber. The sample is measured with an improved 3ω setup. AC input current $i(\omega)$ is supplied to the central heater wire to generate a heat ux by Joule heating. On the sensor located at a distance L (100 m, 200 m), the temperature raise is calculated from the 2ω signal measured with a lock-in amplifier on a DC Wheatstone bridge. (b) Schematic of a suspended SiN sample, where L is the distance between heater and sensor, and d is the thickness of suspended SiN. (c) Scanning electron microscope show top view of the SiN sample. The yellow color highlights the Au wires and the green color highlights the suspended SiN. (d) Illustration of a SiN membrane supporting the heater-to-sensor propagation of SPhPs excited by the Joule effect in the heater wire.

placed 100 and 200 m away from the heater wire, as shown in Figs. 1B-C. Although the SPhPs have intrinsic propagation length up to 1 m^{17} , in our designed measurement, the propagation of the SPhPs is truncated by the sensor, where they thermalize with phonons and raises the temperature detected by the sensor³⁰. Figure 1(d) illustrates how SPhPs are excited by the Joule effect in the heater wire. The in-plane thermal conductivity was extracted by comparing the 3ω signal with an analytical model (Supporting Information "Heat diffusion model"). Thermal radiation losses were taken into account as explained in Supporting Information "Heat diffusion model".

Figure 2(a) reports the temperature dependence of in-plane thermal conductivity of SiN membranes of different thickness. The data measured for the heater-sensor distances of 100 and 200 m are joined by the dashed and solid lines and labelled as κ_{100} and κ_{200} , respectively. Longer heater-sensor distance beyond 200 m were probed yielding at too low signal-to-noise ratio and unworkable data. The thickest membrane ($d = 200\text{ nm}$) at 300 K has $\kappa_{100} \approx \kappa_{200} \approx 3.1\text{ Wm}^{-1}\text{K}^{-1}$, which decreases by about 4% at 400 K. This reduction above room temperature is characteristic of the phonon thermal conductivity driven by the internal scattering processes of phonons. Although the thermal conductivity of 200-nm-thick membranes also shows a difference between $L=100$ and $200\text{ }\mu\text{m}$, this difference is statistically insignificant and lays within experimental uncertainty. Likewise, the thermal conductivity of the 100-nm-thick membrane is nearly independent of the heater-sensor distance and temperature. The independence of the heater-sensor distance also indicates that the thermal transport is mainly driven by the phonons and thus is diffusive at this scale, as predicted by the theory¹⁷. Mean free paths of phonons in SiN are short but still extend to the 100 nm range²⁷ and are larger than the thicknesses of the thinner SiN membranes. Consequently, the phonon mean free path is limited by boundary scattering, leading thermal conductivity to

decrease as the membrane thickness reduces.

Interestingly, the thermal conductivity of the two thinner membranes (30 and 50 nm) shows a 5% increase with temperature (shown in Fig. 2(b)), which differs from that of the thicker ones. For the 50-nm-thick membrane, κ_{100} (κ_{200}) increases from $2.1\text{ Wm}^{-1}\text{K}^{-1}$ ($2.2\text{ Wm}^{-1}\text{K}^{-1}$) at 300 K to $2.24\text{ Wm}^{-1}\text{K}^{-1}$ ($2.29\text{ Wm}^{-1}\text{K}^{-1}$) at 400 K. For the 30-nm-thick membrane, this enhancement raises to 6.6% and 12.4% for the thermal conductivity values κ_{100} and κ_{200} . The observed increase in the thermal conductivity with temperature is the sign of the heat conduction by SPhPs. As SPhP contribution becomes stronger at higher temperatures, it compensates for the thermal conductivity reduction due to the phonon-phonon scattering, thus leading to the overall increase of the thermal conductivity with temperature. This explains the difference in trends for thicker and thinner membranes.

Remarkably, the thermal conductivity measured 200 m away from the heater is higher than that measured 100 μm away ($\kappa_{200} > \kappa_{100}$). Since the phonon transport is diffusive at such a long length scale²⁷, we attribute the observed difference in the thermal conductivity to the ballistic heat conduction by SPhPs. Indeed, length-dependent thermal conductivity is one of the signs of ballistic heat conduction^{1,3,31,32} and implies that heat carriers propagate ballistically at least as far as the length dependence is measured.

Figure 2(a) seems to indicate a similar difference between κ_{100} and κ_{200} in the 30 nm and 50 nm cases only because the thermal conductivities of the 50 nm membrane are higher. A clearer perspective is indeed provided when the thermal conductivity ratio $\kappa_{200}/\kappa_{100}$ is plotted (Supporting Information Fig. S9), where the error bars for this ratio include the unity in the case of the 50 nm thick film. A difference due to heater-sensor distance therefore can not be strictly concluded. Conversely, the lowest value of the error bars clearly increases beyond unity in the 30 nm case. Hence, the difference be-

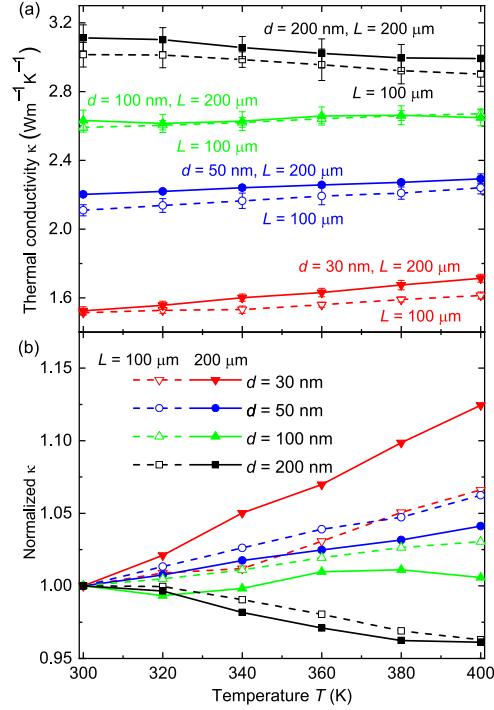


FIG. 2. Thermal conductivity of SiN membranes. (a) Thermal conductivity as a function of temperature for membranes of different thickness. The solid and dashed lines stand for the measurements performed with the sensors placed 100 and 200 m away from the heater, respectively. (b) In-plane thermal conductivity normalized by the values at 300 K.

tween κ_{100} and κ_{200} can only be corroborated in the 30 nm thick membrane, which indicates the ballistic SPhP transport occurs in this case.

To better understand the behaviour of the measured thermal conductivity, we analyze the SPhP contribution to the heat transport in SiN membranes. According to the Boltzmann transport equation, under the relaxation time approximation, the SPhP contribution to the in-plane thermal conductivity (κ_{SPhP}) of a membrane of thickness d is given by¹⁶:

$$\kappa_{\text{SPhP}} = \frac{1}{4\pi d} \int_{\omega_L}^{\omega_H} \hbar \omega \Lambda_e \beta_R \frac{\partial f_0}{\partial T} d\omega, \quad (1)$$

where \hbar is the reduced Planck constant, Λ_e is the effective propagation length of SPhPs propagating along the membrane surface with a complex wavevector β , $\beta_R = \text{Re}(\beta)$, f_0 is the Bose-Einstein distribution function, T is the average membrane temperature, and ω_H and ω_L stand for the highest and

lowest frequencies supporting the propagation of SPhPs, respectively. Since heat generated by SPhPs inside a material is proportional to the imaginary part of its dielectric function¹², this material property is strongly linked to these frequencies and hence to κ_{SPhP} .

To take into account finite lateral size of our SiN membranes, their effective thermal conductivity is determined using Matthiessen's rule $\Lambda_e^{-1} = \Lambda^{-1} + L^{-1}$, where Λ is the intrinsic propagation length of polaritons, and L is the heater-sensor distance (100 and 200 m). Thus, the values of L are much shorter than those of Λ and much longer than the intrinsic mean free path of phonons in amorphous materials^{33,34} around room temperature. Equation 1 thus establishes that the values of κ_{SPhP} are determined by the SPhP dispersion relation $\beta(\omega)$ driven by the membrane dielectric function that usually changes with temperature and membrane thickness³⁵. However, for the thicknesses and temperatures considered in this work, the dielectric function of our SiN membranes is nearly independent of these parameters²⁵.

Figure 3 shows the SPhP thermal conductivity predicted by Eq. 1 for different temperatures, heater-sensor distances, and membrane thicknesses. Thinner and hotter membranes with longer heater-sensor distances exhibit higher SPhP thermal conductivity. This behaviour is expected as reported for SiO₂ and SiC membranes^{16,17} and opposite to the typical behaviour of the phonon thermal conductivity. Thus, it signals the SPhP contribution to the heat transport along the membranes.

For the thinnest membrane ($d = 30$ nm), the measured thermal conductivity enhancement $\Delta\kappa_{\text{SPhP}} = \kappa(T) - \kappa(300\text{K})$ is compared with prediction of the model when heater-sensor distance is 200 m (Fig. 3(a)). However, in thicker membranes ($d > 30$ nm), the phonons make a significant contribution to heat conduction, and the discrepancy between measured (phonons and SPhPs) and theoretical (only SPhPs) values increases with membrane thickness. Remarkably, Fig. 3(b) shows that theoretically, SPhPs can travel ballistically as far as one meter, and the values measured on the 30-nm-thick membrane follow the predicted trend. Since the thermal conductivity enhancement is driven by the SPhPs propagation, which is long (> 1 cm) in polar materials, the observed length dependence for SiN films, is also expected to be present for other polar films, such as SiC and SiO₂³⁶.

In conclusion, we experimentally demonstrated long-distance heat conduction by SPhPs. We measured the in-plane thermal conductivity of SiN membranes and showed that in thin membranes, the heat conduction is mainly driven by SPhPs. Moreover, the measured thermal conductivity was higher when measured further away from the heater. The observed difference in the thermal conductivity is attributed to ballistic heat conduction by SPhPs and is compared with our theoretical model. Thus, our experimental results suggest that the SPhPs can carry heat ballistically over hundreds of micrometers, whereas our model predicts that it is far from the limit. Considering that the coherence length is comparable to the propagation length¹⁹, new engineering possibilities might become available using interference of SPhPs. This work offers alternative approach to improve the heat dissipation in microelectronics and efficiency in silicon photonics.

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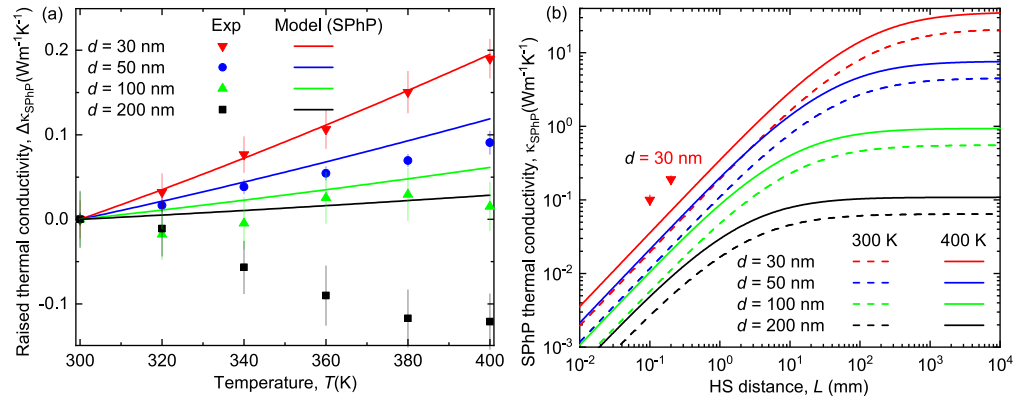


FIG. 3. Theoretical SPhP thermal conductivity is compared with the experimental values. (a) Enhanced SPhP thermal conductivity as a function of temperature, when sensor is 200 m away from heater. (b) Theoretical SPhP thermal conductivity as a function of the heater-sensor distance for four SiN membrane thicknesses at 300 and 400 K. The experimental result of 30-nm-thick membrane (red solid triangles) is compared to theoretical values.

I. SUPPLEMENTARY MATERIAL

Supplementary material to the paper provides the detailed information about the theoretical background, the analysis of the experimental results, and the auxiliary measurements. Further discussion is welcomed by contacting our corresponding authors.

II. ACKNOWLEDGEMENT

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- ¹L. Yang, Y. Tao, Y. Zhu, M. Akter, K. Wang, Z. Pan, Y. Zhao, Q. Zhang, Y.-Q. Xu, R. Chen, *et al.*, "Observation of superdiffusive phonon transport in aligned atomic chains," *Nature nanotechnology* **16**, 764–768 (2021).
- ²R. Anufriev, S. Gluchko, S. Volz, and M. Nomura, "Quasi-Ballistic Heat Conduction due to Lévy Phonon Flights in Silicon Nanowires," *ACS Nano* **12**, 11928–11935 (2018).
- ³D. Vakulov, S. Gireesan, M. Y. Swinkels, R. Chavez, T. Vogelaar, P. Torres, A. Campo, M. De Luca, M. A. Verheijen, S. Koelling, L. Gagliano, J. E. M. Haverkort, F. X. Alvarez, P. A. Bobbert, I. Zardo, and E. P. A. M. Bakkers, "Ballistic phonons in ultrathin nanowires," *Nano Letters* **20**, 2703 (2020).
- ⁴E. Pop, "Energy dissipation and transport in nanoscale devices," *Nano Research* **3**, 147–169 (2010).
- ⁵R. Anufriev, J. Ordonez-Miranda, and M. Nomura, "Measurement of the phonon mean free path spectrum in silicon membranes at different temperatures using arrays of nanoslits," *Phys. Rev. B* **101**, 115301 (2020).
- ⁶A. Malhotra and M. Maldovan, "Surface scattering controlled heat conduction in semiconductor thin films," *Journal of Applied Physics* **120**, 204305 (2016).
- ⁷K. T. Regner, D. P. Sellan, Z. Su, C. H. Amon, A. J. McGaughey, and J. A. Malen, "Broadband phonon mean free path contributions to thermal conductivity measured using frequency domain thermoreflectance," *Nature Communications* **4**, 1640 (2013).

- ⁸D. Thompson, L. Zhu, R. Mittapally, S. Sadat, Z. Xing, P. McArdle, M. M. Qazilbash, P. Reddy, and E. Meyhofer, "Hundred-fold enhancement in far-field radiative heat transfer over the blackbody limit," *Nature* **561**, 216–221 (2018).
- ⁹K. Joulain, J.-P. Mulet, F. Marquier, R. Carminati, and J.-J. Greffet, "Surface electromagnetic waves thermally excited: Radiative heat transfer, coherence properties and Casimir forces revisited in the near field," *Surface Science Reports* **57**, 59–112 (2005).
- ¹⁰D.-Z. A. Chen and G. Chen, "Measurement of silicon dioxide surface phonon-polariton propagation length by attenuated total reflection," *Applied Physics Letters* **91**, 121906 (2007).
- ¹¹D.-Z. A. Chen and G. Chen, "Heat flow in thin films via surface phonon-polaritons," *Frontiers in Heat and Mass Transfer (FHMT)* **1.2** (2010).
- ¹²G. Baffou, C. Girard, and R. Quidant, "Mapping Heat Origin in Plasmonic Structures," *Physical Review Letters* **104**, 136805 (2010).
- ¹³J.-P. Mulet, K. Joulain, R. Carminati, and J.-J. Greffet, "Nanoscale radiative heat transfer between a small particle and a plane surface," *Applied Physics Letters* **78**, 2931–2933 (2001).
- ¹⁴V. Dusastre and L. Martiradonna, "Materials for sustainable energy," *Nature Materials* **16**, 15 (2017).
- ¹⁵K. Biswas, J. He, I. D. Blum, C.-I. Wu, T. P. Hogan, D. N. Seidman, V. P. Dravid, and M. G. Kanatzidis, "High-performance bulk thermoelectrics with all-scale hierarchical architectures," *Nature* **489**, 414–418 (2012).
- ¹⁶D.-Z. A. Chen, A. Narayanaswamy, and G. Chen, "Surface phonon-polariton mediated thermal conductivity enhancement of amorphous thin films," *Physical Review B* **72**, 155435 (2005).
- ¹⁷J. Ordonez-Miranda, L. Tranchant, T. Tokunaga, B. Kim, B. Palpant, Y. Chalopin, T. Antoni, and S. Volz, "Anomalous thermal conductivity by surface phonon-polaritons of polar nano thin films due to their asymmetric surrounding media," *Journal of Applied Physics* **113**, 084311 (2013).
- ¹⁸X. Lin, Y. Yang, N. Rivera, J. J. López, Y. Shen, I. Kaminer, H. Chen, B. Zhang, J. D. Joannopoulos, and M. Soljačić, "All-angle negative refraction of highly squeezed plasmon and phonon polaritons in graphene–boron nitride heterostructures," *Proceedings of the National Academy of Sciences* **114**, 6717–6721 (2017).
- ¹⁹J.-J. Greffet, R. Carminati, K. Joulain, J.-P. Mulet, S. Mainguy, and Y. Chen, "Coherent emission of light by thermal sources," *Nature* **416**, 61–64 (2002).
- ²⁰M. Francoeur, M. P. Mengüç, and R. Vaillon, "Local density of electromagnetic states within a nanometric gap formed between two thin films supporting surface phonon polaritons," *Journal of Applied Physics* **107**, 034313 (2010).

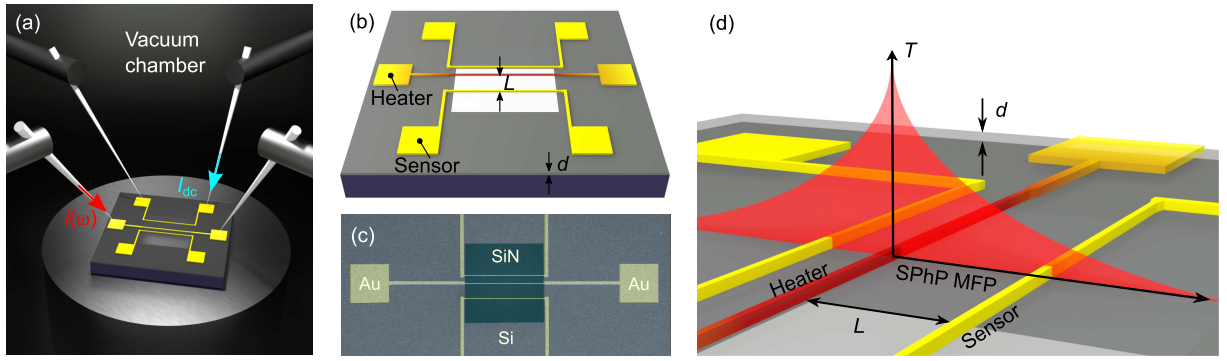
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- (2010).
- ²¹N. Rivera, G. Rosolen, J. D. Joannopoulos, I. Kaminer, and M. Soljačić, "Making two-photon processes dominate one-photon processes using mid-ir phonon polaritons," *Proceedings of the National Academy of Sciences* **114**, 13607–13612 (2017).
- ²²N. Oeclic and R. Hillenbrand, "Subwavelength-scale tailoring of surface phonon polaritons by focused ion-beam implantation," *Nature materials* **3**, 606–609 (2004).
- ²³J. Ordonez-Miranda, L. Tranchant, Y. Chalopin, T. Antoni, and S. Volz, "Thermal conductivity of nano-layered systems due to surface phonon-polaritons," *Journal of Applied Physics* **115**, 054311 (2014).
- ²⁴S. Tachikawa, J. Ordonez-Miranda, Y. Wu, L. Jalabert, R. Anufriev, S. Volz, and M. Nomura, "High surface phonon-polariton in-plane thermal conductance along coupled films," *Nanomaterials* **10** (2020), 10.3390/nano10071383.
- ²⁵Y. Wu, J. Ordonez-Miranda, S. Gluchko, R. Anufriev, D. D. S. Meneses, L. Del Campo, S. Volz, and M. Nomura, "Enhanced thermal conduction by surface phonon-polaritons," *Science Advances* **6**, eabb4461 (2020).
- ²⁶L. Tranchant, S. Hamamura, J. Ordonez-Miranda, T. Yabuki, A. Vega-Flick, F. Cervantes-Alvarez, J. J. Alvarado-Gil, S. Volz, and K. Miyazaki, "Two-Dimensional Phonon Polariton Heat Transport," *Nano Letters* **19**, 6924–6930 (2019).
- ²⁷N. Tambo, Y. Liao, C. Zhou, E. M. Ashley, K. Takahashi, P. F. Nealey, Y. Naito, and J. Shiomi, "Ultimate suppression of thermal transport in amorphous silicon nitride by phononic nanostructure," *Science Advances* **6**, eabc0075 (2020).
- ²⁸D. G. Cahill and R. O. Pohl, "Thermal conductivity of amorphous solids above the plateau," *Physical review B* **35**, 4067 (1987).
- ²⁹D. G. Cahill, "Thermal conductivity measurement from 30 to 750 k: the 3 ω method," *Review of scientific instruments* **61**, 802–808 (1990).
- ³⁰Y. Guo, S. Tachikawa, S. Volz, M. Nomura, and J. Ordonez-Miranda, "Quantum of thermal conductance of nanofilms due to surface-phonon polaritons," *Phys. Rev. B* **104**, L201407 (2021).
- ³¹R. Anufriev, S. Gluchko, S. Volz, and M. Nomura, "Probing ballistic thermal conduction in segmented silicon nanowires," *Nanoscale* **11**, 13407–13414 (2019).
- ³²Q. Zhang, C. Liu, X. Liu, J. Liu, Z. Cui, Y. Zhang, L. Yang, Y. Zhao, T. T. Xu, Y. Chen, *et al.*, "Thermal transport in quasi-1D van der waals crystal Ta₂Pd₃Se₈ nanowires: size and length dependence," *ACS nano* **12**, 2634–2642 (2018).
- ³³Y. Pan, J. Zhou, and G. Chen, "Quantifying thermal transport in amorphous silicon using mean free path spectroscopy," *Physical Review B* **101**, 144203 (2020).
- ³⁴M. C. Wingert, J. Zheng, S. Kwon, and R. Chen, "Thermal transport in amorphous materials: a review," *Semiconductor Science and Technology* **31**, 113003 (2016).
- ³⁵K. Joulain, Y. Ezzahri, J. Drevillon, B. Rousseau, and D. D. S. Meneses, "Radiative thermal rectification between SiC and SiO₂," *Optics Express* **23**, A1388–A1397 (2015).
- ³⁶J. Ordonez-Miranda, S. Volz, and M. Nomura, "Surface phonon-polariton heat capacity of polar nanofilms," *Phys. Rev. Applied* **15**, 054068 (2021).
- ³⁷J. B. Lee, K. Kang, and S. H. Lee, "Comparison of theoretical models of electron-phonon coupling in thin gold films irradiated by femtosecond pulse lasers," *Materials Transactions* **52**, 547–553 (2011).

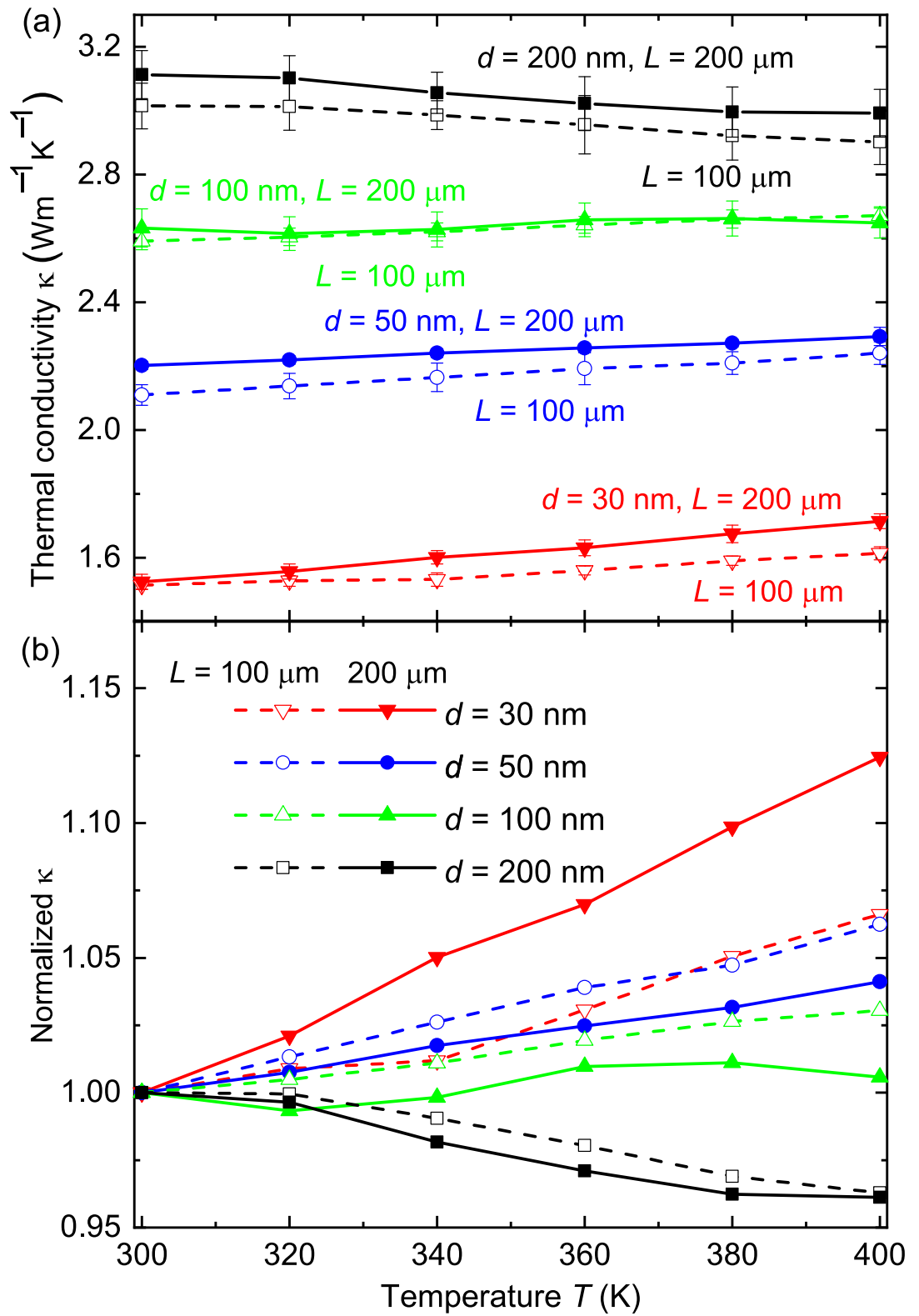
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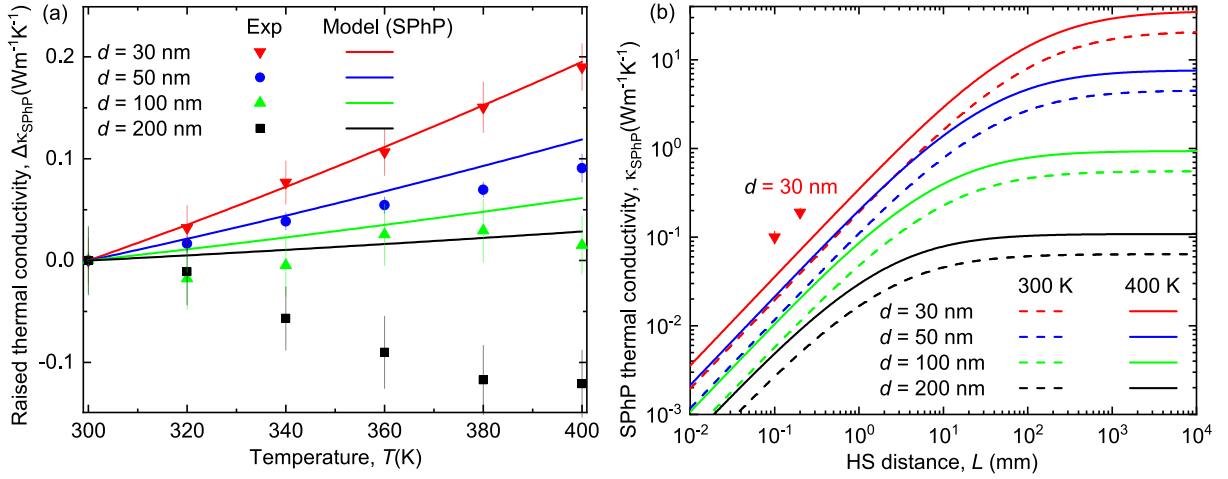
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