

A cryogenic near-field thermal diode leveraging superconducting phase transitions

Received: 14 September 2025

Accepted: 8 December 2025

Published online: 14 January 2026

 Check for updates

Yuxuan Luan^{1,4}, Shen Yan^{1,4}, Jian Guan¹, Ayan Majumder¹, Yuji Isshiki¹, Zhongyong Wang¹, Ratul Mali¹, Renwen Yu², Shanhui Fan²✉, Edgar Meyhofer¹✉ & Pramod Reddy^{1,3}✉

Control of charge and heat transport is essential for computing and thermal management technologies. Recent work with superconducting materials has shown rectified electrical supercurrents near liquid helium temperatures. However, despite large theoretical interest and expected impact on quantum technologies, no experiments have demonstrated control of nanoscale radiative heat currents at cryogenic temperatures. Here we study photon-mediated thermal transport in nanogaps between niobium and gold. Using novel scanning calorimetric probes and nanofabricated devices, we reveal a ~20-fold suppression of radiative heat transport, when niobium transitions from the metallic to the superconducting state. Taking advantage of this effect, we also demonstrate a niobium-based cryogenic thermal diode with a heat rectification ratio of 70%. The experimental techniques and advances presented here will enable studying nanoscale thermal transport in quantum materials and advancing thermal management of superconducting devices.

Rectifying the flow of charge and energy carriers (for example, electrons, phonons and photons) is critical for computing, communication, thermal management and energy conversion^{1–6}. Modern devices require sophisticated strategies to enable fast computation and communication, while reducing heat dissipation and energy loss. Recent work⁴ has sought to advance the control of charge flow using superconducting materials by developing novel superconducting diodes that enable rectification of electric supercurrents. Also, efforts^{7,8} have been made to use superconductors for controlling electronic heat currents. Over the past decade, theoretical works^{9–13} have proposed that, by leveraging superconducting phase transitions and certain nanoscale radiative heat transfer effects, it may be feasible to create thermal diodes capable of tuning radiative heat transport at superconducting transition temperatures.

In the past two decades, studies of nanoscale radiative heat transfer have identified how the far-field blackbody limit¹⁴ breaks

down when the gap size between two objects, or the characteristic size dimension of the objects, becomes comparable to or smaller than the characteristic thermal wavelength (λ_w)^{15–17}, as determined by Wien's law ($\lambda_w \times T = 2,898 \mu\text{m K}$, where T is the environmental temperature). For example, it has been shown that when the gap size between objects is smaller than λ_w , the radiative heat transfer rates at room temperature can exceed the far-field blackbody limit by several orders of magnitude^{18–28} and such enhancements can be used for energy conversion and thermal management^{29–37}. When the temperature decreases from room temperature to cryogenic temperatures (for example, 4 K), λ_w increases from ~10 μm to ~725 μm . Such an increase of characteristic thermal wavelength indicates that, for most modern cryogenic systems involving micro- and nanodevices (for example, solid-state cooling and quantum computing systems), radiative heat transfer is dominated by near-field effects. Moreover, the heat transfer power density is expected to be substantially enhanced when the gap size is

¹Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA. ²Department of Electrical Engineering, Ginzton Laboratory, Stanford University, Stanford, CA, USA. ³Department of Materials Science and Engineering, University of Michigan, Ann Arbor, MI, USA. ⁴These authors contributed equally: Yuxuan Luan, Shen Yan. ✉e-mail: shanhui@stanford.edu; meyhofer@umich.edu; pramodr@umich.edu

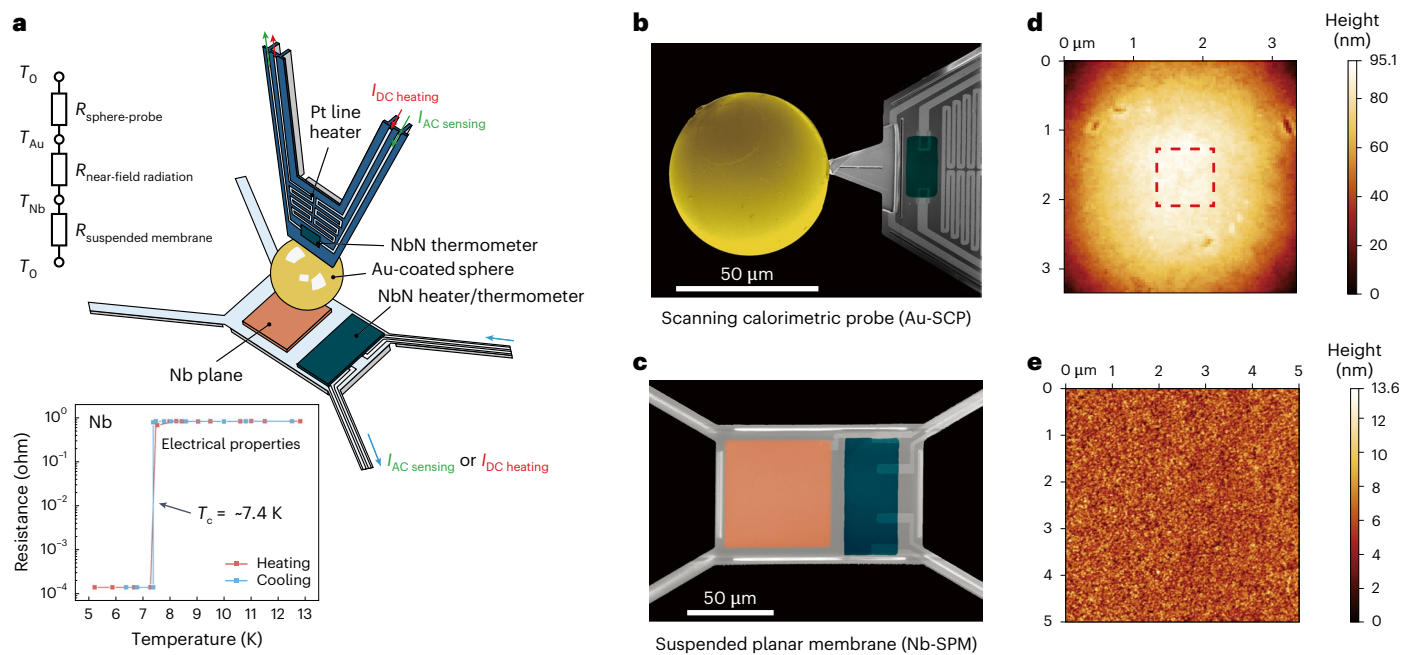


Fig. 1 | Experimental set-up and micro-fabricated devices. **a**, Schematic of the micro-fabricated devices for RHT measurements in nanoscale gaps at liquid helium temperatures. The top device (Au-SCP) is a sphere-probe that consists of two parts: (1) a SiN-based vertical cantilever integrated with a serpentine Pt line heater and a NbN thin film thermometer and (2) a SiO₂ sphere coated with 200 nm of Au that is attached onto the end of the cantilever. The bottom device (Nb-SPM) is a suspended 400-nm-thick SiN membrane coated with a 200-nm-thick Nb thin film and a separate NbN thin film, which serves as a thermometer and heater. The Au-SCP can be heated by applying a DC current to the Pt line heater and the temperature change of the Au-SCP is measured by applying an AC current to the NbN thermometer. For the Nb-SPM, the integrated NbN thin

film is used to either raise the device temperature or measure the temperature change by applying a DC or an AC current, respectively. The top inset of **a** shows a thermal resistance network representing all important thermal resistances, and the bottom inset shows the measured electrical resistance of the sputtered Nb thin film on the Nb-SPM. **b**, False-coloured SEM image of the Au-SCP. The sphere diameter is ~50 μm. **c**, False-coloured SEM image of the Nb-SPM. The NbN thin film thermometer/heater has four-lead connections. **d**, Surface roughness of the attached Au-coated SiO₂ sphere characterized by atomic force microscopy. **e**, Surface roughness of the sputtered Nb thin film measured by atomic force microscopy.

in the nanoscale. However, previous studies on radiative heat transfer near liquid helium temperatures^{38–42} have been limited to micrometre gap sizes owing to many experimental challenges.

Here we report the experimental observation of photon-mediated heat flows in nanoscale gaps between a normal (gold) and a superconducting (niobium) metal. To achieve this, we have developed an experimental set-up that combines a micro-fabricated calorimeter (a suspended membrane with a planar niobium (Nb) region) and scanning probes with an integrated gold (Au) sphere (Fig. 1a). The set-up enables picowatt-resolution thermal measurements at liquid helium temperatures. We find that when Nb transitions from a normal metal to a superconductor, the near-field radiative heat transfer (RHT) in nanoscale gaps between Nb and Au is suppressed. This suppression of photon-mediated thermal transport is quantitatively explained using fluctuational electrodynamics-based modelling^{43,44}. We thus demonstrate the capability of fluctuational electrodynamics to explore fluctuation physics in superconductors. In addition, we show that the superconducting transition of Nb enables highly rectifying thermal transport (rectification ratio (η) of ~70%, as defined in refs. 10,30,45)—the highest reported rectification for a photonic thermal diode.

Device characterization

To probe near-field RHT between a normal metal and a superconductor in nanoscale gaps, we chose Au and Nb as a prototypical system, as Nb features a relatively high superconducting transition temperature (bulk Nb has a superconducting transition temperature at ~9 K). To perform these studies, we fabricated two distinct devices (Methods). First, as illustrated in Fig. 1a, we micro-fabricated a scanning

calorimetric probe (SCP) featuring T-beams, a platinum (Pt) line heater and a niobium nitride (NbN) thin film thermometer. In addition, a silicon dioxide (SiO₂) sphere coated with Au was attached to the distal end of the probe (see Fig. 1b for a scanning electron microscopy (SEM) image and Fig. 1d for the measured surface roughness of the attached sphere). Next, we micro-fabricated a suspended planar membrane (SPM) device that was integrated with a Nb thin film and a NbN thin film thermometer/heater (see Fig. 1c for an SEM image and Fig. 1e for the measured surface roughness of the Nb plane). These two devices, referred to as Au-SCP and Nb-SPM, were designed to enable probing RHT in a sphere-plane configuration at nanometre gap sizes and liquid helium temperatures.

We note that, instead of using the widely used Pt thermometers, we developed NbN thermometers for achieving high-resolution (sub-nanowatt) thermal measurements at cryogenic temperatures. This change was essential as Pt features a poor temperature coefficient of resistance (TCR), which is <0.1 % K⁻¹ at liquid helium temperature, while NbN thin film⁴⁶ features orders of magnitude higher TCR (>1 % K⁻¹; Supplementary Section 2). Before beginning our experiments, we characterized the thermal conductance and the thermal response of the Au-SCP and Nb-SPM devices as described in detail in Methods and Supplementary Information. We also characterized the superconducting transition temperature of the deposited Nb thin film and found it to be ~7.4 K (Fig. 1a), a value smaller than that of bulk Nb. The observed suppression in the superconducting transition temperature is consistent with past work⁴⁷, which reported that the critical temperature of superconducting thin films becomes lower than that of bulk owing to the surface effects and sputtering conditions for thin film depositions (Supplementary Section 1).

Characterization of the dependence of photon-mediated thermal transport on the superconducting phase transition

To characterize the RHT between the Au sphere and the Nb plane at nanometre gaps, we started our experiments under a relatively high temperature differential between the two devices to ensure a heat flow via RHT, which was large enough to be measured (below, we will also discuss how measurements were made under small temperature differentials). Specifically, we performed an experiment where the temperatures of the ambient and the Au-SCP device were both held at 4.4 K, while the Nb-SPM device was heated to 22.8 K (Methods). To begin the experiment, we placed the distal end of the Au sphere at a separation of ~100 nm from the Nb plane (note that this relatively small gap was chosen because the travel range of the sphere was <200 nm, owing to the reduced piezo constant at these low temperatures). Subsequently, the gap size between the sphere and the plane was systematically reduced in steps of 5 nm while measuring the temperature rise of the Au-SCP probe (Methods and Supplementary Section 4). The measured temperature rise in conjunction with the known temperature-dependent thermal conductance of the Au-SCP and Nb-SPM devices allows an estimation of the heat flow (Q_{NFRHT}) and the radiative thermal conductance (G_{NFRHT}) by using the thermal resistance network in Fig. 1a (see Methods for details).

Data obtained from such an experiment are shown in Fig. 2a and reveal that RHT is strongly gap-size dependent. The instant at which contact was established between the sphere and the plane was readily detected by a sudden jump in the temperature of the Au-SCP device. The point of contact was assumed to occur at a gap size of ~5 nm, and all gap sizes before contact were estimated from the known displacements of the piezo during approach with respect to contact (see Supplementary Sections 4 and 5 for a detailed description of the calibration of the gap size and its uncertainty analysis). These data reveal that even at temperatures close to liquid helium temperatures, near-field enhancements in thermal transport can result in about an order of magnitude increase in the heat flux when the gap size is reduced from ~100 nm to <10 nm.

Next, to measure Q_{NFRHT} versus ΔT characteristics between the Au-SCP and Nb-SPM devices, it is necessary to perform experiments, at a fixed gap size, and quantify the heat flux between the two devices under varying temperature differentials. Performing these experiments for small magnitudes of ΔT is challenging as the heat flux in such experiments could be ~100 pW or smaller, which is very close to the heat current resolution of our devices. Below, we elaborate on how these challenges are overcome using an averaging scheme.

First, we placed the distal end of the sphere at a known separation (10 nm) from the Nb plane (as determined from gap-dependent thermal radiation measurements, for example, data in Fig. 2a). Subsequently, we modulated the temperature of the Nb-SPM device and measured the corresponding temperature change on the Au-SCP device, which, in conjunction with the known thermal conductance of the devices, enables characterization of the radiative thermal conductance between the two devices. In Fig. 2b, we show an example where the ambient temperature was ~14 K and the Nb temperature was periodically modulated by ~14.8 K (ΔT_{Nb}) by applying a square-wave current at a frequency of 20 mHz to the NbN heater integrated on the Nb-SPM. The temperature changes in the Nb-SPM (ΔT_{Nb}) and the Au-SCP (ΔT_{Au}) were determined, as described above, by recording the voltage changes across the NbN thin film thermometers integrated on the devices. The recorded voltage change can then be readily used to obtain the time (t)-dependent $T_{\text{Au}}(t)$ and $T_{\text{Nb}}(t)$ as shown in Fig. 2b (middle and bottom panels). The single-period traces clearly show that the temperature of the Au-SCP is periodically modulated (via radiative thermal transport) when a large periodic temperature change is imposed on the Nb-SPM. We also note that the modulation of the temperature of the Nb-SPM has a negligible impact on the gap size owing to the small dimensions of the devices and the low thermal expansion coefficients (see Supplementary Section 6

for details). The measured temperature changes ΔT_{Au} and ΔT_{Nb} , in combination with the known temperature-dependent thermal conductances $G_{\text{Au-SCP}}$ and $G_{\text{Nb-SPM}}$ of the Au-SCP and the Nb-SPM devices, respectively, can be used to estimate the radiative thermal conductance of the nanoscale gap via ($G_{\text{NFRHT}} = Q_{\text{NFRHT}} / (T_{\text{Nb}} - T_{\text{Au}}) = G_{\text{Au-SCP}} \Delta T_{\text{Au}} / (\Delta T_{\text{Nb}} - \Delta T_{\text{Au}})$), as described in Methods and above.

However, before estimating G_{NFRHT} , we asked whether the signal-to-noise ratio in the measured ΔT_{Au} and ΔT_{Nb} can be further enhanced while applying smaller temperature differentials. To accomplish this goal, we reduced the amplitude of the square-wave current applied to the heated device. We show in Fig. 2c an example of the observed temperature rise of the Au-SCP and the Nb-SPM where heat flow via RHT was on the order of 100 s of pW. As can be seen, while ΔT_{Nb} (emitter in this case) can be readily detected, ΔT_{Au} (absorber in this case) was quite noisy and was hard to quantify in a single-period trace. To improve the signal-to-noise ratio in our measurements, we collected tens of these single-period traces and averaged them to improve the signal-to-noise ratio as can be seen in the panels of Fig. 2c. These results indicate that a relatively high signal-to-noise ratio can be obtained by averaging ~50–100 single-period traces (Supplementary Section 10). Similar measurements were also performed by heating the Au-SCP and measuring the resultant temperature rise of the Nb-SPM (data shown in Fig. 2d). We note that, in all these experiments, the frequency for modulation was chosen to be 20 mHz to ensure that the thermal time constant of the two devices (Supplementary Section 3) is much smaller than the time period of modulation (50 s = 1/(20 mHz)). Data from these experiments enable estimation of both G_{NFRHT} under low-bias conditions (<5 K) and probing thermal rectification by switching temperature differentials between the two devices.

By using the above-described approach, we performed measurements of low-bias G_{NFRHT} (T) as a function of the ambient temperature at a fixed gap size of ~10 nm. In performing these experiments, we systematically varied the ambient temperature from 4 K to 18 K, while periodically heating the Au-SCP by ~3 K above the ambient temperature using a square wave at a frequency of 20 mHz. The measured conductance is shown in Fig. 3a where the RHT between the Au sphere and the Nb plane is largely suppressed when the Nb transitions from the normal metal phase to the superconducting phase. To quantitatively compare these experimental observations with theory, we first used fluctuational electrodynamics in conjunction with a temperature-dependent superconducting energy gap ($\Delta(T)$) and a dielectric function obtained from the Bardeen–Cooper–Schrieffer theory (Methods and Supplementary Section 7). To compute the heat flux exchanged between a spherical surface and a planar surface, we used the Derjaguin approximation⁴⁸, which has been used in previous studies^{15,19,20,49,50} of near-field radiation in a sphere–plane configuration (Methods). As seen in Fig. 3a, the computational results obtained using the Derjaguin approximation (solid black line) are in good agreement with the experimental data. We also show in Fig. 3b the temperature-dependent dielectric function of Nb as predicted by the Bardeen–Cooper–Schrieffer theory^{51,52}. It can be seen that the dielectric function is substantially modified, particularly at low frequencies, when Nb transitions from the normal metal phase to the superconducting phase, owing to the temperature-dependent superconducting energy gap. We note that at these environmental temperatures, the characteristic thermal wavelength (on the order of 100 s of μm) is greater than the diameter of the sphere (~50 μm), which brings into question the applicability of the Derjaguin approximation. Therefore, we also computed the gap-dependent thermal conductance using the SCUFF-EM-based method^{53–55} (Supplementary Section 11), which gives numerically exact results. The results obtained from both the Derjaguin approximation and SCUFF-EM-based method (Fig. 3c) show a very similar dependence of the radiative thermal conductance on gap sizes. The computed radiative thermal conductance using the SCUFF-EM-based method is ~0.77× the values obtained from the Derjaguin approximation, suggesting that the relatively simple

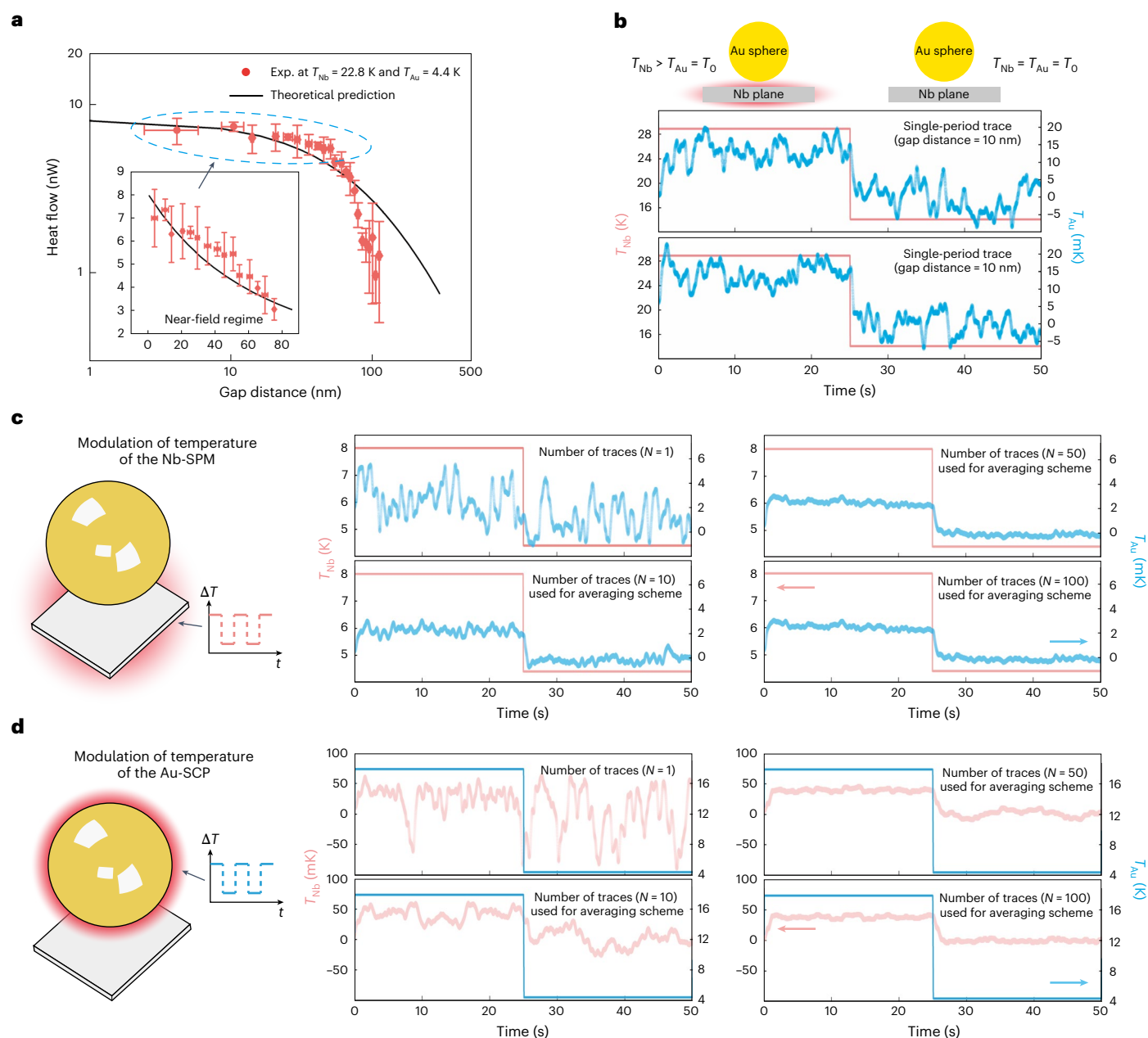


Fig. 2 | Experimental schemes used for probing radiative thermal transport between the Au-SCP and the Nb-SPM. a, Measured gap-dependent near-field RHT when the Au-SCP is at $\sim 4.4 \text{ K}$ and the temperature of the Nb-SPM is elevated to 22.8 K . The RHT gradually increases as the gap size decreases until the two devices make physical contact. Inset: the same data but plotted on a linear scale. Each data point represents the mean of four independent measurements of gap-dependent near-field RHT. Error bars denote the corresponding standard deviations. Exp., experiment. **b**, Representative single-period traces of the measured temperature of the Nb-SPM (T_{Nb}) and the Au-SCP (T_{Au}) when

the ambient temperature was -14 K and the temperature of the Nb-SPM was modulated by -14.8 K . **c, d**, An improved signal-to-noise ratio is achieved by using an averaging scheme where data from multiple experiments are averaged. Data from experiments where the temperature of the Nb-SPM is modulated are shown in (**c**), while data for experiments where the temperature of the Au-SCP is modulated are shown in (**d**). As the number of traces used in the averaging scheme increases from 1 to 100, the measured temperature change of the sensing device (Au-SCP in **c** and Nb-SPM in **d**) can be clearly differentiated from the background noise.

model based on the Derjaguin approximation produces results in good agreement with numerically exact models. Further, we show in Fig. 3d the spectral heat conductance calculated using the SCUFF-EM-based method with various environmental temperatures and gap sizes. Owing to the strong temperature dependence of Bose–Einstein distributions at these low temperatures, the spectral heat conductance across all frequencies decreases with the decrease of temperature. Moreover, on account of the superconducting phase transition of Nb, the spectral heat conductance across all frequencies, particularly at low frequencies (frequencies lower than $\sim 6.4 \times 10^{11} \text{ Hz}$, at 4.4 K), is attenuated,

indicating that the radiative thermal conductance between the Au sphere and the Nb plane is strongly suppressed as Nb transitions from the normal metal phase to the superconducting phase. This suppression in RHT can be understood by noting that when Nb transitions to the superconducting phase, a superconducting energy gap (2Δ) arises in Nb, allowing only photons whose frequency (ν) is above the frequency threshold (that is, $\nu > 2\Delta/h$, where h is Planck's constant) to contribute to the RHT, which is also reflected by the change of the Poynting flux (Fig. 3e,f) and the transmission probability of the supported transverse electric modes (Supplementary Fig. 15).

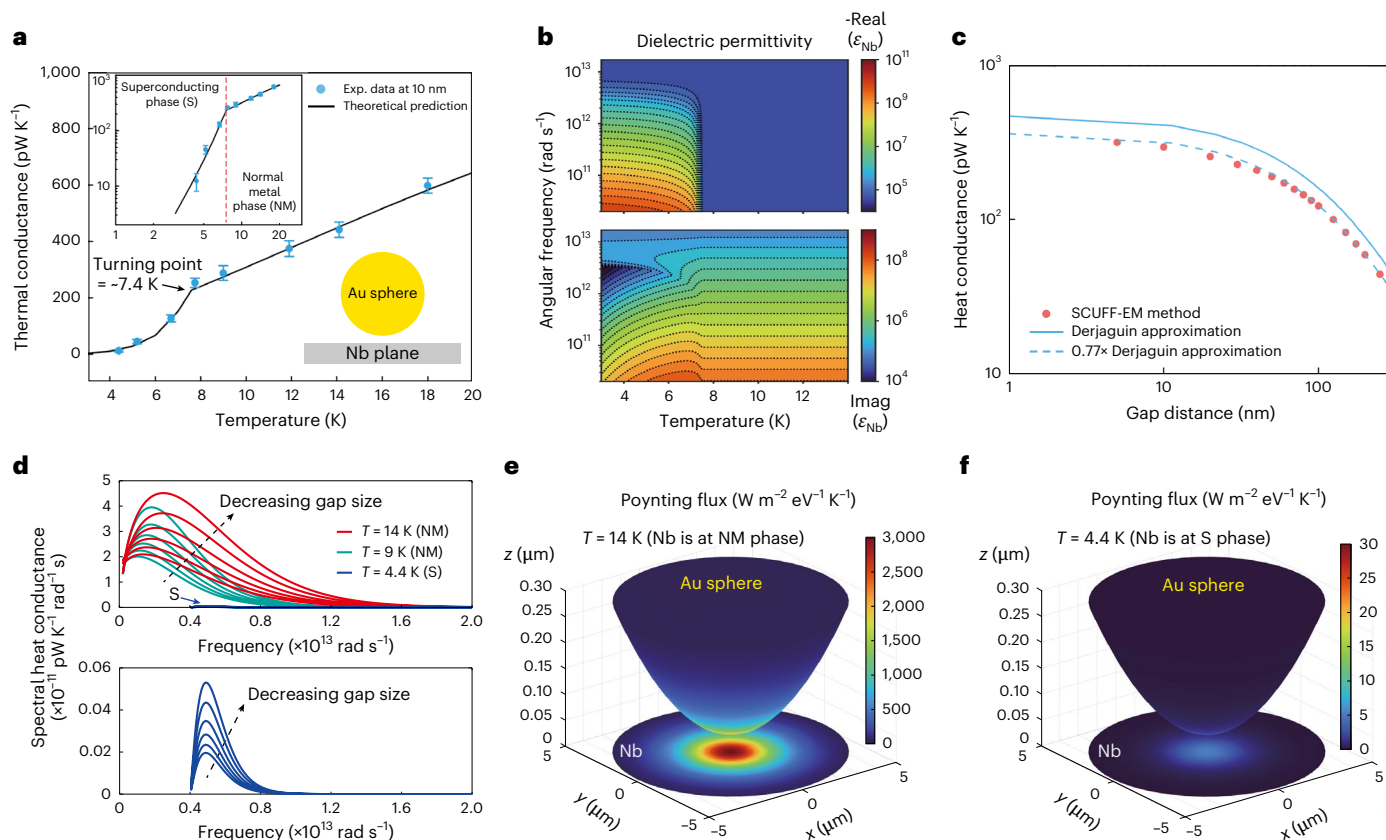


Fig. 3 | Results of temperature-dependent near-field thermal transport between the Au-SCP and the Nb-SPM. a, Measured temperature-dependent, low-bias thermal conductance for a 10 nm gap size (obtained using the averaging scheme). Inset: the same data on a log-scale. The inflection point of the measured thermal conductance is at ~ 7.4 K and is in good agreement with the transition temperature determined in Fig. 1a. Results indicate an ~ 20 -fold suppression of the thermal conductance (from $\sim 253 \mu\text{W K}^{-1}$ at 7.75 K to $\sim 12 \mu\text{W K}^{-1}$ at 4.4 K) when Nb undergoes a superconducting phase transition. The computational results obtained from the Derjaguin approximation are plotted (black solid lines) for comparison. Data points correspond to the mean of the measured thermal conductance, while error bars reflect the standard deviations. The number of averaged traces increased from ~ 50 to 100 as the ambient temperature

decreased. **b**, The temperature-dependent dielectric permittivity of the Nb thin film. Imag., imaginary. **c**, Comparison of the heat conductances obtained using the Derjaguin approximation and SCUFF-EM. **d**, The spectral heat conductance computed using SCUFF-EM. The top panel shows the spectral heat conductance at various gap sizes (5 nm, 20 nm, 40 nm, 60 nm, 80 nm and 100 nm) and different ambient temperatures ($T_0 = 14$ K, 9 K and 4.4 K; the arrow points to the data corresponding to $T_0 = 4.4$ K). The bottom panel is the zoomed-in view for the data corresponding to $T_0 = 4.4$ K. **e, f**, The computed Poynting flux obtained when Nb is in its normal metal phase (**e**) and its superconducting phase (**f**). For **e** and **f**, the axis scale ratio is $x:y:z = 1:1:0.03$. The Poynting flux shown in **e** and **f** corresponds to frequencies of $2.5 \times 10^{12} \text{ rad s}^{-1}$ and $6.6 \times 10^{12} \text{ rad s}^{-1}$, respectively. These frequencies were chosen to correspond to the maxima of the Poynting flux.

Heat rectification in cryogenic thermal diode

Next, we performed experiments to demonstrate thermal rectification when the Nb plane and the Au sphere were separated by a 10 nm gap (see details in Methods). In a first set of experiments, performed at an ambient temperature $T_0 = 4.4$ K, we measured the heat flow under forward bias conditions ($Q_{\text{fwd}}(\Delta T)$), which refers to a scenario where the temperature of the Au-SCP was $T_{\text{Au}} = T_0 = 4.4$ K and the Nb-SPM was heated to reach an elevated temperature $T_{\text{Nb}} = T_0 + \Delta T$ (where the magnitude of ΔT was systematically varied from 0 K to ~ 30 K). Subsequently, we performed experiments under reverse bias conditions, where $T_{\text{Nb}} = T_0 = 4.4$ K and $T_{\text{Au}} = T_0 + \Delta T$ and measured the heat flow ($Q_{\text{rev}}(\Delta T)$). Upon completing these experiments at $T_0 = 4.4$ K, we repeated these experiments at $T_0 = 14.1$ K to characterize the scenario where Nb is always in the normal metal state.

We show in Fig. 4a,b the experimental results obtained at environmental temperatures of 4.4 K and 14.1 K, respectively. The data in Fig. 4a clearly show that $Q_{\text{fwd}}(\Delta T) > Q_{\text{rev}}(\Delta T)$. This rectifying behaviour (that is, thermal diode characteristics) can be understood by noting that under forward bias conditions (that is, when the Nb film is heated), the Nb film transitions from a superconductor to a normal metal greatly increasing the radiative thermal conductance, whereas under reverse bias conditions, Nb remains in the superconducting phase, resulting

in a low radiative thermal conductance consistent with the data in Fig. 3a. In strong contrast, for the data shown in Fig. 4b, the rectifying behaviour is largely lost as the Nb film stays in the normal metal phase for both forward and reverse temperature biases. We note that the experimentally measured data is in very good agreement with the predictions of our fluctuational electrodynamics-based modelling (see black dashed lines in Fig. 4).

To quantify the performance of the thermal diode, we calculated the rectification ratio ($\eta(\Delta T)$) of the thermal diode^{10,30}, which is defined as:

$$\eta(\Delta T) = \frac{||Q_{\text{fwd}}(\Delta T)| - |Q_{\text{rev}}(\Delta T)||}{\max(|Q_{\text{fwd}}(\Delta T)|, |Q_{\text{rev}}(\Delta T)|)}, \quad (1)$$

at different environmental temperatures. The results of the theoretical prediction and the fitting curve for experimental data are shown in Fig. 4c,d with black dashed lines and solid lines, respectively. Notably, at $T_0 = 4.4$ K, the rectification ratio is as high as $\sim 70\%$ for an ~ 10 K temperature bias. In contrast to that data obtained at $T_0 = 4.4$ K, only a very small rectification ratio ($< 5\%$) was observed for the data obtained at $T_0 = 14.1$ K. We believe that the performance of this Nb–Au pair can be further enhanced by decreasing the environmental temperature (T_0)

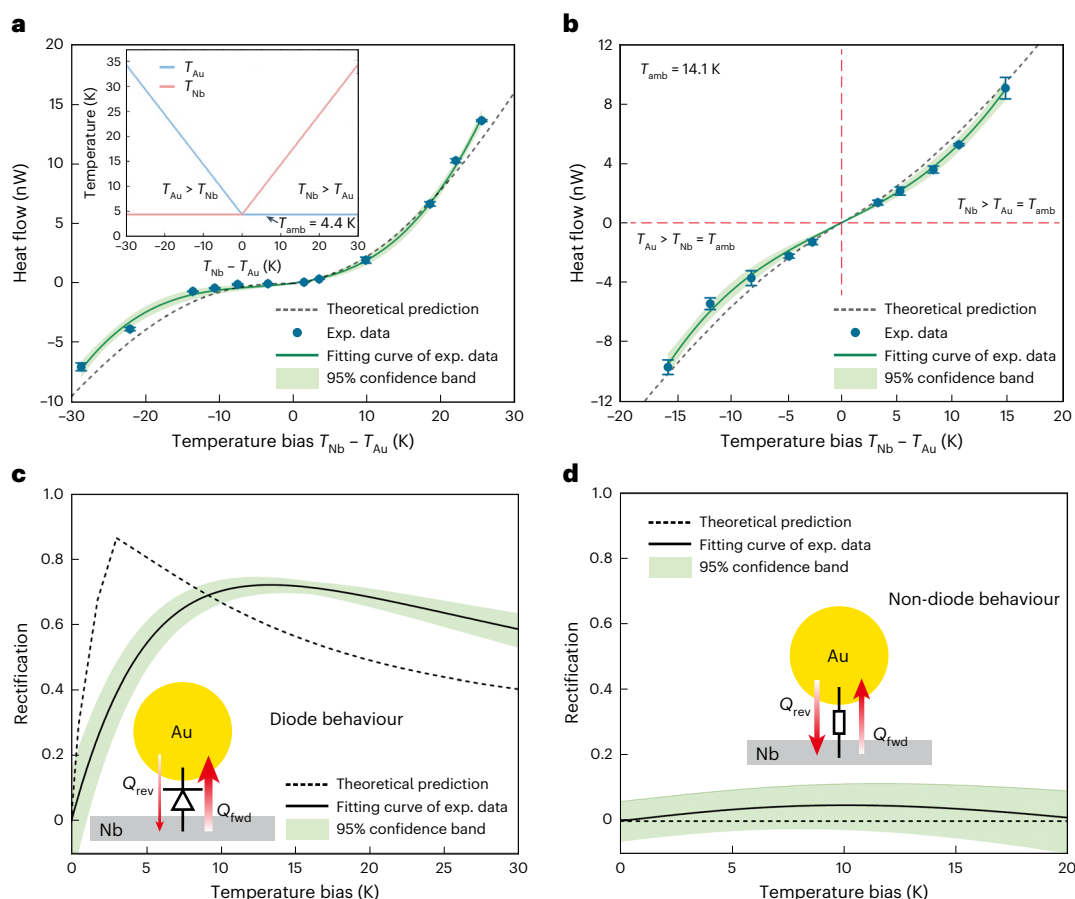


Fig. 4 | Experimental demonstration of a near-field thermal diode for a Nb plane and an Au sphere separated by a 10 nm gap. **a**, Observed thermal diode behaviour at an environmental temperature (T_0) of 4.4 K. In the forward bias, when Nb is heated and transitions from a superconductor to a normal metal, leading to enhanced RHT. Such an enhancement is absent under a reverse bias when the Au sphere is heated, because Nb continues to remain in the superconducting state, resulting in the observed thermal rectification. **b**, No thermal rectification is observed at $T_0 = 14.1$ K, as Nb stays at its normal metal phase for both forward and reverse biases. Data points in **a** and **b** correspond to the mean of the measured heat flow, while error bars reflect the standard

deviations. The number of averaged traces increased from -50 to 100 as the temperature bias (absolute value) decreased. **c**, The rectification ratio for the data presented in **a** reaches ~70% for a temperature bias of -10 K. **d**, The rectification ratio for the data presented in **b**. Note that the non-zero rectification (<-5%) in the experimental results is caused by the uncertainty in the measurements. In **c** and **d**, the theoretically predicted rectification ratios, from fluctuational electrodynamics calculations, are also shown (black dashed lines). The solid black lines in **c** and **d** are obtained using the fitting curves shown in **a** and **b**. The corresponding error bands are calculated from the 95% confidence bands shown in **a** and **b**.

to sub-kelvin (<1 K) values. Finally, we note that the maximum observable rectification ratio is primarily constrained by the magnitude of the superconducting energy gap of the material (see detailed discussion in Supplementary Section 9 following an approach developed in a recent work⁵⁶).

Conclusion

The results presented in this work provide direct evidence of RHT enhancements in nanoscale gaps between superconductors and normal metals at liquid helium temperatures. Further, we demonstrate that thermal rectification can be achieved via superconducting phase transitions. Our results are helpful for advancing thermal management in superconductor-based devices, such as superconducting nanowire photodetectors and superconducting quantum computers, as insights from this work can be leveraged to create thermal switches and diodes for different operating conditions by tuning superconducting transition temperatures and superconducting energy gaps. Since superconducting phase transitions can be controlled via magnetic fields, our work also points to the possibility of controlling heat flows via magnetic fields. Finally, we believe that the micro-fabricated devices and experimental methods developed in this work can become useful

to study fundamental fluctuation phenomena in exotic states of matter, such as superconductors, topological insulators and semi-metals at cryogenic temperatures.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41565-025-02112-x>.

References

- Li, Y. et al. Transforming heat transfer with thermal metamaterials and devices. *Nat. Rev. Mater.* **6**, 488–507 (2021).
- Wehmeyer, G., Yabuki, T., Monachon, C., Wu, J. & Dames, C. Thermal diodes, regulators, and switches: physical mechanisms and potential applications. *Appl. Phys. Rev.* **4**, 041304 (2017).
- Wong, M., Tso, C., Ho, T. & Lee, H. A review of state of the art thermal diodes and their potential applications. *Int. J. Heat Mass Transf.* **164**, 120607 (2021).

4. Nadeem, M., Fuhrer, M. S. & Wang, X. The superconducting diode effect. *Nat. Rev. Phys.* **5**, 558–577 (2023).
5. Liu, X. & Hersam, M. C. 2D materials for quantum information science. *Nat. Rev. Phys.* **4**, 669–684 (2019).
6. Voznyy, O., Sutherland, B. R., Ip, A. H., Zhitomirsky, D. & Sargent, E. H. Engineering charge transport by heterostructuring solution-processed semiconductors. *Nat. Rev. Phys.* **2**, 1–10 (2017).
7. Martínez-Pérez, M. J., Fornieri, A. & Giazotto, F. Rectification of electronic heat current by a hybrid thermal diode. *Nat. Nanotechnol.* **10**, 303–307 (2015).
8. Fornieri, A., Timossi, G., Virtanen, P., Solinas, P. & Giazotto, F. $0-\pi$ phase-controllable thermal Josephson junction. *Nat. Nanotechnol.* **12**, 425–429 (2017).
9. Marchegiani, G., Braggio, A. & Giazotto, F. Highly efficient phase-tunable photonic thermal diode. *Appl. Phys. Lett.* **118**, 022602 (2021).
10. Moncada-Villa, E. & Cuevas, J. Normal-metal–superconductor near-field thermal diodes and transistors. *Phys. Rev. Appl.* **15**, 024036 (2021).
11. Nefzaoui, E., Joulain, K., Drevillon, J. & Ezzahri, Y. Radiative thermal rectification using superconducting materials. *Appl. Phys. Lett.* **104**, 103905 (2014).
12. Ordóñez-Miranda, J., Joulain, K., De Sousa Meneses, D., Ezzahri, Y. & Drevillon, J. Photonic thermal diode based on superconductors. *J. Appl. Phys.* **122**, 093105 (2017).
13. Sun, W., Zhang, Z. M. & Jacob, Z. Superconducting coherence peak in near-field radiative heat transfer. *Phys. Rev. B* **112**, 125423 (2025).
14. Planck, M. *The Theory of Heat Radiation* (Blakiston, 1914).
15. Narayanaswamy, A., Shen, S. & Chen, G. Near-field radiative heat transfer between a sphere and a substrate. *Phys. Rev. B* **78**, 115303 (2008).
16. Hu, L., Narayanaswamy, A., Chen, X. & Chen, G. Near-field thermal radiation between two closely spaced glass plates exceeding Planck's blackbody radiation law. *Appl. Phys. Lett.* **92**, 133106 (2008).
17. Thompson, D. et al. Hundred-fold enhancement in far-field radiative heat transfer over the blackbody limit. *Nature* **561**, 216–221 (2018).
18. Modest, M. F. *Radiative Heat Transfer* 3rd edn (Academic Press, 2013).
19. Song, B. et al. Enhancement of near-field radiative heat transfer using polar dielectric thin films. *Nat. Nanotechnol.* **10**, 253–258 (2015).
20. Rousseau, E. et al. Radiative heat transfer at the nanoscale. *Nat. Photon.* **3**, 514–517 (2009).
21. Song, B. et al. Radiative heat conductances between dielectric and metallic parallel plates with nanoscale gaps. *Nat. Nanotechnol.* **11**, 509–514 (2016).
22. Kim, K. et al. Radiative heat transfer in the extreme near field. *Nature* **528**, 387–391 (2015).
23. St-Gelais, R., Zhu, L., Fan, S. & Lipson, M. Near-field radiative heat transfer between parallel structures in the deep subwavelength regime. *Nat. Nanotechnol.* **11**, 515–519 (2016).
24. Rincón-García, L. et al. Enhancement and saturation of near-field radiative heat transfer in nanogaps between metallic surfaces. *Phys. Rev. Lett.* **129**, 145901 (2022).
25. DeSutter, J., Tang, L. & Francoeur, M. A near-field radiative heat transfer device. *Nat. Nanotechnol.* **14**, 751–755 (2019).
26. Mittapally, R. et al. Probing the limits to near-field heat transfer enhancements in phonon-polaritonic materials. *Nano Lett.* **23**, 2187–2194 (2023).
27. Song, B., Fiorino, A., Meyhofer, E. & Reddy, P. Near-field radiative thermal transport: from theory to experiment. *AIP Adv.* **5**, 053503 (2015).
28. Liu, X., Wang, L. & Zhang, Z. M. Near-field thermal radiation: recent progress and outlook. *Nanoscale Microscale Thermophys. Eng.* **19**, 98–126 (2015).
29. Zhu, L. et al. Near-field photonic cooling through control of the chemical potential of photons. *Nature* **566**, 239–244 (2019).
30. Fiorino, A. et al. A thermal diode based on nanoscale thermal radiation. *ACS Nano* **12**, 5774–5779 (2018).
31. Fiorino, A. et al. Nanogap near-field thermophotovoltaics. *Nat. Nanotechnol.* **13**, 806–811 (2018).
32. Laroche, M., Carminati, R. & Greffet, J.-J. Near-field thermophotovoltaic energy conversion. *J. Appl. Phys.* **100**, 063704 (2006).
33. Mittapally, R., Majumder, A., Reddy, P. & Meyhofer, E. Near-field thermophotovoltaic energy conversion: progress and opportunities. *Phys. Rev. Appl.* **19**, 037002 (2023).
34. Latella, I., Biehs, S.-A. & Ben-Abdallah, P. Smart thermal management with near-field thermal radiation. *Opt. Express* **29**, 24816–24833 (2021).
35. Basu, S., Zhang, Z. & Fu, C. Review of near-field thermal radiation and its application to energy conversion. *Int. J. Energy Res.* **33**, 1203–1232 (2009).
36. Guha, B., Otey, C., Poitras, C. B., Fan, S. & Lipson, M. Near-field radiative cooling of nanostructures. *Nano Lett.* **12**, 4546–4550 (2012).
37. Zhao, B. et al. High-performance near-field thermophotovoltaics for waste heat recovery. *Nano Energy* **41**, 344–350 (2017).
38. Králík, T., Hanzelka, P., Musilová, V., Srnka, A. & Urban, P. Near field radiative heat transfer between macro-scale metallic surfaces at cryogenic temperatures. *Cryogenics* **113**, 103156 (2021).
39. Králík, T., Musilová, V., Fořt, T. & Srnka, A. Effect of superconductivity on near-field radiative heat transfer. *Phys. Rev. B* **95**, 060503 (2017).
40. Kralik, T. et al. Strong near-field enhancement of radiative heat transfer between metallic surfaces. *Phys. Rev. Lett.* **109**, 224302 (2012).
41. Wischnath, U. F., Welker, J., Munzel, M. & Kittel, A. The near-field scanning thermal microscope. *Rev. Sci. Instrum.* **79**, 073708 (2008).
42. Domoto, G., Boehm, R. & Tien, C. L. Experimental investigation of radiative transfer between metallic surfaces at cryogenic temperatures. *J. Heat Transfer* **92**, 412–416 (1970).
43. Rytov, S. M., Kravtsov, Y. A. & Tatarskii, V. I. *Principles of Statistical Radiophysics: Elements of Random Process Theory* (Springer, 1987).
44. Polder, D. & Van Hove, M. Theory of radiative heat transfer between closely spaced bodies. *Phys. Rev. B* **4**, 3303 (1971).
45. Ben-Abdallah, P. & Biehs, S.-A. Phase-change radiative thermal diode. *Appl. Phys. Lett.* **103**, 191907 (2013).
46. Nguyen, T. et al. Niobium nitride thin films for very low temperature resistive thermometry. *J. Low Temp. Phys.* **197**, 348–356 (2019).
47. Wolf, S. A., Kennedy, J. J. & Nisenoff, M. Properties of superconducting rf sputtered ultrathin films of Nb. *J. Vac. Sci. Technol.* **13**, 145–147 (1976).
48. Derjaguin, B., Abrikosova, I. & Lifshitz, E. Direct measurement of molecular attraction between solids separated by a narrow gap. *Chem. Soc. Rev.* **10**, 295–329 (1956).
49. Yan, S. et al. Surface phonon polariton-mediated near-field radiative heat transfer at cryogenic temperatures. *Phys. Rev. Lett.* **131**, 196302 (2023).
50. Guillemot, V. et al. Nonmonotonic radiative heat transfer in the transition from far field to near field. *Phys. Rev. Lett.* **134**, 193801 (2025).
51. Mattis, D. C. & Bardeen, J. Theory of the anomalous skin effect in normal and superconducting metals. *Phys. Rev.* **111**, 412 (1958).
52. Zimmermann, W., Brandt, E., Bauer, M., Seider, E. & Genzel, L. Optical conductivity of BCS superconductors with arbitrary purity. *Physica C Supercond.* **183**, 99–104 (1991).

53. Rodriguez, A. W., Reid, M. H. & Johnson, S. G. Fluctuating-surface-current formulation of radiative heat transfer for arbitrary geometries. *Phys. Rev. B* **86**, 220302 (2012).
54. Rodriguez, A. W., Reid, M. H. & Johnson, S. G. Fluctuating-surface-current formulation of radiative heat transfer: theory and applications. *Phys. Rev. B* **88**, 054305 (2013).
55. Reid, M. H. & Johnson, S. G. Efficient computation of power, force, and torque in BEM scattering calculations. *IEEE Trans. Antennas Propag.* **63**, 3588–3598 (2015).
56. Li, Q., Chen, Q. & Song, B. Fundamental limit to the rectification of near-field heat flow: the potential of intrinsic semiconductor films. *Phys. Rev. B* **106**, 075408 (2022).

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© The Author(s), under exclusive licence to Springer Nature Limited 2026

Methods

Device fabrication

The steps in the fabrication of the Nb-SPM device are shown in Supplementary Fig. 1. First (step 1), the T-shaped beams were defined on a bare Si wafer using deep reactive ion etching (DRIE) followed by a low-pressure chemical vapour deposition (LPCVD) of 600-nm-thick low-stress silicon nitride (SiN). Then (step 2), the 40-nm-thick Au leads for electrical connections were patterned. Next, the Au electrodes for wire bonds were deposited. Subsequently (steps 3 and 4), a 200-nm-thick Nb thin film and a 150-nm-thick NbN thin film were sputtered on the substrate. Lastly (step 5), the Nb-SPM device was released via DRIE.

The fabrication of the Au-SCP device begins (step 1) by defining the T-shaped beams using DRIE and filling the resulting channels with LPCVD low-stress SiN (see also Supplementary Fig. 2 for the fabrication process). Later (step 2), the Au line was defined and electron beam evaporated onto the wafer. Next (step 3), a 50-nm-thick serpentine Pt line was patterned, followed by a 100-nm-thick deposition of a NbN thin film (step 4). Then (step 5), the probe structure was released using DRIE. After the release of the probe from the DRIE of Si (step 6), the distal end of the probe was attached by a 200-nm-thick, Au-coated SiO₂ sphere (the diameter was ~50 μm) utilizing a nanomanipulator integrated into a focused ion beam (FIB) microscope (Thermo Fisher Helios 650 Nanolab SEM/FIB). To elaborate, we first picked up a clean Au-coated sphere by bridging the nanomanipulator and the sphere with Pt via *in situ* Pt depositions. Next, we moved the sphere close to the end of the probe by fine-tuning the position of the nanomanipulator and created an ~10 μm wide and ~1.5-μm-thick Pt connection between the sphere and the probe to ensure an excellent thermal contact. Finally, the Pt bridge formed between the sphere and the nanomanipulator was cut off by applying a large FIB current to the Pt bridge (step 7).

Circuitry for measurement of thermal radiation

Temperature changes of the Nb plane on the Nb-SPM, which were induced by the heated Au sphere, were measured using a half-bridge circuit (Supplementary Fig. 4a). To elaborate, a 1 μA AC current I_{AC} (frequency, $f = 23$ Hz) was applied to the circuit, where the NbN thin film heater/thermometer and a potentiometer (placed at room temperature) were connected in series. The voltage differential across the NbN thin film heater/thermometer and the potentiometer was first amplified by the instrumentation amplifiers (AD524ADZ, Analog Devices) with a gain of 10. Then the differential output of the two signals was further amplified using a second-stage instrumentation amplifier (AD524) with a gain of 10. This signal output from the second stage of amplifications reflected the voltage change in the NbN thin film sensor. The 1ω component of the output signal $V(1\omega)$ was then read by an SR830 lock-in amplifier. Using the measured voltage change $\Delta V(1\omega)$ in the NbN thin film thermometer, the corresponding temperature change can be quantified as $\Delta T(1\omega) = \Delta V(1\omega) / \alpha_{NbN} I_{NbN} R_{NbN}$, where α_{NbN} is the TCR of the NbN thin film thermometer (see details in Supplementary Section 2), I_{NbN} is the amplitude of AC current applied to the thermometer and R_{NbN} is the resistance of the NbN thin film. Similarly, the temperature change of the Au sphere on the Au-SCP can be measured using the NbN thermometer integrated on the Au-SCP (see details in Supplementary Section 2 and Supplementary Fig. 4b).

Determination of the radiative thermal conductance and heat flow between the Au sphere and the Nb plane

With the quantified temperature change ($\Delta T(1\omega)$) discussed above, heat exchanged between the Au sphere and the Nb plane through RHT can be calculated using $Q_{rad} = G_{Nb-SPM} \Delta T(1\omega)$, in conjunction with the known thermal conductance of the Nb-SPM (see details in Supplementary Section 2 and Supplementary Fig. 4a). As a result, the corresponding radiative thermal conductance (G_{rad}) is obtained following $G_{rad} = Q_{rad} / \Delta T_{Au-Nb}$,

where ΔT_{Au-Nb} is the temperature differential between the Au sphere and the Nb plane.

In performing the forward bias experiments for demonstrating thermal rectification, the Nb-SPM was heated up by applying a square-wave current to the NbN thin film integrated onto the Nb-SPM. Meanwhile, a 40 nA AC current at a frequency of 23 Hz was applied to the NbN thin film thermometer integrated onto the Au-SCP to measure the temperature change of the Au sphere (ΔT_{Au}). As a result, the heat flow Q_{fwd} was calculated using $Q_{fwd} = G_{Au-SCP} \Delta T_{Au}$. By changing the amplitude of the square wave, the heat flow $Q_{fwd}(\Delta T)$ was obtained at different temperature biases. Similarly, in the reverse bias experiments, the temperature of the Au sphere was modulated by applying a square-wave current to the Pt line integrated on the Au-SCP. The temperature change in the Nb plane (ΔT_{Nb}) was measured by the NbN thin film thermometer integrated onto the Nb-SPM with an applied 1 μA AC current at a frequency of 23 Hz, and the corresponding heat flow was quantified as $Q_{rev} = G_{Nb-SPM} \Delta T_{Nb}$.

Computational method for near-field RHT

We used the framework of the fluctuational electrodynamics^{43,44} to calculate the near-field RHT for our experiments and analysis. The heat flux exchanged via RHT between two parallel planes shown in Supplementary Fig. 13a can be calculated as

$$Q = \int_0^\infty \frac{d\omega}{2\pi} \left[\frac{\hbar\omega}{\exp(\hbar\omega/k_B T_1) - 1} - \frac{\hbar\omega}{\exp(\hbar\omega/k_B T_3) - 1} \right] \int_0^\infty \frac{dk}{2\pi} k (\tau_s^{13} + \tau_p^{13}), \quad (2)$$

where T_i is the absolute temperature of the layers, k_B is the Boltzmann constant, k is the magnitude of the wavevector parallel to the planar surface. The transmission probability τ with different polarizations contains propagating waves and evanescent waves, which is described as

$$\tau_n^{13} = \begin{cases} \frac{(1 - |r_n^{21}|^2)(1 - |r_n^{23}|^2)}{|1 - r_n^{21} r_n^{23} \exp(2iq_2 d)|^2}, & k < \frac{\omega}{c} \\ \frac{4\text{Im}(r_n^{21})\text{Im}(r_n^{23}) \exp[-2\text{Im}(q_2 d)]}{|1 - r_n^{21} r_n^{23} \exp(2iq_2 d)|^2}, & k > \frac{\omega}{c} \end{cases} \quad (3)$$

where $q_i = \sqrt{\varepsilon_i \omega^2 / c^2 - k^2}$, $r_n^{ij} = (q_i - q_j) / (q_i + q_j)$ and $r_p^{ij} = (\varepsilon_j q_i - \varepsilon_i q_j) / (\varepsilon_j q_i + \varepsilon_i q_j)$. We first show that the sputtered 200 nm Nb thin film and coated 200 nm Au layer can be treated as an infinitely thick layer (Supplementary Fig. 14). Therefore, the inner shell of the SiO₂ sphere and SiN substrate do not contribute substantially to the thermal radiation in our case, implying that it is reasonable to calculate the RHT between infinitely thick Au and Nb planes as a simplified model for calculations of near-field RHT between a Au-coated SiO₂ plane and a Nb plane on the SiN substrate (Supplementary Fig. 13a). As a result, this simplified planar structure can be used for Derjaguin approximation⁴⁸ (Supplementary Fig. 13b) to estimate the RHT between a Au sphere and a Nb plane, which is the configuration used for our experiments. We also note that there are small discrepancies (both the (absolute) values and gap dependence in near-field radiation) between the theoretical prediction and the experimental data, which is likely due to the differences in the optical properties of the sputtered metallic film and bulk metals.

Data availability

All primary data supporting the findings of this study are included in the Article, its Supplementary Information and Source data. For additional information, contact the corresponding authors. Source data are provided with this paper.

Acknowledgements

P.R. and E.M. acknowledge support from DOE-BES through a grant from the Scanning Probe Microscopy Division under award

number DESC0004871 (Scanning Probes and Analysis). P.R. and E.M. acknowledge support from the Office of Naval Research under award number N00014-24-1-2132 (Instrumentation) and the National Science Foundation under award number CBET 2232201 (Calorimetric Devices). We thank the Lurie Nanofabrication Facility and the Michigan Center for Materials Characterization for facilitating the fabrication and calibration of devices.

Author contributions

P.R. and E.M. conceived the work. Y.L. and S.Y. designed the experiments. Y.L., S.Y., J.G., Y.I. and Z.W. fabricated the devices. Y.L. and R.M. conducted the experiments. Y.L. performed the simulations and A.M. performed the SCUFF-EM calculations. Y.L. analysed the data with contributions from R.Y. and S.F. All authors discussed the data analysis and interpretation. The paper was written by Y.L., P.R. and E.M. with comments and input from all authors.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41565-025-02112-x>.

Correspondence and requests for materials should be addressed to Shanhui Fan, Edgar Meyhofer or Pramod Reddy.

Peer review information *Nature Nanotechnology* thanks Philippe Ben-Abdallah and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.