

Supplementary Material

Broadband Enhancement of Near-Field Radiative Heat Transfer via Intrinsic Carrier–Lattice Interactions

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S1. The computational details for the radiative heat transfer and the theoretical dielectric constant

In the framework of fluctuation electrodynamics, the radiative heat flux (RHF) is given by ⁵¹

$$\begin{aligned} Q_{rad} &= \int_0^\infty (\Theta(\omega, T_e) - \Theta(\omega, T_r)) f(\omega, d) d\omega \\ &= \int_0^\infty (\Theta(\omega, T_e) - \Theta(\omega, T_r)) d\omega \int_0^\infty dk \frac{k_\rho}{4\pi^2} [\xi_s(\omega, k_\rho) + \xi_p(\omega, k_\rho)], \end{aligned} \quad (1)$$

where $\Theta(\omega, T) = \hbar\omega / [\exp(\hbar\omega/k_B T) - 1]$ is the mean energy of a Planck oscillator. $\hbar$ and k_B are the reduced Planck constant and the Boltzmann constant, respectively. $f(\omega, d)$ is the spectral transfer function. $\xi_{s,p}(\omega, k)$ correspond to the thermophotonic tunneling probabilities for s - and p -polarization, respectively, representing the tunneling probability of thermal photons from the hot terminal to the cold terminal, which can be written as ⁵¹

$$\xi_{s,p}(\omega, k, d) = \begin{cases} \frac{(1 - |r_{ss,pp}^e|^2)(1 - |r_{ss,pp}^r|^2)}{|D_{ss,pp}|^2} & \text{if } k < \omega/c \\ \frac{4 \operatorname{Im}(r_{ss,pp}^e) \operatorname{Im}(r_{ss,pp}^r) e^{-2 \operatorname{Im}(k_{z0})d}}{|D_{ss,pp}|^2} & \text{if } k > \omega/c \end{cases}, \quad (2)$$

for propagating ($k < k_0$) and evanescent ($k > k_0$) waves where k is the surface parallel wavevector, $k_0 = \omega/c$ is the wavevector in vacuum. $r_{ss,pp}^e$ and $r_{ss,pp}^r$ are the reflection coefficients for thermal emitter and thermal receiver. α stands for the s - and p -polarized. $k_{z0} = \sqrt{k_0^2 - k^2}$ is the tangential wavevector along z direction in vacuum. D is defined as $D_{ss,pp} = 1 - r_{ss,pp}^e r_{ss,pp}^r e^{2ik_{z0}d}$, which describes the usual Fabry-Perot-like denominator resulting from the multiple scattering between the two interfaces. When D is zero, the dispersion of the system can be calculated ⁵².

In this section, a generalized 4×4 T-matrix formalism for hyperbolic media with arbitrary number of layers is developed, from which the general relations for the reflection matrix are derived. Let us first consider a semi-infinite hyperbolic media. Let us write separately the EM field of the p -polarized (TM) and s -polarized (TE) components of the EM wave. The p wave with the magnetic field perpendicular to the plane of incidence possess the EM field components $E_p = \{E_x, 0, E_z\}$, $H_p = \{0, H_y, 0\}$. For the s wave, with the electric field perpendicular to the plane of incidence, the EM field components are $E_s = \{0, E_y, 0\}$, $H_s = \{H_x, 0, H_z\}$. Substituting p -wave and s -wave into boundary conditions of hyperbolic media ⁵³, one obtains the 4×4 T-matrix, which gives the relations between all the electric field components in the media above and below the nodal-ring semimetals:

$$\begin{bmatrix} H_{p1}^+ \\ H_{p1}^- \\ E_{s1}^+ \\ E_{s1}^- \end{bmatrix} = \mathbf{T} \begin{bmatrix} H_{p2}^+ \\ H_{p2}^- \\ E_{s2}^+ \\ E_{s2}^- \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} & T_{14} \\ T_{21} & T_{22} & T_{23} & T_{24} \\ T_{31} & T_{32} & T_{33} & T_{34} \\ T_{41} & T_{42} & T_{43} & T_{44} \end{bmatrix} \begin{bmatrix} H_{p2}^+ \\ H_{p2}^- \\ E_{s2}^+ \\ E_{s2}^- \end{bmatrix}, \quad (3)$$

here, the sign of + and - represent forward and backward waves, respectively. $\mathbf{T}$ is derived as:

$$\mathbf{T} = \frac{1}{2} \begin{bmatrix} \frac{k_{zp}}{\epsilon_{xx,yy}} \begin{bmatrix} P^{++} & P^{--} \\ P^{-+} & P^{+-} \end{bmatrix} & \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} & \frac{1}{k_{z0}} \begin{bmatrix} S^{++} & S^{-+} \\ S^{--} & S^{+-} \end{bmatrix} \end{bmatrix}, \quad (4)$$

where the p -waves components are

$$\begin{aligned} P^{++} &= \frac{1}{k_{z0}} + \frac{\epsilon_{xx,yy}}{k_{zp}}; & P^{--} &= -\frac{1}{k_{z0}} + \frac{\epsilon_{xx,yy}}{k_{zp}}, \\ P^{-+} &= -\frac{1}{k_{z0}} + \frac{\epsilon_{xx,yy}}{k_{zp}}; & P^{+-} &= \frac{1}{k_{z0}} + \frac{\epsilon_{xx,yy}}{k_{zp}}, \end{aligned} \quad (5)$$

where the s -waves components are

$$\begin{aligned} S^{++} &= k_{z0} + k_{zs}; & S^{-+} &= k_{z0} - k_{zs}, \\ S^{--} &= k_{z0} - k_{zs}; & S^{+-} &= k_{z0} + k_{zs}, \end{aligned} \quad (6)$$

where subscripts p and s represent the TM-polarised and TE-polarised, respectively. ϵ_{xx} , ϵ_{yy} , and ϵ_{zz} are the dielectric permittivities in the x , y , and z directions, respectively. polarization, $k_{zs} = (\epsilon_{xx,yy} k_0^2 - k^2)^{1/2}$, and for p polarizations, $k_{zp} = (\epsilon_{xx,yy} k_0^2 - \epsilon_{xx,yy} k^2 / \epsilon_{zz})^{1/2}$. The components of the reflection matrix $\mathbf{R}$ can be obtained based on the T-matrix elements, as follows⁵³:

$$r_{pp} = \frac{H_{p1}^-}{H_{p1}^+} \Big|_{E_{s1}=0} = \frac{T_{21}T_{33} - T_{23}T_{31}}{T_{11}T_{33} - T_{13}T_{31}}, \quad r_{ss} = \frac{E_{s1}^-}{E_{s1}^+} \Big|_{H_{p1}=0} = \frac{T_{11}T_{43} - T_{13}T_{41}}{T_{11}T_{33} - T_{13}T_{31}}, \quad (7)$$

In the case of GaAs, due to its isotropy, its dielectric constant is the same in the x , y , and z directions, $\epsilon_{xx} = \epsilon_{yy} = \epsilon_{zz} = \epsilon$. The necessary conditions for existence of surface plasmon-phonon polaritons at the GaAs/vacuum interface are the following: $\text{Re}(\epsilon) < 0$ ⁵⁴. We assume that the dielectric permittivities of GaAs consists of two contributions, namely the lattice term and electron component:

$$\varepsilon(\omega) = \varepsilon_{\infty} + \frac{\varepsilon_0 - \varepsilon_{\infty}}{1 - \left(\frac{\omega}{\omega_{TO}}\right)^2 - \frac{i\omega\gamma}{\omega_{TO}^2}} - \frac{\varepsilon_{\infty}\omega_p^2}{\omega^2 + i\omega\tau^{-1}} \quad (7)$$

where ε_{∞} is high frequency permittivity, ε_0 is low frequency permittivity, ω_{TO} is transverse optical phonon frequency, γ is damping constant for transverse optical phonon, ω_p is plasma frequency, τ is electron relaxation time. These parameters are determined by the carrier concentration of doped *n*-GaAs. Table S1 lists the parameters from the fits to the experimental data of Ref. 44 at different carrier concentrations.

Table S1 The dielectric permittivities of GaAs from the fits to experimental data at different carrier concentrations ⁴⁴.

N_e (10^{16} cm^{-3})	ω_{TO} (cm^{-1})	ω_{LO} (cm^{-1})	γ (cm^{-1})	ω_p (cm^{-1})	τ^{-1} (cm^{-1})
1.8	268.0	292.0	1.85	45	50
17	267.5	290.5	2.7	136	62
70	267.8	290.1	2.4	275	47
86	268.3	294.0	1.8	300	62
330	267.4	291.5	2.5	570	61
440	267.7	292.5	2.9	650	55
700	267.0	291.3	2.9	795	69

In this work, the measured doping concentration data for the samples are shown in Fig. S1. When performing theoretical calculations, the measured data do not correspond one-to-one with the concentrations reported in the Ref. 44. Therefore, we employ a quadratic polynomial fit to the data provided in the literature to obtain the dielectric constant parameters corresponding to the doping concentrations of our samples.

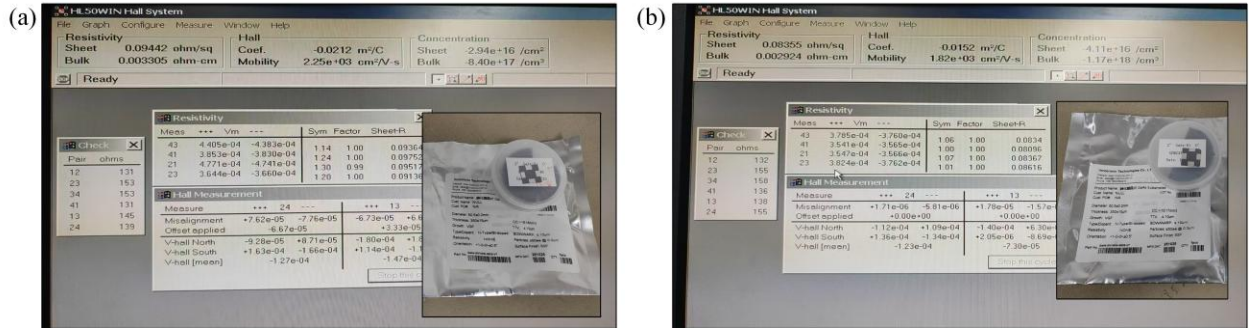


Fig. S1 The carrier concentrations of (a) the moderately doped sample and (b) the highly doped sample, as measured by the Hall effect.

S2. Sample morphology and uncertainty analysis of the true space distance

The key steps for manufacturing the SiO₂ nanopillars used to separate the emitter and receiver are summarized as follows:

1) Prepare the cleaned and dried GaAs substrate. The process involves cleaning the GaAs substrate with acetone, alcohol, and deionized water, followed by drying it with pure nitrogen gas. Firstly, immerse the GaAs substrate in acetone for 15 min of ultrasonic cleaning. Then, soak it in alcohol for another 15 min of ultrasonic cleaning. After cleaning, rinse with deionized water to remove residual reagents. Finally, dry the GaAs substrate using 99.999 % pure nitrogen gas.

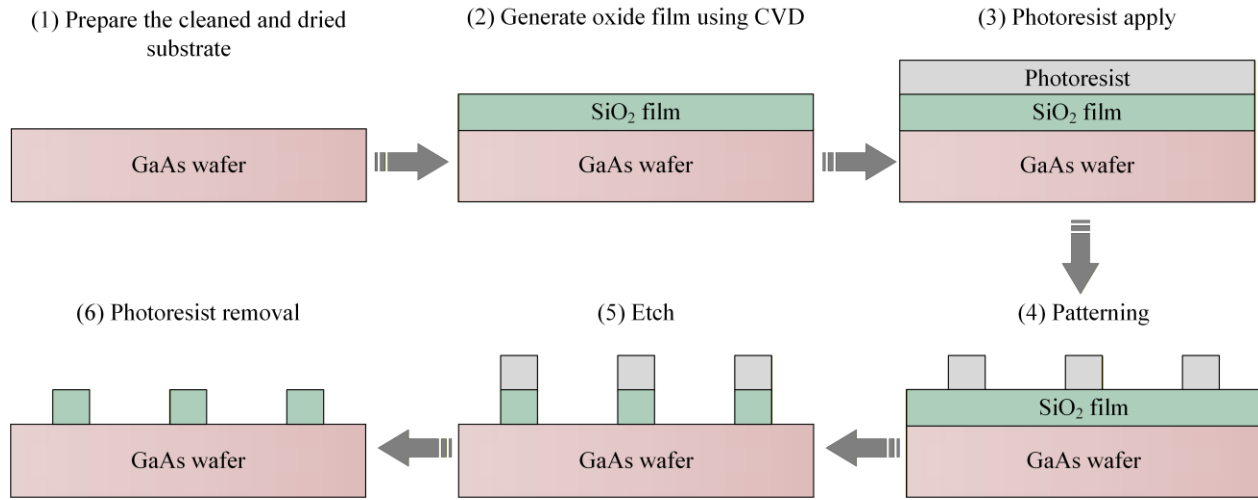


Fig. S2 Main fabrication steps of the samples used for measuring near-field radiative heat transfer.

2) Generate oxide film using chemical vapor deposition (CVD). Silane (SiH₄) + nitrous oxide (N₂O) reacts to form silicon dioxide at a temperature of 300 °C, at a rate of 53 nm per minute. The process involves controlling the deposition rate of oxide film, growing the oxide film, and measuring its thickness. Based on this rate, determine the processing time to grow samples with the specified film thickness. Finally, use ellipsometry to measure the film thickness and verify its consistency with the target thickness. In Fig. S2, we also show the height of the nanopillars.

3) Photoresist applies. Apply S1813 photoresist onto the wafer surface at a rotational speed of 500 rpm for 5 seconds, then switch to a rotational speed of 3500 rpm for another 45 seconds. Bake at 115 °C for 90 seconds.

4) Patterning and Etching. Patterns are formed by first exposing the photoresist to UV radiation through a photomask. The SiO₂ nanopillars are patterned using a dry etching. The etching equipment is ICP-RIE. The etching process involves two gases: C₄F₈ and Ar. The etching rate is 37 nm/min per minute.

5) Photoresist removal. Repeat the process from step (1). Manufacturing the receiver only requires the first three steps and the final cleaning step.

After sample fabrication, the surface morphology of the samples was characterized, since it directly determines the gap distance between the emitter and the receiver in the experiment. The characterization includes surface roughness, surface warpage, and the SiO₂ nanopillar profile.

First, we also characterized the surface roughness of GaAs substrate at different carrier concentrations by Atomic Force Microscope, AFM (Dimension FastScan) scanning in Fig. S3. In Fig. S3, we further present the roughness of undoped, moderately doped and undoped samples. As illustrated in Fig. S3, the roughness of GaAs substrate at different carrier concentrations is less than ~ 2 nm. It is reasonable to assume that, during the NFRHT experiment, the emitter and receiver surfaces are relatively smooth, with no significant surface protrusions that could cause abnormal contact and result in heat conduction; this assumption is also validated by the good agreement between our calculated data and the experimental results.

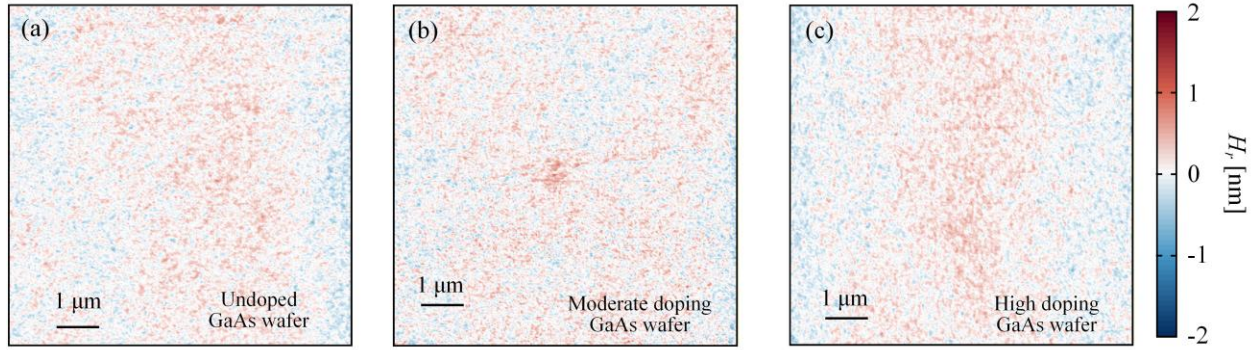


Fig. S3 A $8 \times 8 \mu\text{m}^2$ atomic force microscopy topographic image of (a) undoped GaAs wafer, (b) moderate doping GaAs wafer and (c) high doping GaAs wafer.

The gap spacing between the emitter and receiver is determined based on the measured nanopillar heights and simulations for estimating the nanopillar and surface deflections. In this work, AFM (Dimension FastScan) was also used to characterize the nanopillar morphology and determine its geometrical parameters, as shown in Fig. S4. The scanned images show that the top-view profile of the nanopillars is approximately circular, while the side profile exhibits a trapezoidal shape, with a narrower top and a wider base that changes uniformly. The average diameter of the nanopillars was determined to be $2.72 \mu\text{m}$, and the average height without load was 159.50 nm . These measurements were performed before and after NFRHT experiments to ensure that the nanopillars were not damaged or plastically deformed during the experiments. As mentioned in the main text, a 9.2 g mass was applied to the emitter for mechanical stability but led to a small decrease of the thickness of the SiO₂ nanopillars. However, in our experiment, part of the weight of the PID-controlled

heater is supported by the bracket (to ensure the stability of the heating plate). The actual weight applied should be less than 9.2 g.

The Young's modulus of SiO_2 (E_{SiO_2}) at room temperature is 76.6 GPa⁵⁵, the compression of the nanopillars under load was calculated according to the following equation³⁴:

$$\Delta x = \frac{h \cdot 4mg}{N\pi D^2 E_{\text{SiO}_2}} \quad (8)$$

where h is the height of the nanopillar, D is the diameter of a single nanopillar, m is the applied load mass, and N is the number of nanopillars. Given the aforementioned conditions, the maximal calculated compression Δx equals 6.44 nm, which is significantly smaller than h at 159 nm and has small significant impact on heat transfer. Therefore, it is appropriate to set the reference value for theoretical calculations in the main text to 159 nm.

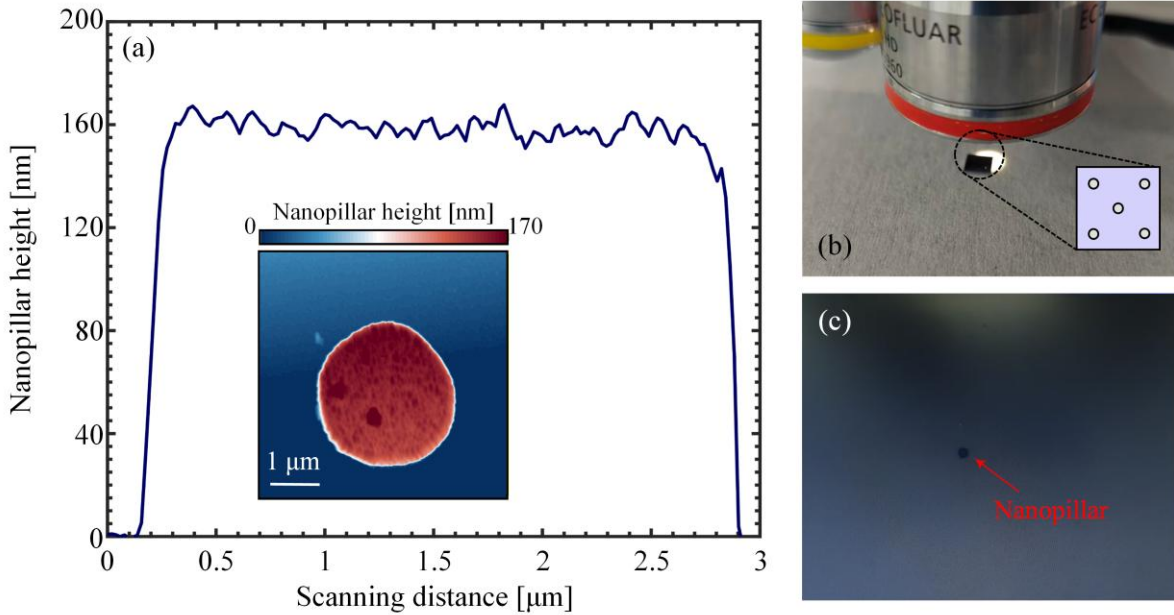


Fig. S4 (a) Measured nanopillar height as a function of the scanning length for the emitter sample. The inset is measured outline of the nanopillar in the emitter sample. (b) Physical picture of emitter sample. (c) Electron microscope image of a nanopillar.

Subsequently, the surface warpage of the samples was characterized using an RTEC UP-Lambda-U-3000 white-light interferometer, which is an important parameter determining the near-field gap range in the experiment. The room-temperature warpage of GaAs samples with three different Si doping concentrations is shown in Fig. S5. For each sample, the surface profile along the 0° and 90° lines passing through the center was measured within a $5 \text{ mm} \times 5 \text{ mm}$ area. The results show that the peak-to-valley warpage of all

three samples is less than 31 nm. Specifically, the warpage ranges are (+15.01, -15.73) nm for the highly doped sample, (+15.11, -12.50) nm for the moderately doped sample, and (+9.28, -19.13) nm for the undoped sample. The same surface nonuniformity was considered for both the emitter and the receiver with different doping concentrations⁵⁶. Accordingly, the possible distance ranges between the emitter and receiver in the experiment are estimated as follows: highly doped sample: upper bound 31 nm, lower bound -30nm, moderately doped sample: upper bound 25 nm, lower bound -30 nm, undoped sample: upper bound 38 nm, lower bound -18 nm. Compared with the nanopillar height under load, the room-temperature surface warpage remains within an acceptable range.

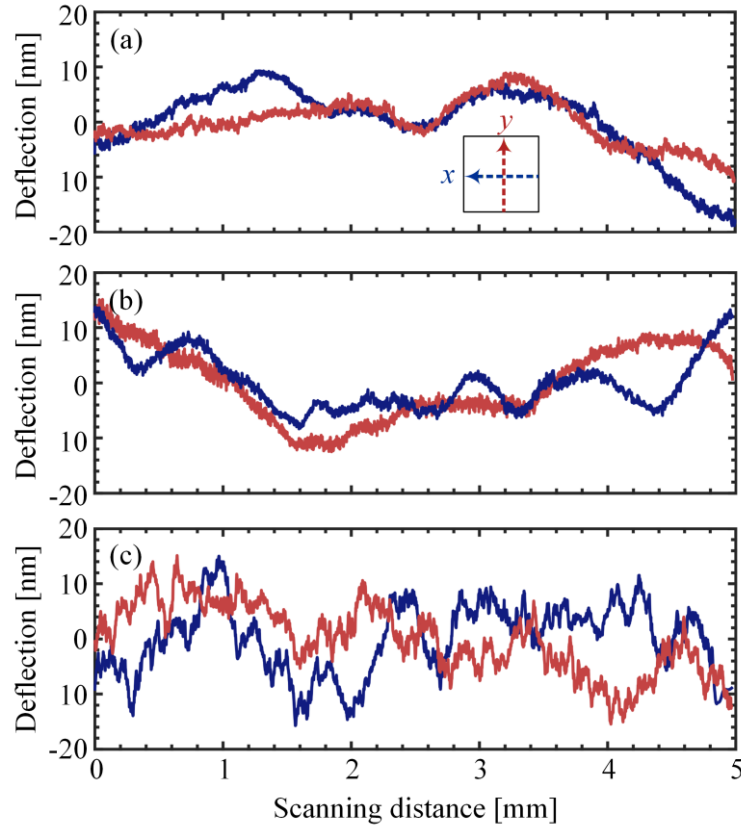


Fig. S5 Surface profiles of GaAs substrates obtained by the three-dimensional white light interference profilometer over a 5 mm × 5 mm scan area for (a) undoped GaAs sample, (b) moderate doping GaAs sample, and (c) high doping GaAs sample.

S3. Accuracy of measurement characterization

Heat flux sensor calibration measurement

Because aerospace connectors were used to connect the electronic components inside and outside the vacuum chamber in order to ensure sealing, the modification of the wiring and connection configuration

may influence the measured values of the heat flux sensor. The ultrathin conductive heat flux sensor is used to measure the conductive heat flux density. The heat flux meter converts the heat flux density into a voltage output signal, and the actual heat flux density is proportional to this signal. This proportionality coefficient is defined as the sensor sensitivity coefficient, denoted as K_s , with units of $\mu\text{V}/(\text{W}/\text{m}^2)$. To ensure the accuracy of the sensitivity coefficient, a separate calibration experiment was designed in this study. The calibration method was based on the work of De Sutter J and co-workers⁴⁷. The calibration was carried out by measuring the heat flux density through a material with a known thermal conductivity. After comparison, a B270 glass plate with a thickness of 3 mm and an area of $5\text{ mm} \times 5\text{ mm}$ was selected. The thermal diffusivity of the glass plate was measured using the laser flash method (laser flash apparatus LFA467), and the corresponding thermal conductivity was obtained, as shown in Fig. S6(a).

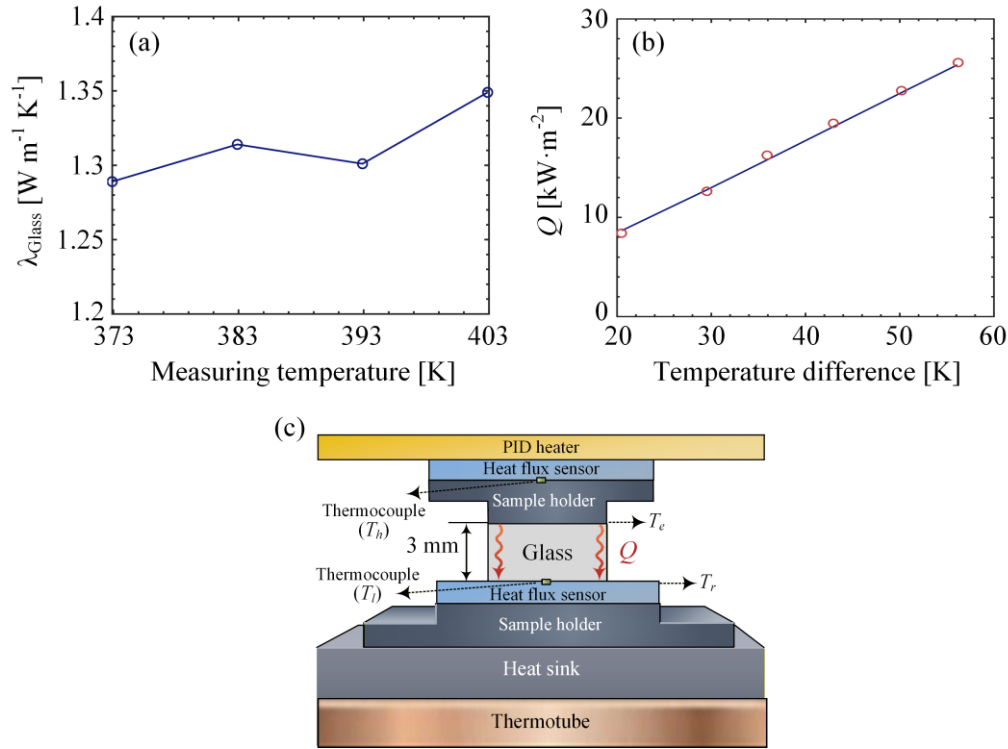


Fig. S6 (a) The thermal conductivity of B270 glass plate. (b) The measured and theoretical values of conductive heat flux density in this calibration system. (c) Schematic diagram of the calibration system.

The calibration setup is illustrated in Fig. S6(c). The entire system can be modeled as a one-dimensional heat conduction system. The heat flux sensor measures the actual conductive heat flow through the glass plate, denoted as Q_{real} . The theoretical heat flow through the glass plate, Q_{theory} , is calculated using Fourier's law is obtained as

$$Q_{\text{theory}} = \frac{T_e - T_r}{R_t}$$

here, R_t is the thermal resistance consisting of two layers of thermal grease and the B270 glass plate, with a value of 91.78 K/W. The relationship between the measured and theoretical values is shown in Fig. S6(b).

Uncertainty analysis

It is well known that near-field radiative heat transfer is influenced by the temperature difference, separation distance, and the dielectric function of the materials. The range of the theoretical predictions is jointly determined by these factors: surface warpage of the samples, nanopillar height, and temperature fluctuations of the receiver. The surface warpage and nanopillar height were characterized using white-light interferometry and AFM, respectively, as discussed in the previous section.

The receiver temperature remained relatively stable within the range of 23–25 °C due to ambient conditions. Consequently, for the same temperature difference, slight variations in the theoretical heat flux density are expected at different receiver temperatures. Specifically, the predicted heat flux density at 23 °C is slightly lower than that at 25 °C. Based on the above considerations, the minimum (maximum) vacuum gap was first determined by combining the nanopillar height with the lower (upper) bound of the surface warpage. Subsequently, theoretical predictions were calculated by considering the receiver temperature of 25 °C (23 °C), corresponding to the upper (lower) bound of the predicted heat flux density. Finally, the upper and lower theoretical curves of the near-field radiative heat flux density were obtained.

The uncertainty of the measured data arises from multiple factors, including measurement errors of the thermocouples and heat flux sensor, the relative alignment between the emitter and receiver samples, the vacuum level during measurements, and the cleanliness of the sample surfaces. To ensure experimental reliability while minimizing external disturbances, the heat flux density at each temperature difference was measured repeatedly. At each temperature point, multiple measurements were conducted, and each data point was recorded only after the heat transfer process had reached a steady state for more than 4 min. The scatter points shown in the figure represent the average values of each measurement set, and the uncertainty in the measured heat flux is reflected in the error bars.

Moreover, according to the equivalent thermal circuit shown in Fig. 1(c) of main text, the total heat flow Q measured by the heat flux sensor located beneath the receiver consists of two components: the conductive heat transfer through the SiO₂ nanopillars (Q_{cond}) and the near-field radiative heat transfer (Q_{rad}). Therefore, the experimentally obtained near-field radiative heat flux density Q_{rad} can be determined by subtracting the calculated conductive heat flux density Q_{cond} from the measured total heat flux density Q . The conductive heat flux density Q_{cond} can be calculated using the following equation ⁵⁶:

$$Q_{\text{cond}} = \frac{(T_e - T_r) \cdot N \lambda \pi D^2}{4HA_s}$$

where T_e is the temperature of the emitter and T_r is the temperature of the receiver; $N = 5$ is the number of nanopillars; λ is the thermal conductivity of SiO_2 (approximately $1.4 \text{ W m}^{-1} \text{ K}^{-1}$)⁵⁶; D is the diameter of the nanopillars; H is the height of nanopillars, taken as 159 nm according to the previous calculation; and A_s is the overlap area between emitter and receiver.

In conclusion, the unloaded nanopillar height and diameter were measured by AFM to be 159.50 nm and 2.72 μm on average, respectively. The maximum elastic compression under the applied load was calculated to be 6.44 nm. Macroscopic wafer profiles were independently measured over a $5 \times 5 \text{ mm}^2$ area using white-light interferometry, and the measured deflection limits were combined with the nanopillar height to determine the minimum and maximum possible vacuum gaps for each sample pair. The receiver temperature varied between 23 and 25 $^\circ\text{C}$ during measurement. The upper and lower theoretical heat-flux curves were obtained by evaluating the fluctuational-electrodynamics model using the corresponding limiting combinations of gap distance and receiver temperature. Thus, the shaded bands in Fig. 2 represent the prediction range arising from experimentally determined gap and temperature variations, whereas the experimental error bars describe the repeatability and instrumental uncertainty of the heat-flux measurements.

S4. Measurement and theoretical analysis of heat flux at a larger spacing

In the main text, we demonstrate the enhancement of thermal radiation induced by the intrinsic carrier–lattice interaction at a spacing gap of 159 nm. As shown in Fig. 2(a) in the main text, this enhancement effect is not limited to spatial dimensions of around 100 nm. It persists even at larger spacings. In this section, we also demonstrate the enhancement of radiative heat transfer due to carrier-lattice interactions when the spacing is approximately 410 nm. As shown in Fig. S7(b), the radiative heat flux in the highly doped case remains higher than that of the undoped system at this gap distance. However, compared to the phenomenon observed at $d = 159 \text{ nm}$, this doping-induced radiative enhancement gradually diminishes as the gap distance increases. At a temperature difference of 50 K, the heat flux of the highly doped sample reaches 1.84 kW m^{-2} , compared to 1.62 kW m^{-2} for the undoped case. Although this doping-induced enhancement is weaker than that observed at a 159 nm gap in the main text, a clear increase in heat flux is still maintained.

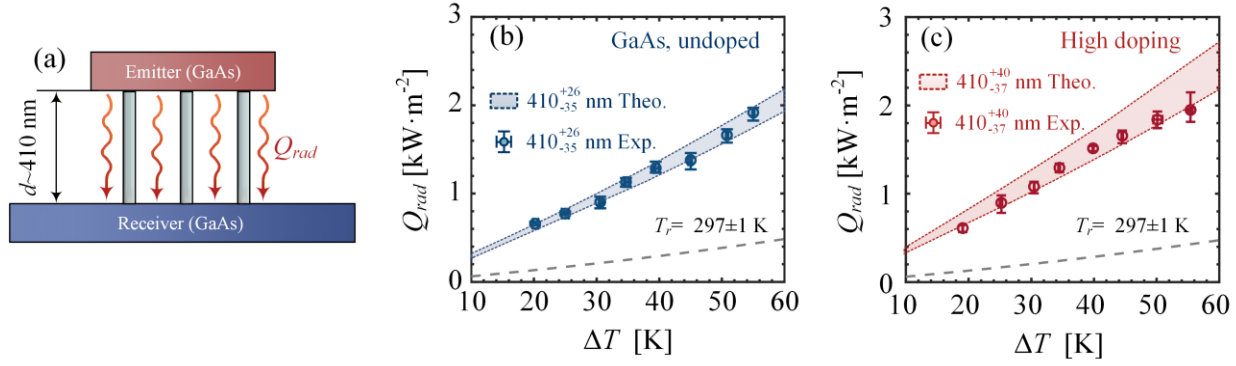


Fig. S7 (a) Schematic illustration of NFRHT within a larger spacing. (b) Experimentally measured RHF for the undoped and highly doped GaAs samples as a function of the temperature difference, with the receiver stabilized at $T_r = 297 \pm 1$ K. The shaded colored bands represent the theoretical predictions derived from fluctuational electrodynamics. These bands incorporate the experimental uncertainties in the vacuum gap spacing, accounting for inherent nanopillar height variations and macroscopic sample bow.

The surface warpage of samples at larger gap spacings was characterized using a white-light interferometer (RTEC UP-Lambda-U-3000). The room-temperature warpage of GaAs samples with three Si doping concentrations is shown in Fig. S8. For each sample, the surface profile along the central 0° and 90° lines was measured over a $5 \text{ mm} \times 5 \text{ mm}$ area. The results indicate that the peak-to-valley warpage of all samples remains below 38 nm. Specifically, the warpage ranges from $+18.38$ to -20.11 nm for the highly doped sample and from $+17.56$ to -12.79 nm for the undoped sample. Under different doping conditions, the emitter and the receiver both use the same batch of wafer samples, and the degree of surface unevenness is usually at the same level. Accordingly, the possible gap variation ranges are estimated to be $+40/-37$ nm for the highly doped sample and $+26/-35$ nm for the undoped sample. Compared with the nanopillar height under load, the room-temperature warpage remains within an acceptable range.

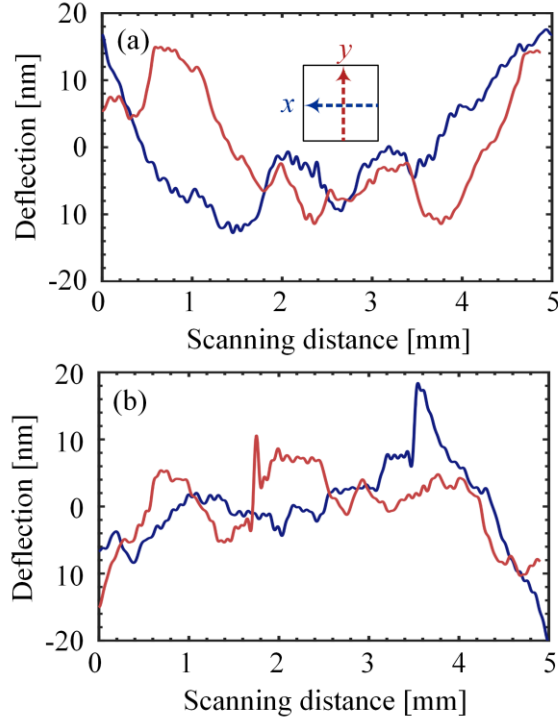


Fig. S8 Surface profiles of GaAs substrates obtained by the three-dimensional white light interference profilometer over a $5\text{ mm} \times 5\text{ mm}$ scan area for (a) undoped GaAs sample and (b) high doping GaAs sample for the larger spacing system.

AFM images (Fig. S9) show that the nanopillars exhibit an approximately circular top view and a trapezoidal side profile, with a narrower top and a wider base. The average nanopillar diameter is $2.96\text{ }\mu\text{m}$, and the average unloaded height is 410.73 nm . Measurements conducted before and after the NFRHT experiments confirm that no structural damage or plastic deformation occurs during testing.

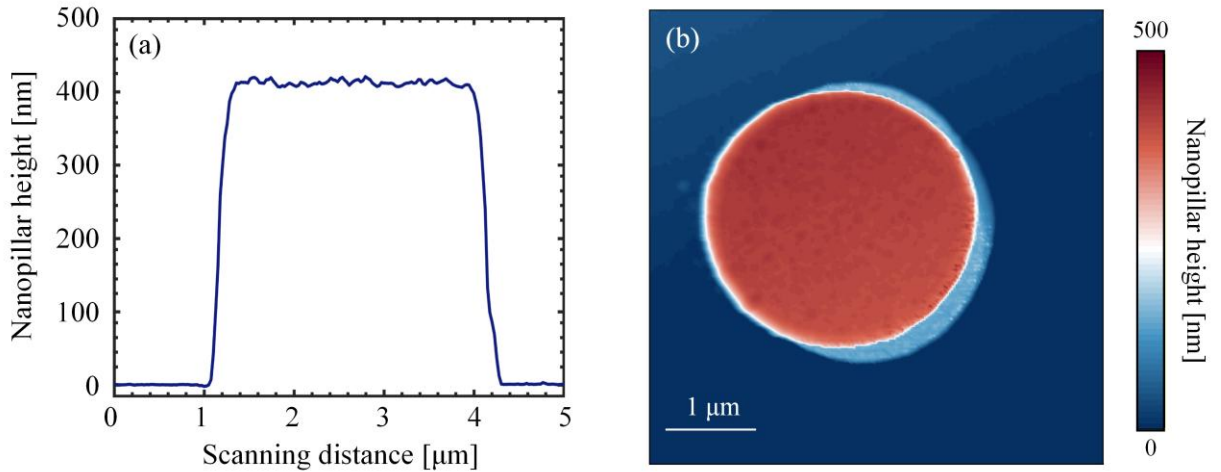


Fig. S9 (a) Measured nanopillar height as a function of the scanning length for the emitter sample for the larger spacing system. (b) Measured outline of the nanopillar in the emitter sample.

The spectral transfer coefficient further elucidates the heat transfer mechanisms at larger gap distances (Fig. S10). Consistent with the main text, increasing the carrier concentration introduces an additional spectral peak in GaAs. The phonon-dominated peak exhibits a blueshift accompanied by significant spectral broadening, which directly contributes to the observed radiative enhancement. To further resolve this behavior, the thermophotonic tunneling probability in momentum space is analyzed (Fig. S11). In the undoped case, the tunneling spectrum is characterized by a narrow, large- k_ρ band, indicative of strongly confined surface phonon polariton modes. With increasing carrier concentration, an additional broadband branch emerges, and the original phonon-dominated band broadens substantially. However, unlike the small-gap regime, increasing the carrier concentration at larger gaps slightly reduces the characteristic wavevector of tunneling photons. This reduction weakens the contribution of high- k_ρ modes, thereby explaining the diminished doping-induced enhancement compared to the small-gap case.

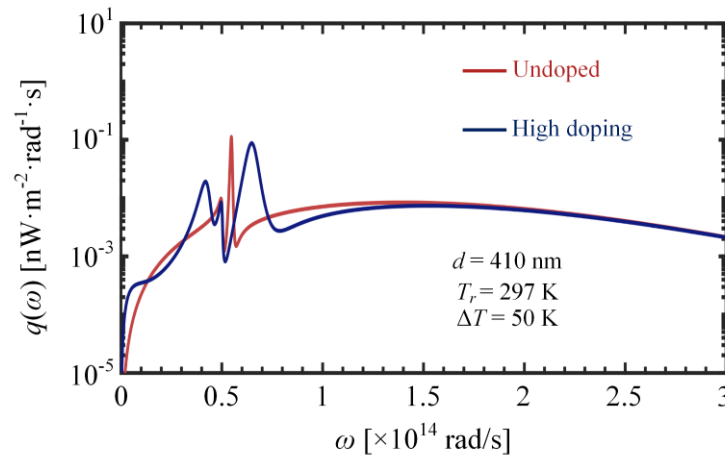


Fig. S10 Calculated total spectral heat flux for undoped GaAs and highly doped GaAs. All theoretical spectral calculations are performed at a fixed vacuum gap of $d = 410$ nm and a temperature difference of $\Delta T = 50$ K.

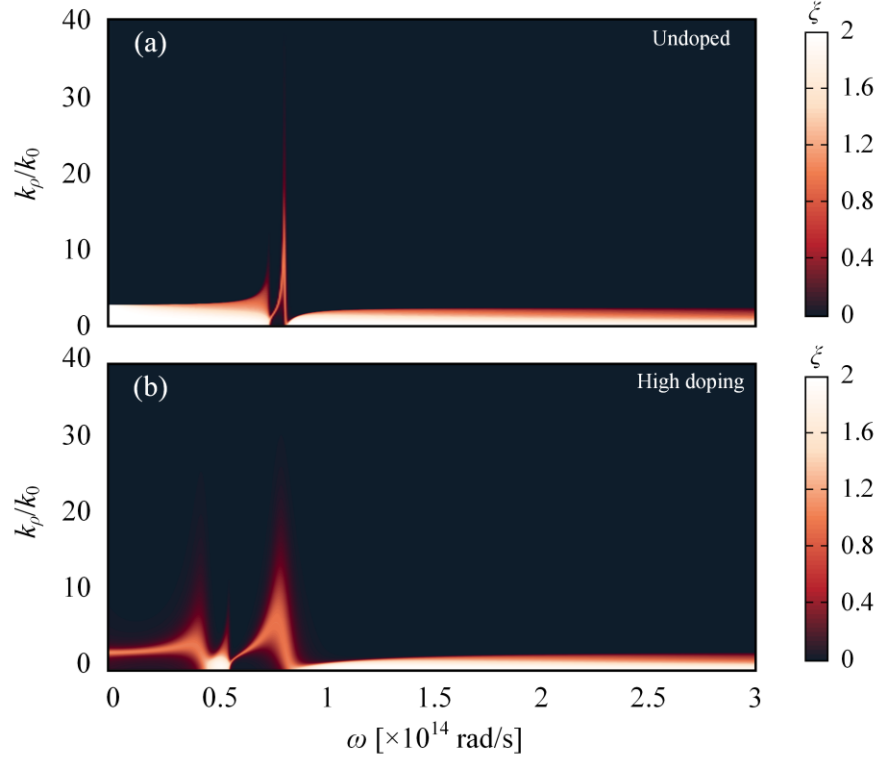


Fig. S11 Theoretical **thermal photon** tunneling probability contours for (a) undoped and (b) highly doped GaAs at a fixed vacuum gap of $d = 410$ nm.

Figure S12 presents the real-space distributions of the out-of-plane electric field component, $\text{Re}(E_z)$, excited by a z -polarized dipole positioned 400 nm above the GaAs surface, for both undoped and highly doped cases. In the undoped GaAs [Fig. S12(a)], the field exhibits a relatively extended oscillatory pattern with well-defined concentric fringes, characteristic of phonon-polariton-dominated surface responses at $\omega = 5.46 \times 10^{13}$ rad/s. In contrast, for the highly doped GaAs [Fig. S12(b)], the field becomes more spatially confined and localized around the dipole at $\omega = 6.47 \times 10^{13}$ rad/s, accompanied by a reduction in the oscillation wavelength. This transition reflects the emergence of carrier-induced plasmonic contributions and their coupling with intrinsic phonon modes, which modifies the surface electromagnetic response. Such enhanced field confinement and redistribution indicate a tuned local density of optical states, providing a direct microscopic origin for the strengthened photon tunnelling and the observed enhancement of near-field radiative heat transfer in doped GaAs.

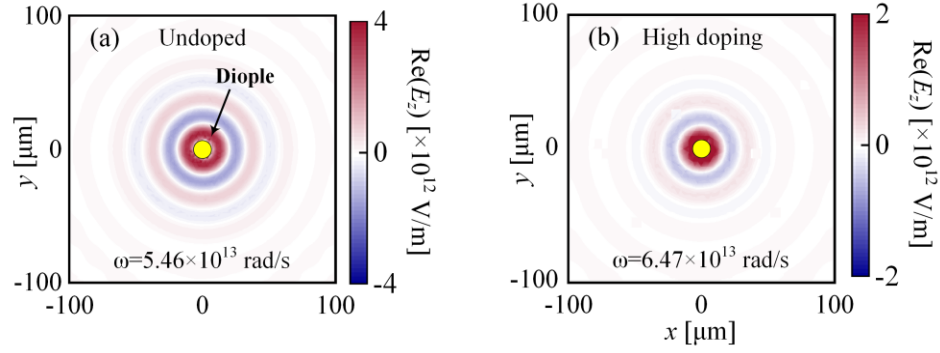


Fig. S12 The real-part of electric field distributions $\text{Re}(E_z)$ of metasurface at different structural perturbations in real space: (a) undoped GaAs at the frequency of 5.46×10^{13} rad/s and (b) highly doped GaAs ($N_e = 1.2 \times 10^{18} \text{ cm}^{-3}$) at the frequency of 6.47×10^{13} rad/s. The field is excited by a dipole polarized along z placed 400 nm above the GaAs surface.

S5. Measurement The radiation spectral characteristics among samples with different doping concentrations

To examine the influence of different carrier concentrations between emitter the receiver, we calculated the spectral heat flux and photon-tunneling maps for three dissimilar pairings: undoped–moderately doped, undoped–highly doped, and moderately doped–highly doped GaAs (Fig. S13). As shown in Fig. S13(a), the two pairings involving undoped GaAs exhibit relatively narrow spectral features near the optical-phonon resonance region. In contrast, the moderately doped–highly doped pairing exhibits more pronounced peaks over a broader low-frequency range. The tunneling probability contours in Figs. S13(b–d) clarify this behavior. For the pairings involving undoped GaAs, appreciable evanescent transmission is largely confined to narrow frequency intervals. The moderately doped–highly doped pairing supports broader transmission regions and multiple resonant features, consistent with its enhanced low-frequency spectral heat flux. These results show that unequal doping does not eliminate polaritonic coupling across the gap. The different carrier concentrations modify the resonance frequencies and linewidths on the two surfaces, and their spectral overlap determines which tunneling channels remain effective. Therefore, in the main text, the same doping was selected to maintain the consistency of the material response, and to capture the effect of carrier concentration on near-field radiation heat transfer in GaAs without introducing additional influences of emitter-receiver mismatch.

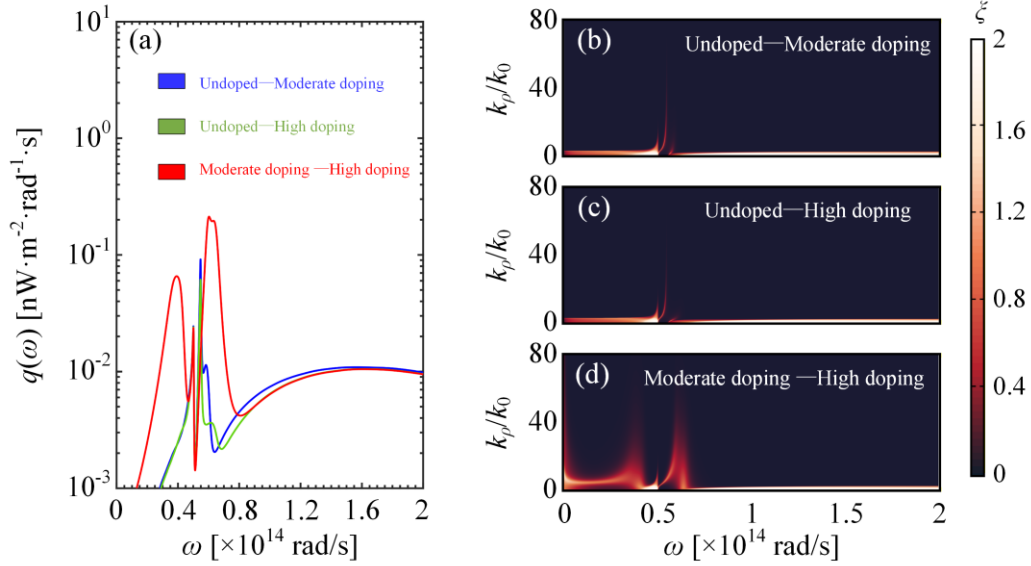


Fig. S13 (a) Spectral heat flux for undoped–moderately doped, undoped–highly doped, and moderately doped–highly doped pairings. Theoretical thermal photon tunneling probability contours for (b) undoped–moderately doped, (c) undoped–highly doped GaAs, (d) moderately doped–highly doped pairings. The calculation parameters for spacing and temperature are the same as those shown in Figs 3(c-d) in the main text.

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