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Hongliang Yi

yihongliang@hit.edu.cn

Harbin Institute of Technology <https://orcid.org/0000-0002-5244-7117>

Cheng-Long Zhou

Harbin Institute of Technology

Dong-Xu Li

Harbin Institute of Technology

Gui-Cheng Cui

Harbin Institute of Technology

Yong Zhang

Harbin Institute of Technology

Mauro Antezza

Université de Montpellier <https://orcid.org/0000-0003-4540-5864>

Shui-Hua Yang

National University of Singapore

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

Cheng-Long Zhou,^{1,2, a)} Dong-Xu Li,^{1,2, a)} Gui-Cheng Cui,^{1,2, a)} Shui-Hua Yang,³ Yong Zhang,^{1,2} Mauro Antezza,^{4,5} and Hong-Liang Yi^{1,2, b)}

¹⁾*School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China*

²⁾*Key Laboratory of Aerospace Thermophysics, Ministry of Industry and Information Technology, Harbin, China*

³⁾*Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583, Singapore*

⁴⁾*Institut Universitaire de France, 1 rue Descartes, F-75231 Paris, France*

⁵⁾*Laboratoire Charles Coulomb (L2C), UMR 5221 CNRS-Université de Montpellier, F-34095 Montpellier, France*

In nanoscale semiconductor devices, heat dissipation is often limited by interfacial thermal resistance and structural discontinuities, where conventional phonon-mediated conduction becomes constrained. Although near-field radiative heat transfer (NFRHT) provides a non-contact pathway that can exceed the blackbody limit, it remains unclear how carrier dynamics and lattice vibrations jointly influence NFRHT in semiconductors. Here, we experimentally investigate NFRHT in the polar semiconductor gallium arsenide (GaAs) across different doping levels. By measuring the heat flux between macroscopic GaAs wafers separated by a ~ 159 nm vacuum gap, we observe that heavily doped GaAs exhibits a $\sim 230\%$ increase in heat transfer compared to its undoped counterpart, with the heat flux exceeding the blackbody limit by more than an order of magnitude. **Combined fluctuational electrodynamics analysis and Raman spectroscopy indicate that this enhancement is associated with a coupled plasmonic–phononic response arising from intrinsic carrier–lattice interactions, leading to a broadened spectral distribution and enhanced thermal photons tunneling.** These results reveal a link between carrier–lattice dynamics and near-field thermal radiation, providing insight into the development of tunable, non-contact thermal management strategies in nanoelectronic systems.

I Introduction

The development of three-dimensional (3D) integration has driven semiconductor devices toward unprecedented computing densities^{1–3}. However, as device dimensions continue to shrink and active tiers are vertically stacked, thermal management has become a critical bottleneck^{4,5}. In these densely integrated architectures, adjacent active components are separated by ultrathin dielectric layers and complex bonding interfaces, where solid-state heat conduction is increasingly constrained by phonon–boundary scattering and interfacial thermal resistance^{5–8}. Moreover, imperfect solid–solid contacts, micro-delamination, and engineered electromechanical isolation further suppress phonon-mediated heat transport across nanoscale non-contact regions^{9–13}. Because key reliability metrics are highly temperature-sensitive, such localized heat accumulation can severely degrade device performance⁵. Therefore, developing efficient non-contact heat dissipation pathways is essential for next-generation nanoelectronics.

To overcome the intrinsic limitations of phonon-mediated thermal transport, near-field radiative heat transfer (NFRHT) offers a complementary and highly efficient mechanism^{14–17} [see Fig. 1(a)]. When two bodies are separated by subwavelength distances, evanescent electromagnetic modes can couple across the nanoscale gap, enabling thermal photon tunneling and producing radiative heat fluxes that exceed the blackbody limit by orders of magnitude^{18–23}. This enhancement is typically mediated by surface electromagnetic modes, such as surface phonon polaritons (SPhPs) in polar dielectrics^{24,25} and surface plasmon polaritons (SPPs) in metals or doped semiconductors^{26,27}. In semiconductor materials relevant to

integrated electronics, these surface excitations are intrinsically linked to their carrier properties^{28,29}. This is particularly evident in polar semiconductors, including second-generation materials such as gallium arsenide (GaAs) and indium phosphide (InP), as well as third-generation materials such as silicon carbide (SiC) and gallium nitride (GaN). These polar semiconductors exhibit a richer electrodynamic behavior, in which SPPs associated with free carriers interact with SPhPs generated by lattice vibrations^{30,31}, resulting in modified dispersion relations and an altered photonic density of states³². However, how these intrinsic carrier–lattice dynamics in semiconductors governs radiative energy transport across nanoscale gaps remains poorly understood. Clarifying this relationship not only advances our understanding of the interplay between thermal transport and semiconductor carrier physics but also may enable new strategies for high-efficiency thermal management at the nanoscale.

In this work, we experimentally and theoretically investigate near-field radiative heat transfer between parallel GaAs wafers separated by a vacuum gap of ~ 159 nm over a range of carrier concentrations, as shown in Fig. 1(b). We observe that the radiative heat flux (RHF) in the undoped system exceeds the blackbody limit by nearly an order of magnitude. Under identical nanoscale gap conditions, increasing the carrier concentration leads to a pronounced enhancement of the RHF, with a ~ 2.3 -fold increase at high doping levels. Analysis based on fluctuation electrodynamics and Raman spectroscopy indicates that this enhancement effect is not only attributable to carrier-induced SPPs excitation but is also related to broadband coupling between plasmonic modes and lattice-related SPhPs [Fig. 1(d)].

^{a)}These three authors contributed equally

^{b)}Electronic mail: [Corresponding author: yihongliang@hit.edu.cn](mailto:yihongliang@hit.edu.cn)

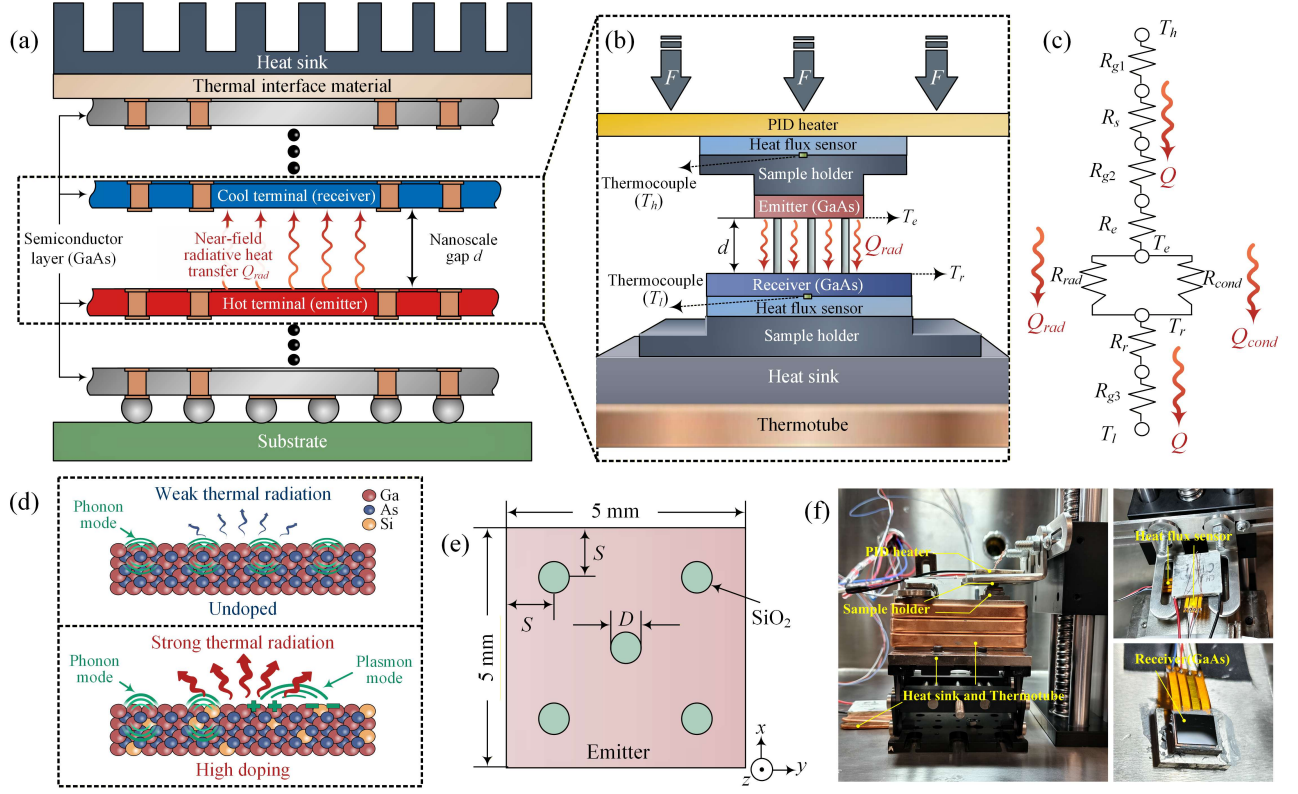


FIG. 1. **Experimental setup and sample characterization for measuring near-field radiative heat transfer.** (a) Schematic illustration of NFRHT within a 3D stacked chip architecture. (b) Configuration of the NFRHT measurement setup. The GaAs emitter and receiver are separated by a nanoscale vacuum gap of ~ 159 nm, maintained by five SiO_2 nanopillars. The measured total heat transfer rate, Q , includes both the near-field radiative contribution across the vacuum gap (Q_{rad}) and parasitic solid-state conduction through the nanopillars (Q_{cond}). The intrinsic surface temperatures of the emitter (T_e) and receiver (T_r) are reconstructed from the measured temperatures (T_h and T_l) by accounting for the thermal resistances of the thermal grease, bulk substrates, and interfaces. (c) Equivalent thermal resistance network of the experimental system. Here, R_g , R_s , R_e , and R_r denote the interfacial and bulk thermal resistances associated with the sample holder, emitter, and receiver. (d) Schematic illustration of doping-modulated near-field radiative excitation. (e) Layout of the SiO_2 nanopillars microfabricated on the emitter surface. Each nanopillar has a diameter of ~ 3 μm (see Supplementary Materials (SM)³³ for details). (f) Photograph of the experimental setup.

II Results and Discussion

A Experimental set-up and experimental scheme for measuring NFRHT

The experimental configuration for measuring near-field radiative heat flux consists of an emitter and a receiver, with surface areas of 5×5 mm^2 and 10×10 mm^2 , respectively. Both components are fabricated from GaAs wafers (thickness 375 μm ; Innostronix, GaAs-2S100U-350D-VT and GaAs-2N100Si-350S-VT) with a nanoscale surface roughness. The atomic force microscopy (AFM) images of the GaAs surface are provided in the SM³³. A nanoscale vacuum gap of ~ 159 nm is maintained by five SiO_2 nanopillars [Fig. 1(d)], each with a diameter of ~ 3 μm and fabricated on the emitter (see SM³³ for details). The nanopillars occupy only $1.41 \times 10^{-4}\%$ of the effective heat exchange area, ensuring that parasitic solid-state conduction remains negligible. To investigate carrier-dependent electrodynamic coupling between surface plasmon modes and surface phonon modes, GaAs wafers with three doping levels were studied: undoped, moderately doped ($N_e = 8.4 \times 10^{17} \text{ cm}^{-3}$), and highly doped ($N_e =$

$1.2 \times 10^{18} \text{ cm}^{-3}$). The carrier concentrations were verified by Hall measurements (ACCENT HL5550-LN2; see SM,³³). To ensure optimal spectral matching of surface modes, the emitter and receiver were prepared from wafers with identical doping levels, as asymmetric configurations are known to suppress near-field coupling^{34,35}.

The vacuum gap spacing was characterized *ex situ* by combining nanopillar height measurements (Dimension FastScan) with sample deflection obtained via white-light interferometry (RTEC UP-LAMBDA-U-3000). The resulting gap distances are estimated to be 159^{+38}_{-19} nm, 159^{+30}_{-25} nm, and 159^{+32}_{-30} nm for the undoped, moderately doped, and highly doped samples, respectively (see SM for structural characterization). Figure 1(b) presents a schematic of the apparatus used for the NFRHT measurements. **The emitter temperature is controlled and maintained at the prescribed value using a PID-regulated heater.** To ensure that the system reaches a steady state, heat accumulated in the receiver must be efficiently dissipated to maintain a relatively constant low temperature. To this end, thermotubes are installed between the heat sink and the vacuum chamber to transfer heat effectively to the external en-

vironment, thereby ensuring efficient cooling of the receiver. The receiver is actively stabilized at ~ 297 K by dissipating excess heat into a massive tungsten–copper heat sink and the vacuum chamber. A photograph of the experimental setup is shown in Fig. 1(f).

The total heat flux Q consists of radiative heat transfer across the nanoscale vacuum gap (Q_{rad}) and parasitic solid-state conduction through the SiO_2 nanopillars (Q_{cond}). The thermal conductivity of SiO_2 at room temperature is taken as $1.3 \text{ W m}^{-1} \text{ K}^{-1}$ (see Section 3 of the SM³³ for details of Q_{cond} evaluation). The total heat flux is continuously monitored using a high-precision heat flux sensor (FS13-HFM-8) placed between the receiver and the bottom sample holder. A second sensor is installed on the emitter side to verify one-dimensional heat transport; the agreement between the two measurements confirms negligible lateral heat leakage. The temperatures T_h and T_l are recorded by thermocouples embedded in the heat flux sensors. To obtain the intrinsic near-field thermal transport, the interface temperatures T_e and T_r across the vacuum gap are reconstructed from T_h and T_l using the thermal resistance network shown in Fig. 1(c), which accounts for the bulk resistances (R_e , R_r , R_s) and interfacial contact resistances (R_g) at the sensor–tungsten–copper, emitter–tungsten–copper, and receiver–tungsten–copper interfaces. For the receiving end, the total thermal resistance ($R_{g3} + R_r$) is influenced only by the interface between sample and sensor, as well as the thermal resistance of sample itself; therefore, the total thermal resistance is relatively low, at only $2.02 \times 10^{-5} \text{ K/W}$. For the emitting end, its total thermal resistance ($R_{g1} + R_s + R_{g2} + R_e$) is 13.23 K/W . These reconstructed temperatures are then used as inputs for the theoretical calculations. Prior to measurements, the heat flux sensors were calibrated using a standard K9 borosilicate glass reference. All experiments were conducted in a high-vacuum chamber maintained at $\sim 10^{-4} \text{ Pa}$ to eliminate convective heat transfer.

B Significant enhancement of NFRHT driven by carrier engineering

Figure 2 presents the theoretical and experimental NFRHT for GaAs samples with different carrier concentrations. The RHF between the emitter and the receiver is expressed as,^{36,37}:

$$\begin{aligned} Q_{rad} &= \int_0^\infty q(\omega) d\omega \\ &= \int_0^\infty d\omega [\Theta(\omega, T_e) - \Theta(\omega, T_r)] f(\omega, d), \end{aligned} \quad (1)$$

where $\Theta(\omega, T) = \hbar\omega / (e^{\hbar\omega/k_bT} - 1)$ denotes the mean energy of a Planck oscillator at frequency ω , and k_b is the Boltzmann constant. The spectral flux $q(\omega)$ represents the energy transferred by thermal photons at different frequencies^{38,39}. The spectral transfer function is given by $f(\omega, d) = \int_0^\infty \frac{k_p dk_p}{4\pi^2} [\xi_s(\omega, k_p) + \xi_p(\omega, k_p)]$ ^{40,41}, where $k_p = \sqrt{k_x^2 + k_y^2}$ represents the magnitude of the wavevector component parallel to the interfaces. It should be noted that when $k_p \leq \omega/c$, the radiative heat transfer is dominated by propagating waves, whereas when $k_p > \omega/c$, it is governed by evanescent waves⁴². The terms ξ_s and ξ_p correspond to the **thermal pho-**

tons tunneling probabilities for *s*- and *p*-polarizations, respectively⁴³. The total tunneling probability, $\xi = \xi_s + \xi_p$, is determined by the wavevector and the dielectric functions of the materials (detailed derivations are provided in the SM³³). The dielectric permittivity of *n*-doped GaAs, $\epsilon(\omega)$, is modeled to include both lattice and free-carrier contributions⁴⁴:

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_0 - \epsilon_\infty}{1 - \left(\frac{\omega}{\omega_{\text{TO}}}\right)^2 - \frac{i\omega\gamma}{\omega_{\text{TO}}^2}} - \frac{\epsilon_\infty \omega_p^2}{\omega^2 + i\omega\tau^{-1}}, \quad (2)$$

where ϵ_∞ is the high-frequency permittivity, ϵ_0 is the low-frequency permittivity, ω_{TO} is the transverse optical (TO) phonon frequency, γ is the damping constant of the transverse optical phonon, ω_p is the plasma frequency, and τ is the electron relaxation time. For specific parameters, please refer to the SM³³. **Carrier doping has been widely employed to regulate NFRHT in nonpolar semiconductors such as Si, where its principal role is commonly understood as introducing or tuning a Drude-type free-carrier response and the associated surface plasmon polaritons. Polar semiconductors present a different physical situation. In GaAs, mobile carriers coexist and interact with infrared-active polar optical phonons. Consequently, changing the carrier concentration modifies not only the plasmonic response but also the optical-phonon-related dielectric response, thereby reshaping the coupled surface-polariton spectrum governing NFRHT. The scientific question addressed here is therefore not whether conventional doping-induced SPPs can enhance NFRHT, but whether carrier concentration can serve as an intrinsic material-level parameter for controlling the plasmon–phonon response of a polar semiconductor without relying on artificial photonic structures.**

To elucidate the impact of carrier engineering on near-field thermal radiation, Fig. 2(a) shows the theoretical near-field RHF of GaAs as a function of the vacuum gap (100–500 nm) at different carrier concentrations, with the emitter and receiver temperatures fixed at $T_e = 347 \text{ K}$ and $T_r = 297 \text{ K}$, respectively. A clear monotonic increase in RHF is observed with increasing carrier concentration. For example, at a gap of $d = 160 \text{ nm}$, increasing the carrier concentration from the undoped case to $N_e = 10^{17} \text{ cm}^{-3}$ enhances the heat flux from 3.06 to 4.21 kW m^{-2} . As the carrier concentration increases further to $N_e = 10^{18} \text{ cm}^{-3}$, the heat flux can reach 6.87 kW m^{-2} . For comparison, doped Si is also evaluated as a non-polar reference system⁴⁵. At the same carrier concentration ($N_e = 10^{17} \text{ cm}^{-3}$), GaAs exhibits a ~ 1.7 -fold higher heat flux than Si at $d = 160 \text{ nm}$.

The experimental near-field RHF, Q_{rad} , is plotted as a function of the temperature difference $\Delta T = T_e - T_r$ in Figs. 2(b–d). This intrinsic radiative flux is obtained by subtracting the parasitic solid-state conduction through the SiO_2 nanopillars, Q_{cond} , from the total measured heat rate, Q , and then normalizing by the effective surface area. In this work, to ensure high measurement accuracy, near-field thermal radiation must dominate the overall heat transfer process. At a temperature difference of $\Delta T = 50 \text{ K}$, the conductive contribution Q_{cond} accounts for less than 15.87% of Q in the undoped samples, decreasing to below 7.85% for the moderately doped config-

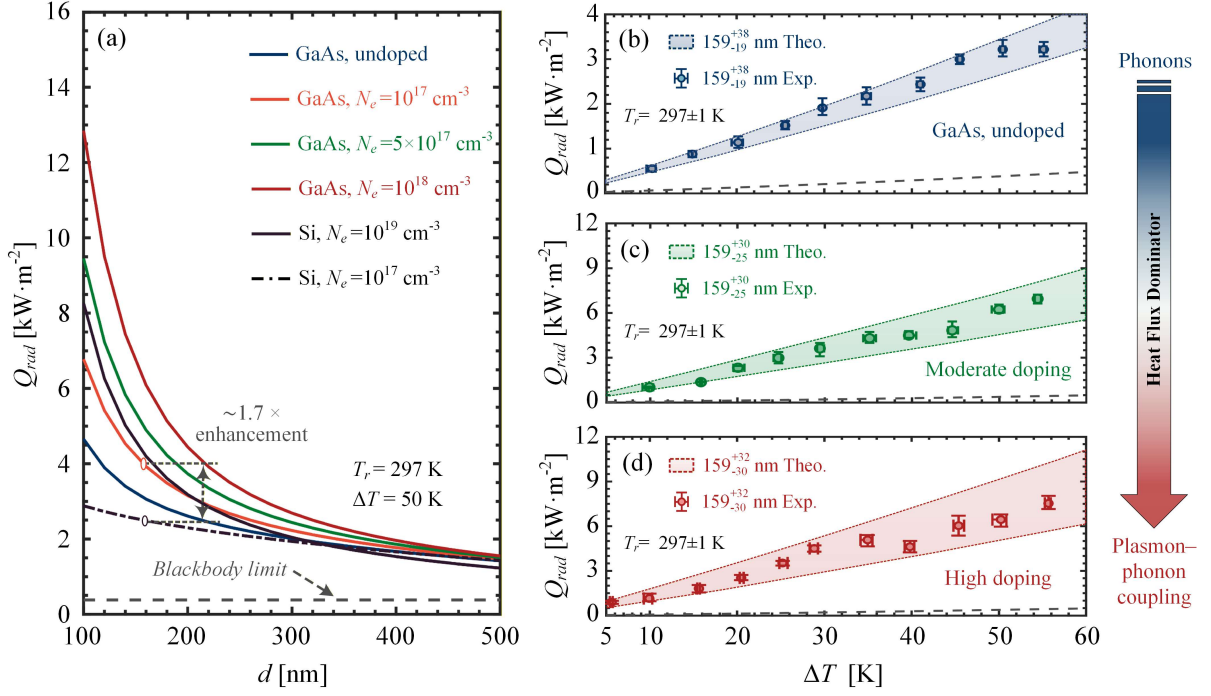


FIG. 2. **Enhancement of radiative heat transfer induced by carrier engineering.** (a) Theoretical RHF of GaAs as a function of the vacuum gap at varying carrier concentrations, evaluated at an emitter temperature of $T_e = 347$ K and a receiver temperature of $T_r = 297$ K. To highlight the thermal enhancement driven by plasmon-phonon coupling in polar semiconductors, the theoretical RHF of silicon (Si) at different carrier concentrations is also provided as a fundamental reference. (b–d) Experimentally measured RHF for the (b) undoped, (c) moderately doped ($N_e = 8.4 \times 10^{17} \text{ cm}^{-3}$), and (d) highly doped ($N_e = 1.2 \times 10^{18} \text{ cm}^{-3}$) GaAs samples as a function of the temperature difference, $\Delta T = T_e - T_r$, with the receiver stabilized at $T_r = 297 \pm 1$ K. The shaded regions represent theoretical predictions based on fluctuational electrodynamics, accounting for uncertainties in receiver temperature and structural parameters. The gray dotted line indicates the far-field black-body radiation limit as described by the Stefan-Boltzmann law $Q_{bb} = \sigma(T_e^4 - T_r^4)$, where σ is the Stefan-Boltzmann constant.

uration and to below 7.14% for the highly doped configuration. In Figs. 2(b–d), the experimental radiative fluxes are systematically compared with predictions from fluctuational electrodynamics. The theoretical uncertainty bands (shaded regions) explicitly account for deviations in receiver temperature and structural variations (actual nanopillar height and macroscopic sample deflection). Across all doping levels, the experimentally measured radiative fluxes show good agreement with theoretical predictions. As shown in Figs. 2(b–d), the radiative heat flux exhibits a clear increasing trend with carrier concentration. At $\Delta T = 55$ K, the undoped GaAs system exhibits a heat flux of $\sim 3.22 \text{ kW m}^{-2}$, whereas the highly doped sample reaches $\sim 7.53 \text{ kW m}^{-2}$, corresponding to an enhancement of approximately 2.3 times. When normalized to the far-field blackbody limit [Fig. 3(a)], the measured flux exceeds this limit by nearly an order of magnitude in the undoped case and by more than a factor of 20 at a carrier concentration of $1.2 \times 10^{18} \text{ cm}^{-3}$. **The doping-induced enhancement is distance dependent.** At a larger vacuum gap of approximately 410 nm and $\Delta T = 50$ K, the radiative heat fluxes are 1.84 and 1.62 kW m^{-2} for the highly doped and undoped configurations, respectively, corresponding to an enhancement of approximately 14 % (SM³³, Fig. S7).

C Material-intrinsic plasmon–phonon coupling mechanism of NFRHT enhancement

To gain insight into the origin of the observed NFRHT enhancement, we show theoretical spectral analysis alongside Raman spectroscopy measurements (LabRam HR Evolution), as shown in Figs. 3(b–e). The undoped GaAs sample exhibits a pronounced longitudinal optical (LO) phonon peak [Fig. 3(b)]. With increasing carrier concentration, this peak gradually redshifts, accompanied by spectral broadening and redistribution of intensity. Such changes are induced by the doping-induced modifications of the lattice response in GaAs. In an ideal crystal, phonons propagate as plane waves and are restricted to excitations at the Brillouin zone center. Doping introduces lattice mismatch dislocations and structural disorder, reducing phonon correlation lengths and perturbing lattice vibrations⁴⁶. In addition, the substitution of trivalent Ga by tetravalent Si induces local stress and modifies lattice force constants^{47,48}. These effects collectively soften the vibrational modes, leading to the observed redshift.

The observed shift and broadening of Raman feature provide experimental evidence that introducing carriers modifies the longitudinal lattice response, rather than merely adding a free-carrier plasmonic response to an unchanged phononic background. These observations support the carrier–lattice

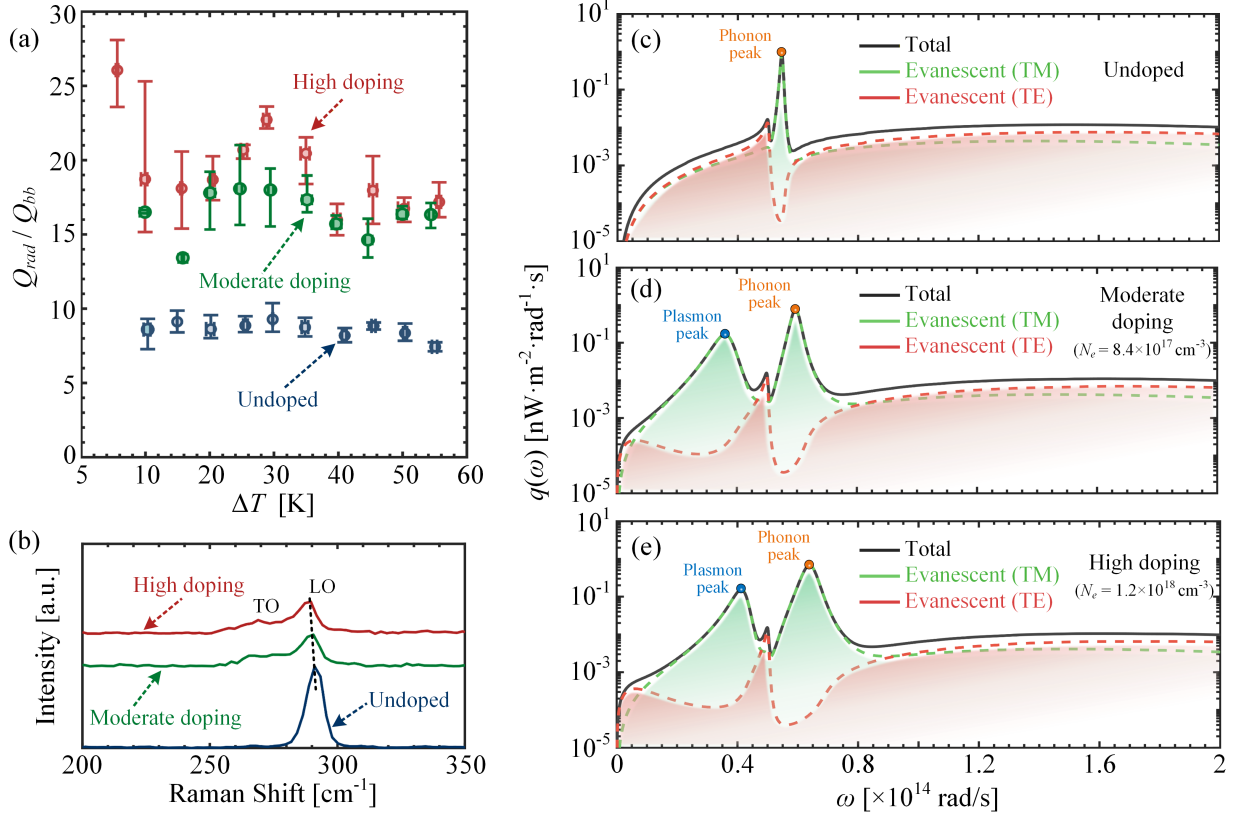


FIG. 3. **Spectral signatures and experimental evidence of carrier-enhanced NFRHT.** (a) Radiative heat flux enhancement factor, normalized to the far-field blackbody limit (Q_{rad}/Q_{bb}), as a function of the temperature difference for different carrier concentrations. **It is noticed that the local fluctuations in the experimental ratios are attributable to measurement uncertainties.** (b) Experimental Raman spectra of GaAs at different doping levels, showing doping-dependent modifications of the optical phonon response. (c–e) Calculated total spectral heat flux, together with the individual TM- and TE-polarized components, for (c) undoped GaAs, (d) moderately doped GaAs ($N_e = 8.4 \times 10^{17}$ cm⁻³), and (e) highly doped GaAs ($N_e = 1.2 \times 10^{18}$ cm⁻³). All theoretical spectral calculations are performed at a fixed vacuum gap of $d = 159$ nm and a temperature difference of $\Delta T = 50$ K.

interaction underlying the intrinsic plasmon–phonon self-hybridization mentioned in this work. Because the optical-phonon response contributes to the dielectric function, its interaction with free carriers reshapes the phonon-derived surface-polaritonic modes and consequently the thermal-photon tunneling spectrum. However, it is worth noting that the measured Raman peak positions cannot be used to fit the radiation heat transfer model. The dielectric parameters related to the carrier concentration used in the fluctuating electrodynamics calculation, including the TO and LO phonon frequencies, phonon damping constants, plasma frequency, and carrier relaxation rate, were obtained by fitting the Hall measurement (SM³³, Table S1). Therefore, Raman spectroscopy thus supports the material-level origin of the proposed mechanism, although it does not directly measure the surface modes responsible for NFRHT.

The calculated spectral heat flux further elucidates this **heat-flux enhancement** [Figs. 3(c–e)]. Across all carrier concentrations, the spectral response is dominated by TM polarization, indicating that near-field heat transfer in GaAs is primarily driven by surface polaritonic modes (SPPs and

SPhPs)^{49,50}. In the undoped configuration, the spectrum exhibits a narrowband peak associated with SPhPs. As the carrier concentration increases, an additional plasmonic contribution emerges and shifts with carrier density, consistent with the corresponding variation in plasma frequency [Eq. (2)]. At the same time, as the carrier concentration increases from undoped GaAs to highly doped GaAs, the half-width at half-maximum of the original phonon-dominated spectral feature increases from 8.45×10^{12} to 5.36×10^{13} rad s⁻¹, corresponding to a 7.5-fold spectral broadening. Together with the emergence of an additional lower-frequency branch, this broadening expands the range of spectral channels and accounts for the broadband enhancement observed in the total near-field radiative heat flux [Figs. 3(c–e)]. These results indicate that, with increasing carrier concentration, the NFRHT of GaAs evolves from a narrow-band, phonon-dominated response to a broader spectral distribution mediated by coupled plasmon–phonon modes, forming a multichannel energy-transfer network. This explains the RHF enhancement phenomenon observed in Fig. 2 as the carrier concentration increases.

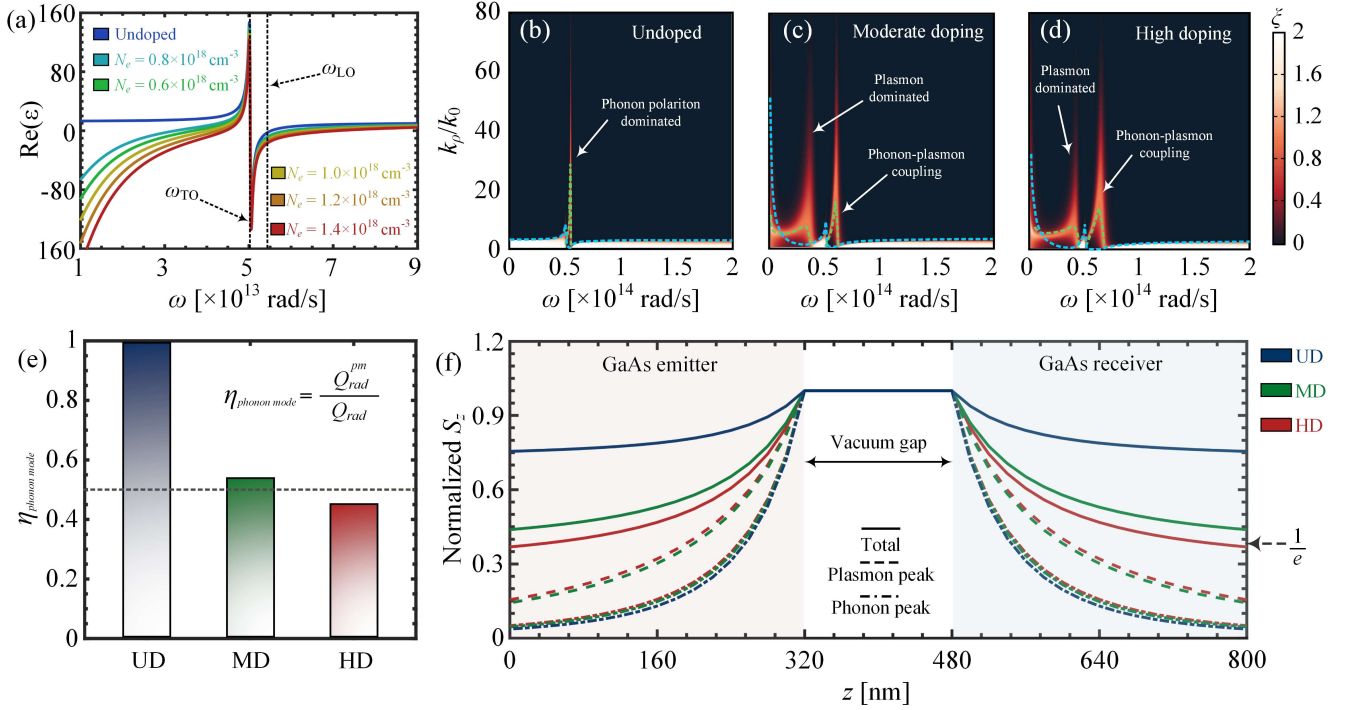


FIG. 4. **Electrodynamics analysis of plasmon–phonon-related heat transfer enhancement.** (a) Real part of the permittivity of GaAs at different carrier concentrations. (b–d) Calculated **thermal photons** tunneling probability contours for (b) undoped, (c) moderately doped, and (d) highly doped GaAs. The green dashed lines represent the dispersion relations at different carrier concentrations (see SM³³ for details). The cyan dashed lines denote the light line in GaAs ($k_p = k_0\sqrt{\epsilon}$). (e) Calculated fractional contribution of the phonon-related component to the total NFRHT at different carrier concentrations. Here, UD, MD, and HD denote undoped, moderately doped, and highly doped GaAs, respectively. (f) Spatial distribution of the z -component of the Poynting vector (S_z) within the emitter and receiver at representative frequencies, as well as the frequency-integrated result. The Poynting vector is normalized to its value in the vacuum gap.

To provide a conceptual visualization, Fig. 1(d) illustrates the evolution of near-field radiative processes with carrier concentration. In the undoped regime, near-field thermal radiation is primarily mediated by surface phonon polaritons. As the carrier concentration increases, additional plasmonic modes are introduced, which interact with phononic excitations and modify the overall spectral response. As shown by the dielectric function in Fig. 4(a), doping leads to a negative real part of the permittivity of GaAs at low frequencies, enabling the excitation of SPPs. Meanwhile, within the phonon resonance band $[\omega_{\text{TO}}, \omega_{\text{LO}}]$, the real part of the permittivity decreases with increasing carrier concentration. In Section 4 of the SM³³, we further demonstrate the real-space electric field excitation behavior of surface modes in GaAs at different carrier concentrations. The **thermal photons** tunneling probability in momentum space is presented in Figs. 4(b–d). The **thermal photons** probability represents the tunneling probability of thermal photons between the emitter and receiver. In the undoped case, the tunneling probability exhibits a narrow, high- k_p feature, characteristic of SPhPs-mediated NFRHT^{24,25}. However, as shown in Fig. 4(b), the tunneling band of thermal photons mediated by SPhPs is excessively narrow. This results in a limited excitation of high-wavevector thermal photon energy, while frustrated modes ($k_0 < k_p < k_0\sqrt{\epsilon}$) dominate the spectral contribution, which

severely restricts the overall radiative heat transfer capability. With increasing carrier concentration, an additional broader branch emerges, while the phonon-related high-intensity band becomes more pronounced. Meanwhile, the **thermal photons** tunneling at large wavevectors ($k_0\sqrt{\epsilon} < k_p$) becomes increasingly significant (that is, having a wider bright band branch at higher wavevector region) [Figs. 4(b–d)]. This shift in **thermal photons** tunneling behavior indicates that a greater number of high-wavevector photons participate in the tunneling process, enabling highly doped GaAs to achieve enhanced near-field radiative energy transport. The green dashed lines represent the dispersion relations of the system at different carrier concentrations (see SM³³ for details), which align well with the locations of the tunneling bands. As the carrier concentration increases, the phonon-related dispersion feature shifts toward lower wavevectors and becomes spectrally broader.

Figure 4(e) shows the calculated fractional contribution of the phonon-related component to the total radiative heat flux. Here, the phonon contribution ($Q_{\text{rad}}^{\text{pm}}$) is obtained by considering only the lattice term in the dielectric function [Eq. (2)]. The relative contribution of this component decreases with increasing carrier concentration, indicating the growing importance of carrier-related effects. **The comparison in Fig. 4(e) is intended only to illustrate that the influence of the free-carrier Drude response becomes increasingly pronounced with in-**

creasing carrier concentration. It should not be interpreted as a quantitative decomposition of the total heat flux into independent plasmonic and phononic contributions, because the carrier and lattice responses jointly determine the complete surface-polariton and near-field photon-transmission characteristics. To further examine the spatial characteristics of energy transfer, the z -component of the Poynting vector (S_z) is plotted in Fig. 4(f) across the emitter and receiver separated by the 159-nm vacuum gap. As discussed above, as the carrier concentration increases, the radiative heat transfer process in GaAs is gradually dominated by SPPs and SPPs-SPhPs coupling modes characterized by large wavevectors. Since evanescent waves with larger wavevectors exhibit reduced skin depths within the solid¹⁴, the energy flux becomes more localized near the vacuum/GaAs interface. This trend is consistent with the more rapid decay of the Poynting vector observed in the highly doped system compared to the undoped case [Fig. 4(f)].

It is noticed that, here, 'material-intrinsic' denotes that the interacting free-carrier and polar-lattice excitations coexist within uniformly doped GaAs and couple through their internal long-range Coulomb fields. Carrier concentration therefore regulates the coupled dielectric response at the material level. This differs from hybridization implemented by combining distinct materials or fabricating resonant structures, as exemplified by graphene/h-BN heterostructures³⁹, metal-dielectric multilayers⁵¹, and patterned resonators⁵². Here, different resonance modes reside in the same semiconductor, allowing the polaritonic spectrum to be tailored without additional heterostructure assembly or resonator patterning. This structural simplicity, together with compatibility with semiconductor doping and planar processing, offers a complementary route to broadband NFRHT enhancement.

III Conclusion

In summary, we have experimentally and theoretically investigated near-field radiative heat transfer between GaAs wafers separated by a ~ 159 -nm vacuum gap. We find that increasing the carrier concentration leads to a substantial enhancement of the radiative heat flux, with heavily doped GaAs exhibiting an approximately 2.3-fold increase compared to the undoped case, and a heat flux that exceeds the Stefan-Boltzmann limit by more than an order of magnitude. Combined fluctuational electrodynamics analysis and Raman spectroscopy indicate that this enhancement originates from carrier-induced surface plasmon-phonon coupling, which modifies the thermal photons tunnelling behavior and spectral characteristic of GaAs sample. As the carrier concentration increases, an additional low-frequency tunnelling branch mediated by plasmonic resonance emerges, accompanied by significant broadening and intensification of the original phonon-dominated tunnelling band. These results provide experimental evidence linking microscopic electrodynamic behavior to near-field thermal radiation and offers insight into the modulation of near-field radiative heat transfer via carrier concentration. The carrier-lattice coupling mechanism identified in GaAs may extend to other doped polar semiconductors containing mobile carriers and infrared-active optical

phonons, such as InSb⁵³ and TiO₂⁵⁴, motivating broader exploration of carrier-engineered NFRHT.

This work offers a pathway toward controllable, non-contact thermal management strategies in semiconductor systems. Moreover, the present measurements establish carrier-dependent NFRHT enhancement in a near-room-temperature to moderate-temperature regime. Extending the emitter temperature above 600 K represents an important direction for future investigation. At elevated temperatures, changes in optical-phonon frequency and damping, carrier relaxation, and the thermally excited spectral range may further reshape the plasmonic-phononic response and the resulting near-field heat transfer.

IV Data Availability

Data available on request from the authors.

V Acknowledgments

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