

Response to comments from the Reviewer #4

Comment: This paper reports a broadband enhancement effect of near-field radiative heat transfer (NFRHT) driven by intrinsic carrier-lattice interactions in doped GaAs. Unlike traditional approaches that achieve the hybridization of plasmonic polaritons and phononic polaritons through multilayer photonic crystals, this work reveals a new mechanism of polariton coupling at a more microscopic level. By combining carefully designed experiments with wave electrodynamic theoretical analysis, the authors reveal the mechanism by which carrier concentration modulation significantly enhances the near-field radiative heat flux, and point out that this enhancement stems from broadband thermophoton tunneling resulting from plasma-phonon coupling. Overall, this work addresses a cutting-edge topic, features a rigorous experimental design, and presents a clear physical picture, demonstrating high levels of innovation and academic value. I recommend acceptance after revisions. Detailed review comments and revision suggestions are provided below.

Response: We sincerely thank the Reviewer for the positive assessment of our work and the recommendation for publication in *Light Science & Application* after revision. We appreciate the constructive suggestions concerning the experimental motivation, the physical interpretation of the coupling mechanism, the meaning of spectral broadening, and the scope of our conclusions. Our point-by-point responses and the corresponding proposed manuscript text are provided below.

Comment 1: In the introduction, the author mentions that layering defects may exist in semiconductor layered structures, and that near-field radiation heat transfer may provide an unexpected heat transfer pathway in such defects. Please cite relevant references in the introduction to further support the view that layering defects exist

Response 1: We thank the Reviewer for this suggestion. The relevant defects are interfacial voids and locally unbonded regions in wafer-bonded structures. Direct experimental evidence is available: Zhang and Raskin examined void formation in low-temperature Si–Si and SiO₂–SiO₂ wafer bonding [R1], while Nagano et al. identified post-annealing voids at SiO₂–SiO₂ bonding interfaces used for three-dimensional integration and compared their formation with SiCN–SiCN interfaces [R2]. These studies directly support the existence of interfacial discontinuities in semiconductor integration.

These references confirm the presence of interfacial defects and voids in wafer-bonded structures. Such discontinuities interrupt direct solid-state heat conduction across locally unbonded regions, hindering heat dissipation and potentially causing localized heat accumulation and reduced temperature uniformity. When these non-contact regions have sufficiently small separations, near-

field radiative heat transfer may provide an additional pathway for energy exchange across the gaps, partially compensating for the disruption of conductive heat transport. This possibility motivates our investigation of carrier-enhanced near-field radiative heat transfer between semiconductor wafers.

We realize that the original text may not have conveyed this motivation with sufficient accuracy. Therefore, we have included relevant references [11] and [13] in the first paragraph of the “Introduction” to help readers better understand it.

References cited in this response

- [R1] X. X. Zhang and J.-P. Raskin, “Low-temperature wafer bonding: A study of void formation and influence on bonding strength,” *Journal of Microelectromechanical Systems* 14, 368–382 (2005).
- [R2] F. Nagano et al., “Origin of voids at the SiO₂/SiO₂ and SiCN/SiCN bonding interface using positron annihilation spectroscopy and electron spin resonance,” *ECS Journal of Solid State Science and Technology* 12, 033002 (2023).
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Comment 2: The mechanism of carrier-induced plasma-phonon polariton coupling revealed in this paper is innovative. It arises entirely from the material’s intrinsic electron-phonon interaction and forms spontaneously in uniformly doped semiconductors without the need for artificial photonic crystal structures—a fundamental distinction from traditional ion-phonon polariton hybridization achieved through periodic dielectric structures. Since both share the term “polariton interaction” but have fundamentally different physical origins, we recommend that the authors add a brief conceptual clarification at the end of the section titled “Intrinsic plasmon-phonon coupling mechanism,” explicitly stating that this work pertains to “intrinsic material modulation” rather than “hybridization via artificial structures,” to prevent reader misunderstanding.

Response 2: We thank the Reviewer for this insightful suggestion. We agree that the term “polariton interaction” requires a clearer explanation of the physical origin and implementation of the coupling considered here. In doped GaAs, collective oscillations of free carriers couple to the polarization associated with polar optical lattice vibrations through the long-range Coulomb interaction, giving rise to hybrid plasmon–phonon excitations within the same material [R1]. Changing the carrier concentration modifies the plasma frequency and its spectral relationship with the optical phonons, thereby reshaping the coupled dielectric response and the surface-polariton modes relevant to NFRHT. Thus, “intrinsic” refers to the origin of the coupling within the doped semiconductor itself. This interpretation is consistent with studies of plasmon–phonon hybridization in doped semiconductors [R2].

Artificially micro-nano photonic crystals provide another powerful route to polariton coupling. For example, Lu et al. demonstrated the effect of hybridization between graphene plasmons and h-BN phonon polaritons by assembling a graphene/h-BN heterostructure for NFRHT [R3]. Lim et al. experimentally tailored NFRHT through the coupling of surface plasmon polaritons at multiple interfaces in metallo-dielectric multilayers [R4]. More recently, Wang et al. demonstrated enhanced NFRHT using patterned gold split-ring resonators whose resonances couple strongly to surface phonon polaritons in SiN membranes [R5]. These studies illustrate how combining distinct constituents or designing resonant structures can produce and control coupled modes. The relevant distinction concerns where the interacting excitations originate and how their coupling is realized: in these micro-nano photonic systems, the constituent interfaces or resonator geometry establish the hybrid electromagnetic response; in our system, the carrier and lattice degrees of freedom interact within doped GaAs.

This intrinsic approach offers several practical advantages. It enables plasmon–phonon coupling without adding a separate plasmonic coating, constructing a multilayer optical stack, or patterning resonators to generate the hybrid response. Carrier concentration provides a material parameter for tailoring the polaritonic spectrum while retaining a simple planar configuration. Consequently, the approach reduces the structural fabrication requirements associated with establishing the coupling and offers a route compatible with semiconductor doping and planar wafer processing. In the present work, this material-level control enables broader spectral participation in near-field energy transfer and enhanced radiative heat flux. It therefore provides a complementary strategy to artificial structural engineering for controlling NFRHT.

We recognize that the original wording did not make this distinction sufficiently explicit. Following the Reviewer’s suggestion, we have added the following conceptual clarification at the end of the subsection “Material-intrinsic plasmon-phonon coupling mechanism of NFRHT enhancement”:

“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.”

References cited in this response

- [R1] B. B. Varga, “Coupling of Plasmons to Polar Phonons in Degenerate Semiconductors,” *Physical Review* 137, A1896–A1902 (1965).
- [R2] J.-M. Lihm and C.-H. Park, “Plasmon-Phonon Hybridization in Doped Semiconductors from First Principles,” *Physical Review Letters* 133, 116402 (2024).
- [R3] L. Lu, B. Zhang, H. Ou, B. Li, K. Zhou, J. Song, Z. Luo, and Q. Cheng, “Enhanced Near-Field Radiative Heat Transfer between Graphene/hBN Systems,” *Small* 18, 2108032 (2022).
- [R4] M. Lim, J. Song, S. S. Lee, and B. J. Lee, “Tailoring Near-Field Thermal Radiation between Metallo-Dielectric Multilayers Using Coupled Surface Plasmon Polaritons,” *Nature Communications* 9, 4302 (2018).
- [R5] Z. Wang et al., “Metamaterial-Enhanced Near-Field Radiative Heat Transfer,” *Nature* 654, 64–68 (2026).

Comment 3: Although the title and abstract emphasize “broadband enhancement,” the spectral analysis in the main text (Fig. 3(c-e)) shows that this enhancement primarily manifests as the introduction of a plasma branch and the broadening of the phonon branch, rather than continuous broadband coverage. It is recommended that the authors define the physical meaning of “broadband” more precisely in the conclusions or abstract, for example, by specifying the frequency range (e.g., from terahertz to tens of terahertz) or by comparing the increase in spectral width relative to the undoped case.

Response 3: We thank the Reviewer for pointing out this ambiguity. We agree that the original manuscript described the broadband effect primarily in qualitative terms and that a quantitative spectral metric is needed to substantiate this terminology. Here, “broadband enhancement” refers to the expansion and redistribution of the spectral channels relative to the narrow phonon-dominated response of undoped GaAs. It does not imply a spectrally flat enhancement at every frequency or a single uninterrupted high-transmission band. As shown in Figs. 3(c–e), increasing the carrier concentration not only introduces an additional lower-frequency plasmon-related branch but also substantially broadens the original phonon-dominated spectral feature. Quantitatively, the half-width at half-maximum of this feature increases from approximately ($\sim 8.45 \times 10^{12} \text{ rad s}^{-1}$) for undoped GaAs to approximately ($\sim 5.36 \times 10^{13} \text{ rad s}^{-1}$) for highly doped GaAs, corresponding to a 7.5-fold increase in spectral width.

Following the Reviewer's suggestion, we have added the following quantitative description to the 2nd paragraph on page 5

“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 $5.36 \times 10^{13} \text{ rad s}^{-1}$, 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...”

Comment 4: Although the supplementary material shows that the enhancement persists but weakens at a 410 nm spacing, the main text does not mention this scale dependence. We recommend briefly mentioning the distance dependence of the enhancement effect in the conclusions or discussion section of the manuscript to enhance the completeness of the conclusions and to indicate the trend of this effect attenuation at greater spacings.

Response 4: We agree that the distance dependence is important for interpreting the enhancement and its practical range. The larger-gap results are provided in Section S4 and Fig. S7 of the Supplementary Material. At $d \approx 410 \text{ nm}$ and $\Delta T = 50 \text{ K}$, the reported radiative heat fluxes are 1.84 kW m^{-2} for the highly doped configuration and 1.62 kW m^{-2} for the undoped configuration. Their ratio is approximately 1.14, corresponding to an enhancement of approximately 14%. Thus, the enhancement still exists but is substantially weaker than the approximately 2.3-fold ratio measured near 159 nm.

Importantly, increasing the gap does not eliminate the carrier-induced modification of the material response. As shown in Fig. S10, the additional lower-frequency spectral feature and the broadening and shift of the phonon-dominated feature remain observable at $d=410 \text{ nm}$. Figure S11 also shows that doping continues to modify the distribution of thermal photons tunnelling channels.

However, at smaller gap, doping can effectively improve the tunneling of thermal photons at large wavevector, thereby significantly enhancing radiative heat transfer. As the gap increases, the thermal photons tunneling at large wavevector is filtered out by the vacuum gap, at which point the enhancement effect for thermal photons tunneling of doping on large wavevectors ceases to be effective. This reduction can be understood from the momentum-dependent attenuation of evanescent waves across the vacuum gap. For an evanescent mode, the transmission contains an exponential factor proportional to $\exp(2ik_z d)$. Increasing the gap therefore acts as a momentum-space filter that preferentially suppresses large-wavevector modes of thermal photons tunneling. These large-wavevector modes make an important contribution to NFRHT at small separations. When the gap increases to approximately 410 nm, the range of wavevectors of efficiently tunnelling

across the gap contracts markedly. Furthermore, doping actually suppresses the tunneling of thermal photons with smaller wavevectors ($< 4 k_0$), as shown in Fig. S11. Therefore, the spectral signature of the intrinsic carrier–lattice interaction remains visible, whereas its effect on the total transferred heat is substantially reduced. This explains why a clear modification of thermal photons tunnelling persists at 410 nm, but the enhancement effect of doping on radiative heat transfer gradually diminishes.

Following the Reviewer’s suggestion, we have added the following quantitative description to the 1st paragraph on page 4:

“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).”

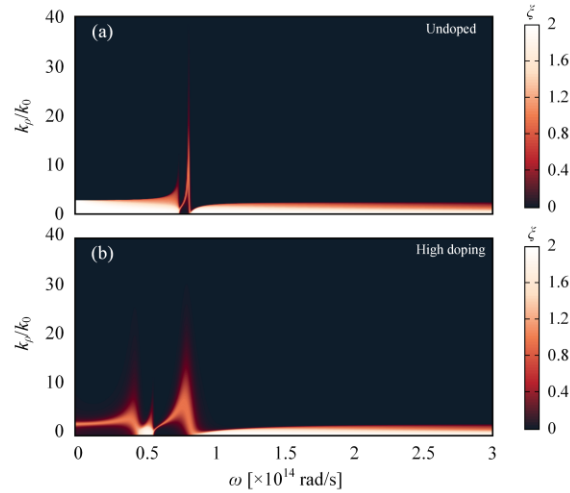


Fig. S11 Theoretical thermophotonic tunneling probability contours for (a) undoped and (b) highly doped GaAs at a fixed vacuum gap of $d = 410$ nm.

Comment 5: In the article, the author only presents heat transfer between samples with the same doping concentration. Although the author emphasizes that this arrangement can produce the strongest heat transfer effect, I am curious to know what the heat transfer would be like between samples with different doping concentrations. I would ask the author to provide an explanation, at least from a theoretical perspective.

Response 5: We thank the Reviewer for raising this important question. Near-field radiative heat transfer mediated by surface polaritons depends strongly on the spectral matching of the electromagnetic modes supported by the emitter and receiver. In fluctuational electrodynamics, efficient evanescent-wave transmission occurs when the two surfaces support compatible modes at

the same frequency and in-plane wavevector. When the two GaAs wafers have the same carrier concentration, their carrier-dependent dielectric responses and surface-polariton dispersions are closely matched, favoring strong coupling of the evanescent fields across the vacuum gap.

When the emitter and receiver have different carrier concentrations, the plasma frequency and the associated carrier-modified surface-polariton spectrum differ between the two surfaces. Consequently, their resonant regions overlap only partially. This spectral detuning weakens the cross-gap coupling of the corresponding surface modes and generally reduces the resonant contribution to the total heat flux. Namely, the intrinsic carrier–lattice interaction within each doped GaAs wafer remains present; what is weakened is the coupling between the differently tuned surface modes across the vacuum gap.

This interpretation is supported by previous theoretical and experimental studies of NFRHT between dissimilar materials. Messina et al. theoretically demonstrated that mismatch between the surface-polariton resonances of two materials can strongly reduce their radiative heat exchange and that restoring the spectral overlap enhances the transfer [R1]. Tang et al. experimentally measured NFRHT between SiC and doped Si and found a smaller integrated enhancement for the dissimilar SiC–Si configuration than for the matched Si–Si configuration, which they attributed to the mismatch between their surface-polariton resonances and dispersion relations [R2]. More recently, Habibzadeh et al. experimentally showed that the weaker NFRHT between dissimilar SiC and LiF surfaces could be substantially enhanced by using graphene to restore coupling between their surface modes [R3]. These studies confirm the importance of spectral matching for resonant near-field energy transfer.

In the present experiments, we intentionally paired emitter and receiver wafers with the same doping concentration. Our primary objective was to determine how carrier concentration modifies the intrinsic dielectric response of GaAs and thereby regulates NFRHT. Comparing undoped–undoped, moderately doped–moderately doped, and highly doped–highly doped configurations keeps the two surfaces spectrally matched at each doping level. Using different doping concentrations on the two sides would introduce an additional spectral-detuning effect and make it more difficult to distinguish this mismatch from the intrinsic influence of carrier concentration.

Since the decrease in heat flux caused by this mismatch between the emitter and the receiver has been extensively studied, we did not include it in our initial manuscript. Following the Reviewer’s suggestion, we have added a theoretical analysis of the asymmetric doping configurations to Section S5 and Fig. S13 of the Supplementary Material.

“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.”

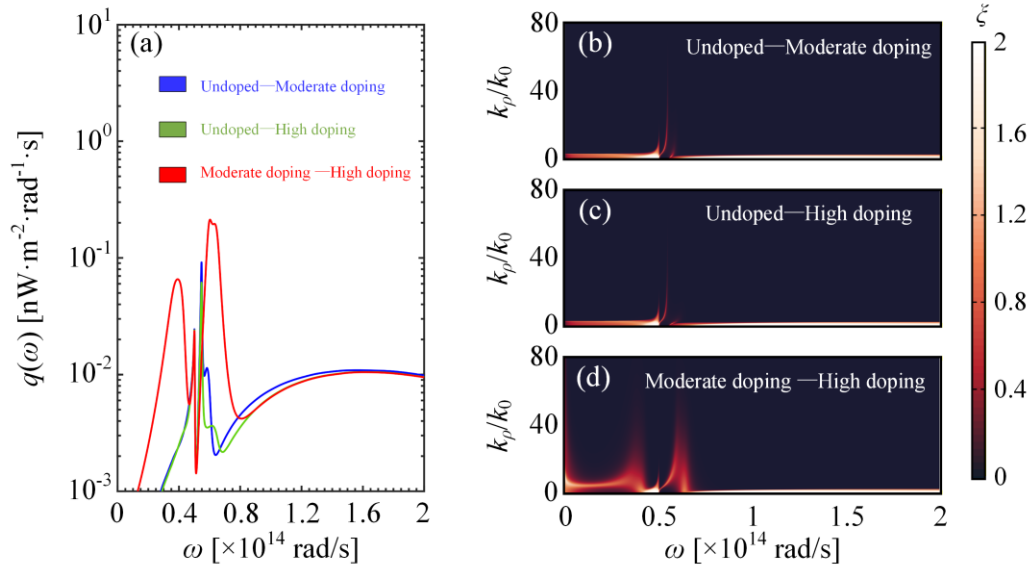


Fig. S13 (a) Spectral heat flux for undoped–moderately doped, undoped–highly doped, and moderately doped–highly doped pairings. Theoretical thermal photon tunneling probability contours for (b) undoped–moderately doped, (c) undoped–highly doped GaAs, (d) moderately doped–highly doped pairings. The calculation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

References cited in this response

[R1] R. Messina, P. Ben-Abdallah, B. Guizal, and M. Antezza, “Graphene-based amplification and tuning of near-field radiative heat transfer between dissimilar polar materials,” *Physical Review B* 96, 045402 (2017).

- [R2] L. Tang, J. DeSutter, and M. Francoeur, “Near-field radiative heat transfer between dissimilar materials mediated by coupled surface phonon- and plasmon-polaritons,” *ACS Photonics* 7, 1304–1311 (2020).
- [R3] M. Habibzadeh, Md. S. Islam, P. K. Chow, and S. Edalatpour, “Enhancing near-field radiative heat transfer between dissimilar dielectric media by coupling surface phonon polaritons to graphene’s plasmons,” *ACS Photonics* 11, 4101–4110 (2024).
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Comment 6: Does this enhancement of radiative heat transfer, resulting from the interaction between these charge carriers and the lattice, also occur in other materials? The authors could perform calculations on several other materials to demonstrate the universality of this work.

Response 6: We thank the Reviewer for raising this important question. The underlying carrier–lattice coupling mechanism is not unique to GaAs. In principle, it can also occur in other doped polar semiconductors in which mobile carriers coexist and interact with infrared-active optical phonons. Related coupled carrier–phonon responses have been reported in materials such as InSb and doped TiO₂ [R1, R2], supporting the broader applicability of this mechanism.

However, the existence of carrier–phonon coupling does not necessarily guarantee the same enhancement of NFRHT in every material. The resulting heat-transfer enhancement depends on the carrier and phonon resonance frequencies, material losses, doping concentration, and vacuum-gap distance. The present work experimentally establishes this enhancement in GaAs. A systematic comparison among other materials would require material-specific optical parameters and calculations and will be investigated in future work. We have therefore revised the manuscript to distinguish the general applicability of the coupling mechanism from the material-dependent magnitude of the NFRHT enhancement.

The following statement has been added at the end of the Conclusion:

“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.”

References cited in this response

- [R1] J.-M. Lihm and C.-H. Park, “Plasmon-phonon hybridization in doped semiconductors from first principles,” *Physical Review Letters* 133, 116402 (2024).
- [R2] E. Moncada-Villa and J. C. Cuevas, “Near-field radiative heat transfer between one-dimensional magnetophotonic crystals,” *Physical Review B* 103, 075432 (2021).
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We would like to thank the Reviewer’s review of the article and careful reading of our manuscript and many constructive comments. We think that the implementation of these suggestions has resulted in great improvements to the present paper.