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DOI: 10.1039/D3NR02079G
License: Unspecified

Document Version
Peer reviewed version

Citation for published version (Harvard):

Link to publication on Research at Birmingham portal

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ARTICLE

Enhanced far-field coherent thermal emission using mid-infrared bilayer metasurfaces

Sichao Li, Robert E Simpson, and Sunmi Shin

A classical thermal source, such as an incandescent filament, radiates according to Planck’s law. The feasibility of super-Planckian radiation has been investigated with sub-wavelength-sized sources in the last decade. In such sources, a crystal-dependent coupling of photons and optical phonons is possible at thermal energies corresponding to that of room temperature. This interaction can be used to tailor the far-field thermal emission in a coherent manner, however, understanding heat transfer during this processes is still nascent. Here, we used a novel measurement platform to quantify thermal signals in a GeSbTe/SiO$_2$ nanoribbon structure. We were able to separate and quantify the radiated, and conducted heat transfer mechanisms. The thermal emission from the GeSbTe/SiO$_2$ nanoribbons was enhanced by 3.5 compared to that of a bare SiO$_2$ nanoribbon. Our model revealed that this enhancement was directly due polaritonic heat transfer, which was possible due to the large and lossless dielectric permittivity of GeSbTe, at mid-IR frequencies. This study directly probes the far-field emission with a thermal gradient stimulated by Joule heating in temperature ranges from 100 to 400 K, which bridges the gap between mid-IR optics and thermal engineering.

Introduction

Thermal emission is determined by Planck’s law and is generally considered fixed by the material properties. However, many recent studies have tuned the thermal radiation spectrum using photonic crystals, cavities, and gratings. The technique essentially relies on nanostructuring the material’s surface to modify its optical absorption. Kirchhoff’s law states that the equilibrium thermal emission spectrum corresponds to the absorptance of the material, hence the radiated spectrum can be modified. The spectral and temporal coherency in the emission spectrum has been studied by adopting metasurfaces where the mid-IR optical property is closely correlated with the crystal lattice, mainly optical phonons. The dominant thermal wavelength at finite temperature is determined by the Wien’s law ($\lambda_T = b/T$), where $b$ is the Wien’s displacement constant, and $T$ is the temperature. Hence, this implies there is a blurred boundary between two distinct disciplines, optics and thermal engineering. However, it is still questionable whether one can simply treat thermal sources as alternatives to mid-IR optical sources. Clarifying this knowledge gap is important for utilizing radiative heat flux that is driven by a temperature gradient. The possibility of super-Planckian thermal emission is controversial. Golyk et al. reported suppressed thermal emission from structures with dimensions smaller than the skin depth. Contrarily, Biexs and Ben-Abdallah revealed that there is no theoretical upper limit to thermal emission from finite-sized systems in the far-field. While many theoretical studies have recently predicted non-Planckian thermal emission, it has not yet been confirmed experimentally.

There are two perspectives involved to understand the super-Planckian behavior: 1) enhanced radiation beyond the blackbody limit and 2) radiation distribution deviating from Planck’s law. The term super-Planckian thermal emission has been introduced to describe the enhanced thermal radiation beyond the blackbody in near-field radiation across the nano-gaps between two objects. Recent experimental and computational developments to study far-field radiation from a nano-object have opened the era to discuss the revisit of the super-Planckian thermal emission in the far-field. The emissivity and absorptivity of an object are equal under the equilibrium imposed by the thermodynamics laws. As such, it has been admitted that the far-field radiation cannot be beyond the blackbody limit, and therefore, the upper limit of radiation from an infinite planar media is bounded by the blackbody emission. Similarly, the implementation of nanostructured arrays in a large unit rarely leads to enhanced thermal emission. The beauty of investigating super-Planckian thermal emission in far-field origins from enhanced absorption cross-section in subwavelength thermal emitters, which could result in the

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Electronic Supplementary Information (ESI) available: [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x
emissivity beyond 1 with no upper limit in the modulated spectral and/or spatial range. However, the potential of the upper limit by enlarging the absorption cross-sectional area has not been clarified yet. Our study employs a state-of-the-art thermometry platform to quantify the emissivity of a single object by sensitively detecting the temperature rises at equilibrium and investigates enhanced far-field emission in nanostructures.

Experimentally studying non-Planckian thermal emission is challenging due to the low emission powers of an object with sub-wavelength dimensions. Indeed, very few experimental investigations have been attempted. Thermal emission control by photonic structures has mainly been studied using metals at high temperatures; typically around 1000 K. However, directly and accurately probing powers down to the nW-level without significantly heating the structure makes measuring sub-wavelength emitters at room temperature exceedingly difficult. To achieve measurable emission, it is important to access a wide range of the photon density of states, which can increase the radiation rate to the far-field. One technique to do this involves exploiting internal reflection by introducing evanescent waves confined along the emitter’s surface. Remarkably, surface phonon polaritons (SPhPs) can confine Mid-IR electromagnetic waves along the surface of polar dielectrics. The effect originates from coupling photons to optical phonons. It occurs within the so-called Reststrahlen band where transverse optical phonons resonate at frequencies \( \omega_{TO} \) similar to longitudinal optical phonons \( \omega_{LO} \). These confined phonon-photon coupled surface waves have enhanced near-field thermal radiation, which can even exceed the blackbody limits. Our previous study reported

Figure 1. Schematics of electric field distribution of (a) confined SPhPs mode generated by the amorphous SiO\(_2\) nanoribbon structure and (b) ultra-confined SPhPs enabled by Ge\(_2\)Sb\(_2\)Te\(_5\) (GST) thin layer covered SiO\(_2\) nanoribbon at both x-y plane view. The schematics are mimicked from the numerical electrical field distribution for (c) bare SiO\(_2\) and (d) Ge\(_2\)Sb\(_2\)Te\(_5\)/SiO\(_2\), respectively. (e) Plots of calculated thermal conduction due to phonon conduction and radiation heat loss as a function of the sample length. Input emissivity value is 0.17 which is corresponding to the emissivity we got from Ge\(_2\)Sb\(_2\)Te\(_5\)/SiO\(_2\) sample at room temperature. (f) Schematic of our sample, with continues GST thin layer deposited on suspended SiO\(_2\) nanoribbon. Zoom-in schematic of the joint of sample and beams highlights that, to avoid electrical leakage from Pt to GST material, we did pre-etching of the GST layer for the electrode pattern areas to make sure the disconnection between Pt and GST. (g) SEM images of our suspended Ge\(_2\)Sb\(_2\)Te\(_5\)/SiO\(_2\) nanoribbon sample with (h) Zoom-in image of the sample and beam structure. The width of nanoribbon was designed as 5 \( \mu \)m which is the half of the thermal wavelength (10 \( \mu \)m at room temperature) to further enhance the coherent thermal emission by SPhPs. Final sample width is 5.42 \( \mu \)m (with \( \pm 0.3 \) \( \mu \)m error range from each sample).
8.5 × higher emissivity of the SiO₂ nanoribbons compared to a thin film with an otherwise similar structure. The enhancement stemmed from a strong resonance at thermal wavelengths. Furthermore, controlling dispersion via Au-dots/SiO₂ metasurfaces, enabled the enhanced thermal emission by broadening the effective energy range to support SPhPs.

Herein, we study the influence of a thin polar dielectric layer on far-field coherent emission. Recent studies using different optical experiments on nanophotonic bilayer systems have shown enhanced radiated intensities in the mid-infrared. However, it is noteworthy that direct thermal observations have been seldom investigated due to the lack of experimental platforms to study low-energy and low-intensity far-field radiation. We customized nanostructures to emit radiation that can be distinguished from the convection and conduction heat transfer mechanisms. The specimens were integrated into a sensitive thermometer to probe the emissivity. Our novel measurement platform allowed us to quantify thermal signals and to exploit mid-infrared photonic metasurfaces to modulate heat transfer. We compared the emissivity of a bare SiO₂ nanoribbon with the one of Ge₂Sb₂Te₅ (GST)/SiO₂ bilayer nanoribbons. The additional thin layer of a dielectric film with large but lossless refractive index induced highly confined evanescent waves at the interface between Ge₂Sb₂Te₅ and the SiO₂, and the tailored energy dispersion of the bilayer metasurfaces could enhance the thermal emission.

We designed bilayer nanoribbon structures to enlarge the surface-to-volume ratios and concomitantly make the radiative heat transfer dominant. A state-of-the-art methodology, which uses a sensitive thermometry platform, was adopted to probe the emissivity of a single nanostructure. The technique involved fabricating finite-sized emitters integrated into a suspended micro-thermometer. The bilayer nanostructure consisted of a thin layer of amorphous-phase Ge₂Sb₂Te₅ (a-GST) on top of an SiO₂ nanoribbon. The high contrast in the permittivity (ε = ε’ + iε”) of the two different layers produced an asymmetric electric field distribution across the top and bottom surfaces as well as at the interface between them. Previously, we used the micro-thermometry platform to directly measure the far-field emissivity of individual nano-objects. Here, we demonstrate the enhanced emissivity using the Ge₂Sb₂Te₅/SiO₂ bilayer and report the enhanced emissivity of over 3.5 times that of the bare SiO₂ emitter.

**Methods**

**Design of suspended nanoribbon samples.** We designed a nano-specimen to reveal the dominant heat transfer by coherent thermal emissions. First, we considered that thermal transport by conduction (G) is either comparable with or insignificant compared to the G by radiation. As shown in Fig. 1(e), the contributions by conduction ($G_{\text{cond}} = \frac{U}{\Delta T}$) and radiation ($G_{\text{rad}} = 4\pi\sigma A T^4$, where $\sigma$ is the Stefan-Boltzmann constant) can be distinguished by varying the length of the nanostructures. In general, the higher the aspect ratio of the surface to volume of the emitter, the more significant the heat transfer by radiation. Furthermore, coherent thermal emission from the solid volume was suppressed by limiting one of the structure’s dimension to be smaller than the skin depth in the mid-IR regime. In this study, we designed our structures to be much thinner (e.g., 100 nm thickness) than the skin depth of ~1 μm in SiO₂ to make the influence of incoherent thermal emission from the volume, rather we investigate the surface effect to study the enhanced coherent thermal emission by SPhPs, the width of 5 μm and varied its length from 70 to 800 μm. Unlike most crystalline solids, amorphous SiO₂ rarely presents size-dependent thermal conductivity due to the short mean free path of <100 nm. This fact was used to calibrate our measurement system, as well as to observe the distinct change of the apparent thermal conductivity ($k_{\text{app}}$), which is influenced by radiation when the lattice thermal conductivity is maintained. Furthermore, we introduced a Ge₂Sb₂Te₅ layer on top of the SiO₂ nanostructure, which was sufficiently thin to make a negligible contribution to the total heat transported by conduction.

Figure 1(e) shows the estimated thermal conductance by conduction and radiation. In the analytical model, a 5 μm wide and 130 nm thick Nano Ribbon (NR) was considered with the emissivity of 0.17. These values are the designed and measured values from the Ge₂Sb₂Te₅/SiO₂ samples, which we will introduce later. Heat transfer by radiation dominates for NRs longer than ~800 μm. This critical length decreases for the higher emissivity and at higher operating temperatures. Thus, for this study we fabricated NRs with different lengths varying up to 800 μm.

The Ge₂Sb₂Te₅/SiO₂ NRs were integrated into our thermometry micro-devices as shown in Fig. 1(f), where the specimen is located across two suspended metal beams. Notably, the sample specimen and beams are fabricated based on a single unit of SiO₂, which gives negligible contact thermal resistance from the beam to heat channel. Generally, the NRs were measured by applying AC-modulated heating and detecting the temperature rises at both beams to evaluate the $k_{\text{app}}$. Importantly, the AC-modulated heating method allowed us to systematically control thermal penetration by varying the heating frequency. Further analysis in the frequency domain could differentiate the influence of the conduction and radiation heat transfer mechanisms. We compared the thermal emissions of bare SiO₂ and the bilayer Ge₂Sb₂Te₅/SiO₂ NRs.
Note, our experiments were entirely thermal-based. They rely on directly probing the far-field emission with a thermal gradient stimulated by Joule heating, which can be different from the optical methods using monochromatic incident waves.

Sample fabrication.

We first sputtered a 30 nm thick amorphous Ge$_2$Sb$_2$Te$_5$ layer on a 100 nm thermal oxide Si wafer (Fig. S1). As shown in the inset of Fig. 1(f), the Ge$_2$Sb$_2$Te$_5$ area along the sample specimen was set slightly smaller than the SiO$_2$ NR. Next, a 4 nm thick Ti layer and a 76 nm Pt layer were deposited by the e-beam evaporation. Note, the resistivity of Ge$_2$Sb$_2$Te$_5$ abruptly switches from $10^4$ to $10^5$ ohm/m at its amorphous to Face Centered Cubic (FCC) phase transition temperature$^{39}$, therefore the Ge$_2$Sb$_2$Te$_5$ layer was patterned and pre-etched by reactive ion etching (RIE) to avoid direct contact with the Ti/Pt metal layer. Subsequent patterning and etching were used to define the suspended area covering the beams and sample bridge. Lastly, the Si substrate was etched by isotropic XeF$_2$ etching to make the patterned Ge$_2$Sb$_2$Te$_5$/SiO$_2$ bilayer suspended.

AC-modulated thermometry.

We employed an AC-modulated thermometry platform (illustrated in Fig. 3(a)) with the measurement resolution of <1 nW/K to accurately detect temperature rises in the nano ribbons$^{36}$. The temperature rise at heating side ($\Theta_H$) with AC joule heating at 1$\omega$ angular frequency can be detected by the 3$\omega$ harmonic voltage signal ($V_{3\omega}$), which is the well-known 3$\omega$ method$^{40}$. On the sensing side, the temperature rise ($\Theta_J$) is measured by detecting the 2$\omega$ harmonic voltage signal ($V_{2\omega}$) with direct current (DC) applied. To further increase the sensitivity, a Wheatstone bridge circuit was applied at the...
sensing side. The measurement was conducted in high vacuum (< 10⁻⁶ Torr), thus, the convective heat transfer was negligible in our experiment. The theoretical temperature distribution for samples with different lengths can be seen from Fig. S2. When there is no significant heat loss (short samples), the temperature distribution along the sample is dominated by phonon conduction, which led to the observed linear trend, as described by the Fourier’s law (blue line). Nevertheless, when radiative heat loss starts to dominate in the longer samples, the radiative heat transfer coefficient (h = 4σεT³) needs to be considered, which results in the lower temperature rise along the sample (red line). The exact temperature of the NR can be determined by the voltage signal:

\[ \theta_H = \frac{V_{K,3omega} dR_{H}}{I_{o,AC} dT} \] (1)

\[ \theta_S = \sqrt{2} \frac{V_{Z,2omega} \left( R_S + R_{SP} + R_1 + R_2 \right) dR_S}{I_{s,DC} R_2} \] (2)

where \( T \) is the ambient temperature modulated by the temperature controller, \( I_{o,AC} \) and \( I_{s,DC} \) are the AC heating current and DC sensing current, respectively; \( R_H \) and \( R_S \) are the electrical resistance of the heating and sensing beams, respectively; \( R_{SP} \), \( R_1 \) and \( R_2 \) are the pair resistance and balance resistance in Wheatstone bridge. The above equations convert an electrical signal into a temperature rise, and are valid for the entire frequency range used in our experiment. Note, the frequency dependent \( \frac{\theta_S}{\theta_H} \) can represent the modulation of the permittivity was fitted using the Eq (3).

\[ \varepsilon_{\text{GST}}(E, \omega) = \begin{cases} \frac{\Gamma}{\omega \left( \omega^2 + \Gamma^2 \right)} f & \text{for } E > E_\theta \\ \frac{A_\text{RT}E_\text{RT}C (E - E_\theta)^2}{E \left( E - E_\theta \right)^2 + C^2 E^2} f & \text{for } E < E_\theta \end{cases} \] (3)

The Kramers–Kronig relation was used to calculate the real part of the dielectric constant as:

\[ \varepsilon_{\text{GST}}(\omega) = \frac{2}{\pi} \int_{0}^{\infty} \frac{\omega \varepsilon_{\text{GST}}'(\omega')}{\omega^2 - \omega'^2} d\omega' \] (4)

where \( \Gamma \) is the damping factor, \( \omega_p \) is the plasma angular frequency, \( E_0 \) is peak transition energy, \( E_\theta \) is the band gap energy, and \( \omega \) is the angular frequency of measured \( \varepsilon_{\text{GST}} \) range. All fitted parameters from reported experimental values are summarized in Table S1.

In general, amorphous \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) possesses an almost zero imaginary part of the permittivity in the mid-IR regime and a constant real part of 13.8 (Fig. 2(b)). The lossless optical property within the Reststrahlen band of \( \text{SiO}_2 \) can be utilized to realize highly confined modes within the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5}/\text{SiO}_2 \) bilayer system. The obtained permittivity was applied to calculate the energy dispersion relation in the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5}/\text{SiO}_2 \) bilayer NRs.

Results and discussion

Modelling of ultra-confined SPhPs by the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5}/\text{SiO}_2 \) bilayer.

We modelled the dispersion relation of the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5}/\text{SiO}_2 \) bilayer and compared it with that of bare \( \text{SiO}_2 \). Full-wave numerical simulations using the finite-element method in frequency domain (COMSOL Multiphysics) were performed to study the confined surface modes supported by the bilayer structures. A bare \( \text{SiO}_2 \) nanoribbon itself can support SPhPs as shown in Fig.1(a), but when a thin \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) layer is added on top of the \( \text{SiO}_2 \) layers, it supports further confined SPhPs within the Reststrahlen band.

The thickness of the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) layer was systematically varied to find the optimal thickness to maximize thermal emission. The dispersion energies for \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) thicknesses from 5 nm to 30 nm on a 100 nm thick and 5 \( \mu \text{m} \) wide \( \text{SiO}_2 \) nanoribbon were studied. As shown in Fig. 1(c), adding the thin \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) layer increases the allowed wavevectors compared to bare \( \text{SiO}_2 \) NRs. This effect is consistent with that predicted in a study by Li et al.². Approximately 30× higher wavevectors (\( q \)) were achieved by adding the 5 nm thick \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) layer. Moreover, the peak \( q \) wavevector is red-shifted in the bilayer system, which implies the coupling of the dielectric layer and the \( \text{SiO}_2 \). Similarly, we also analyzed the energy dispersion of the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5}/\text{SiO}_2 \) bilayer after crystallizing the \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) into its FCC phase, see Supplementary Information (Fig. S3). However, the negligible imaginary component of the amorphous \( \text{Ge}_{2}\text{Sb}_{2}\text{Te}_{5} \) dielectric function deems it more suitable for studying the influence of SPhPs.

We designed the bilayer specimens to behave similarly as thin films to maximize the influence of surface phonon polaritons by multilayers (including the top and bottom surfaces as well as the interface), rather than the side walls or edges in the nanostructured specimen. At the same time, we optimized the width of nanoribbons to be small to suppress the conductance by heat conduction while maintaining relatively large surface area to effectively enlarge the conductance by radiation. In result, we employed ~5 \( \mu \text{m} \) width and confirmed that energy dispersion of bilayer specimens with 5 \( \mu \text{m} \) behaves as one of thin films in Fig. 2(d). This result means that the surface waves...
are confined along the interfaces between SiO$_2$ and Ge$_2$Sb$_2$Te$_5$ layers, rather than the side walls or edges. Also, the imaginary part of the wavevector ($\beta$) and the propagation length ($\lambda$) in the 5 $\mu$m-wide NR are well overlapped with the ones for thin films. It was clearly seen that the addition of 30 nm thick Ge$_2$Sb$_2$Te$_5$ on SiO$_2$ results in highly confined modes with the high $q$ and correspondingly, more energy losses with the short $\lambda$. It indicates efficient energy absorption (=emission) of mid-IR waves from the thin structures.

Enhanced far-field emission from GST/SiO$_2$ nanoribbons.

We first conducted the thermal conductivity measurement at various temperatures ranging from 100 to 400 K. It is noteworthy that the temperature-controlled measurement allows us to differentiate the radiative and conductive heat transfer. At higher temperatures, radiative heat transfer is dominant. Similarly, we also varied the surface area of

Figure 3. (a) Illustration of the AC-modulated thermometry platform with the cryostat vacuum chamber. Our thermal measurement was conducted at high vacuum level (<10$^{-6}$ Torr) to suppress the convection with the surrounding. And additional three radiative shields were applied to avoid radiative heat loss to the ambient. (b) Metal beam emission check by comparing the input power dependent sensing side temperature rise with and without NR sample. No heating power dependent temperature rise at sensing side observed with the empty beams which indicates the direct beam emission (background) can be negligible for our sensitive measurement platform, and all the sensing side signal came from our NR sample. (c) Plot of temperature dependent apparent thermal conductivity of bare SiO$_2$, as well as Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NR with same width design (5 $\mu$m) but various length (70, 400 and 800 $\mu$m). Our bulk thermal conductivity measurement data is well fitted with the reference 18, the shadowed areas represent the range for fitted emissivity values. The difference between 70 $\mu$m sample group comes from the intrinsic bulk conductivity between bare SiO$_2$ and 30 nm a-GST + 100nm SiO$_2$ because for 70 $\mu$m length the thermal emission has not become dominate due to its short length. The large error bars of long specimens at high temperature are due to the larger systematic errors as we discussed in Supplementary Note 5. (d) Plot of frequency dependent temperature rise ratio between sensing and heating side with experimental data (diamond marks) and fitting curves, shadowed area represents the radiative heat loss. Inserted plot shows the frequency dependent thermal penetration depth ($L_p$). With frequency increasing, the $L_p$ decreases which has can lead to the dynamic change of the effective length for emission, thus can provide the fitting process for the experimental data and calculated curves.
specimens by adopting a wide range of lengths from 70 to 800 μm. Larger surface areas should increase thermal emission. Empty devices, without NRs, were also measured to compare with the NR samples such that the effect of NR can be determined. The temperature rises were measured for different heating power in the empty device in both heating (θ₁) and sensing (θ₂) beams, as shown in Fig. 3 (b). There is a negligible temperature rise at the sensing beam in response to heating the heater. This measurement directly confirms that there is insignificant far-field thermal emission between the long metal beams in our device. Thus, we can infer that any radiative heat transfer must be due to the surface of nanoribbons.

Figure 3(c) compares the $\kappa_{\text{app}}$ of bilayer Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NR with the bare SiO$_2$ NR. The $\kappa_{\text{app}}$ is influenced by both radiation and conduction. Short SiO$_2$ NRs with 20 and 70 μm show the almost bulk-like thermal conductivity over the wide range of temperatures due to insignificant radiative heat loss on the surface. It clearly indicates that nano-emitters need to be designed with high surface-to-volume ratios to detect thermal emission. However, the aspect ratio required increases with the thermal conductivity of the solids, and therefore much longer and thinner suspended nanostructure need to be fabricated, which is technically more challenging. In our experiment, we chose SiO$_2$ as a polar dielectric with a low thermal conductivity of ~1.4 W/m-K (c.f., Si$_3$N$_4$ with 9 W/m-K$^{13}$, SiC with 490 W/m-K$^{44}$ and hBN with 751 W/m-K$^{29}$). Also, importantly, the amorphous SiO$_2$ should not exhibit size-dependent thermal conductivity for the dimensions of our samples, which are down to 100 nm owing to the short phonon mean free paths$^{37, 38}$. This design allows us to calibrate our measurement system and quantify the contribution of the heat conduction for different samples. The 30 nm thin layer of Ge$_2$Sb$_2$Te$_5$ on top of the SiO$_2$ has a lower intrinsic thermal conductivity (below 0.5 W/m-K)$^{46}$ than the 100 nm thick layer of SiO$_2$ (1.4 W/m-K) at 300 K, which matches with our fitted effective thermal conductivity $\kappa_{\text{fit}}$ in Fig. 4(a).

The thermal emission is greater for emitters with a larger surface. As shown in Fig. 3(c), the $\kappa_{\text{app}}$ starts deviating from the bulk thermal conductivity of SiO$_2$ for the 400 μm and 800 μm long specimens. One can see that the $\kappa_{\text{app}}$ dramatically decreases with the increasing nanoribbon length; indicating that radiative heat loss has been enhanced for the larger surface areas. By comparing the $\kappa_{\text{app}}$ of bare SiO$_2$ and the Ge$_2$Sb$_2$Te$_5$/SiO$_2$, we quantified the enhanced thermal emission for the bilayer nanoribbons. In Fig. 3(c), the colored area presents the predicted $\kappa_{\text{app}}$ determined by the emissivity, which ranges from 0.15 to 0.25 (0.07 to 0.1) for Ge$_2$Sb$_2$Te$_5$/SiO$_2$ (bare SiO$_2$). At low temperatures, the emitting power is relatively small, and becomes insignificant compared to the thermal conductance in the solid volume. Thus, the $\kappa_{\text{app}}$ of most samples is similar to the thermal conductivity of bulk SiO$_2$.

Larger $\kappa_{\text{app}}$ deviations were observed at higher temperatures. Note that for all the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ samples we controlled the ambient temperature below 400 K, which is well below the amorphous—FCC phase transition temperature (~420 K). Hence, the amorphous phase of Ge$_2$Sb$_2$Te$_5$ was retained throughout the experiment.

To extract the thermal emissivity of the NRs, we analyzed the temperature rise at different heating frequencies. Effectively, this experiment controls the thermal penetration depth ($L_P$). In our thermometry platform the suspended emitter is connected to the heating metal beam, and this generates heat flux parallel to the sample length and thus 1D heat transfer can be considered. The frequency-dependent $L_P$ can be expressed by equation (5):

$$L_P = \frac{\sqrt{\alpha}}{2\omega J} = \frac{\sqrt{\kappa}}{2\rho C\omega J} \quad (5)$$

where, $\alpha$, $\kappa$, $\rho$ and $C$ are thermal diffusivity, thermal conductivity, density and specific heat capacity, respectively. Note that $\omega J$ represents the angular frequency of the electric
As indicated in the inset of Fig. 3(d), the higher heating frequency results in a shorter $L_P$. Consequentially, using the heating frequency to control $L_P$ effectively provides a means to control the surface area influenced by the heating, and correspondingly the emitted thermal power. We analyzed the frequency-dependent temperature rises at the heating and sensing beams using Eq. (6).

$$\frac{\theta_S}{\theta_H} = \frac{1}{\cos(h(a_2L_2) + \frac{\kappa_Aa_1}{\kappa_2a_2} \sin h(a_2L_2))}$$

(6)

where 1, 2 represents the beam and NR sample respectively.

$$\frac{(a_1)^2}{(a_2)^2} = \frac{j\omega}{a_1}$$

(7)

$$\frac{(a_2)^2}{(a_2)^2} = \frac{j\omega}{a_2} + \frac{hP_2}{\kappa_2A_2}$$

(8)

where $h$ is the radiative heat transfer coefficient ($h = 4\sigmaT^3$), $P_2$ is the perimeter of the sample cross-section.

In the low frequency regime, the $L_P$ becomes much longer than the length of samples, where the $\kappa_{app}$ was determined. The $\kappa_{app}$ is influenced by both conduction and radiation. By fitting the measured overall frequency-dependent temperature rises with the modelled ones, we separated the influence of the two different heat transfer mechanisms. In Fig. 3(d), the colored area represents the radiative heat loss carried by SPhPs. By applying the $\kappa_{fit}$ and considering radiative heat loss for an emissivity of 0.23, the modelling data (red solid line) can fully fit with our experimental data (black diamonds), as plotted in Figure 4(a). This result suggests that the emissivity value of our current NR sample is exactly 0.23. These emissivity and thermal conductivity ($\kappa_{fit}$) values were extracted. This observed value for $\kappa_{fit}$ is almost identical to $\kappa_{bulk}$, as shown in Fig. 4(a).

In Fig. 4(b), we repeated the analysis to measure the emissivity of specimens at various temperatures and observed that higher values of emissivity are present at lower temperatures for both sample groups (e.g., SiO$_2$ and Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NRs). This trend is explained by changes to the optical permittivity of SiO$_2$, which is a major contributor to determine the radiative properties in mid-IR regime. Specifically, as the temperature decreases, the lifetime of optical phonons is expected to increase, leading to a smaller damping term in the dielectric function$^{47,48}$. This results in stronger and more coherent thermal emission which is

Figure 5. Plot of electrical field intensity of (a) bare SiO$_2$ and (b) Ge$_2$Sb$_2$Te$_5$/SiO$_2$ NR with 10 nm thickness a-GST at wavelength of 8.7 to 9.1 $\mu$m (highest confinement points at the Ge$_2$Sb$_2$Te$_5$/SiO$_2$ system). The electrical field intensity is normalized at same peak height. Bare SiO$_2$ system has minor gradually and symmetrically intensity change while peak electrical field location of Ge$_2$Sb$_2$Te$_5$/SiO$_2$ changed from the SiO$_2$ bottom surface to the interface between the GST and SiO$_2$ which also shows significant intensity change.
consistent with the observation of enhanced far-field radiation by Thompson et al.\textsuperscript{22} as we discussed in Supplementary Note 6. Additionally, we compared the emissivity of bare SiO\textsubscript{2} and bilayer Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}/SiO\textsubscript{2} emitters and found that the bilayer metastable interfaces could achieve a higher emissivity up to 0.3. This value corresponds to an emissivity enhancement up to 3.5× greater than that of the bare SiO\textsubscript{2} at 100 K. Numerical modelling of the normalized spectral absorption cross-sectional area of 5 μm wide Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}/SiO\textsubscript{2} nanoribbon (\(σ_{\text{abs}}/σ_{\text{geom}}\)) is shown in Supplementary Note 7 (Fig. S5), indicating that peak emissivity enhancement happens at the resonant frequencies (\(ω_{\text{LO}}\) and \(ω_{\text{TO}}\)) of SPhPs.

Electromagnetic field intensity distribution.

We conducted a detailed analysis of the electric field intensity for SiO\textsubscript{2} NRs with and without a 30 nm thick Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} layer, as depicted in Figures 5(a) and 5(b), respectively. We selected wavelengths near the peak of \(q\) in the energy dispersion, which ranged from 8.7 μm to 9.1 μm, and compared the normalized electric field intensity distribution along the thickness of the nanoribbon (y-axis). The SiO\textsubscript{2} nanoribbon without the Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} layer exhibits symmetric peak intensities at the top and bottom surfaces. On the other hand, the Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5}/SiO\textsubscript{2} bilayer nanoribbon, with three interfaces, displays asymmetric peaks, where stronger energy confinement is observed at the interface between the Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} and the SiO\textsubscript{2}. This characteristic indicates that energy is highly confined within the newly introduced interfaces of the layers that have dissimilar permittivity.

Conclusions

We studied the enhanced far-field thermal emission from mid-IR bilayer nanostructures. We designed bilayer nanoribbon structures that enhance the radiative heat transfer to the point that it dominates over other heat transfer mechanisms. This enhancement enabled us to detect the emissivity of individual nanoribbon structure by making meticulous measurements of the apparent thermal conductivity. The emitter was integrated into a sensitive thermometry platform, and we performed temperature- and frequency-dependent measurements to separate the radiative and conductive heat transfer mechanisms. The separation enables us to evaluate the emissivity and thermal conductivity of specimens simultaneously. This direct measurement of the heat transfer revealed greater than adding a thin high refractive index layer, Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} to the nanoribbon could enhance radiative heat transfer by 3.5×. Our analytical and numerical modeling showed that the electric field is highly confined along the interface of the Ge\textsubscript{2}Sb\textsubscript{2}Te\textsubscript{5} and SiO\textsubscript{2}, which leads to the observed enhanced radiative emission to the far-field. The results show strong and direct experimental evidence for the non-Planckian mid-IR thermal emissions at low temperatures. This experimental verification was only possible due to our sensitive platform for separating conductive and radiative heat transfer in nanodevices.

Data Availability

The data that support the findings of this study are available from the corresponding author on reasonable request.

Author Contributions

S.L. and S.S. devised the experimental designs. S.L. and R.S. prepared samples. S.L. conducted the thermal measurement and numerical modeling. All authors discussed the results and wrote the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The authors acknowledge Prof. Renkun Chen and Yu Pei (UC San Diego) for their insightful comments and valuable assistance on the XeF\textsubscript{2} etching process for isotropic Si etching. We acknowledge support from Singapore ministry of education academic research fund tier 1 (A-0009121-01-00 and A-0009061-01-00).

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