Thermal electromagnetic transport mediated by coupled surface phonon-polaritons in nanostructures

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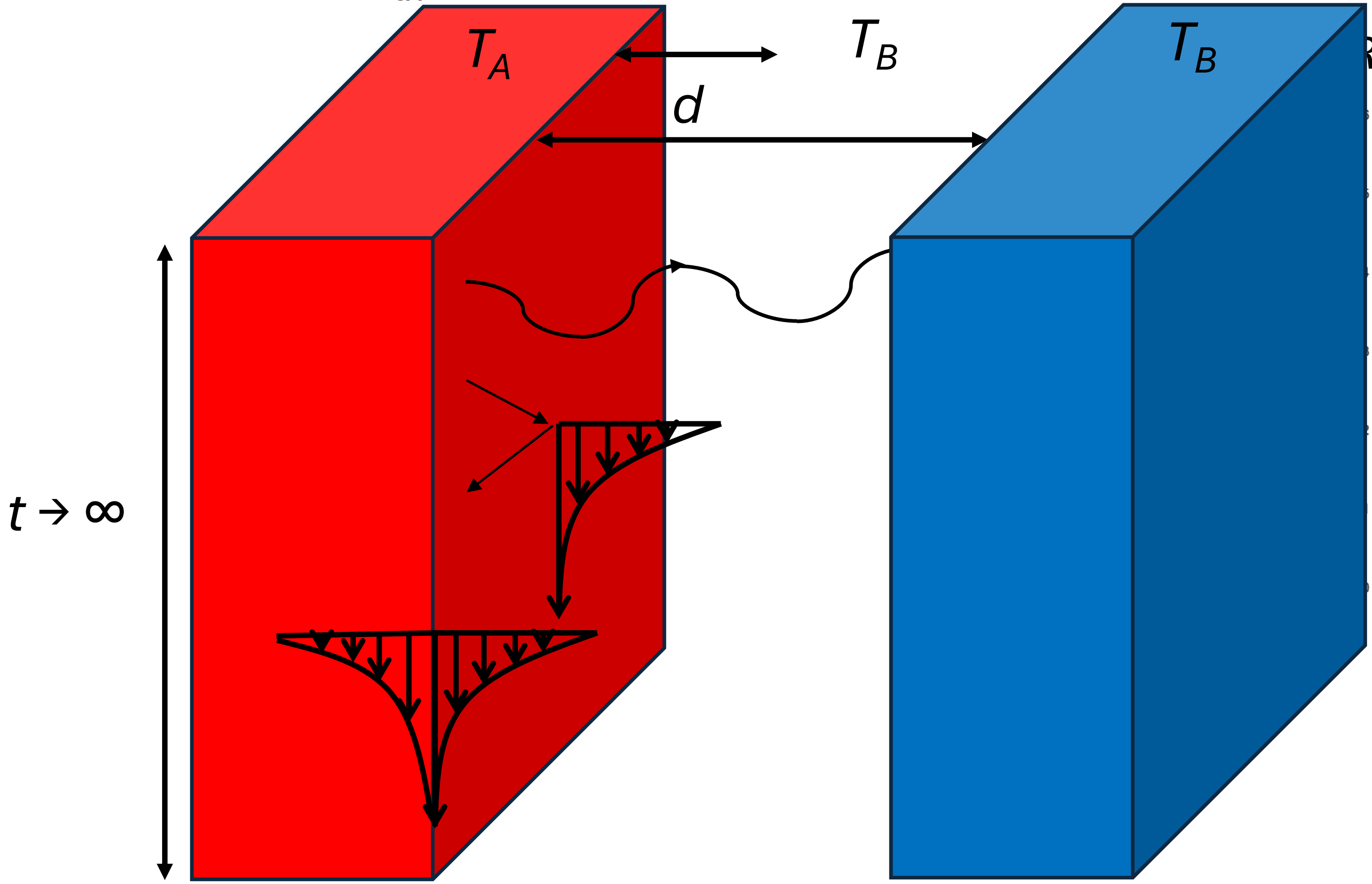
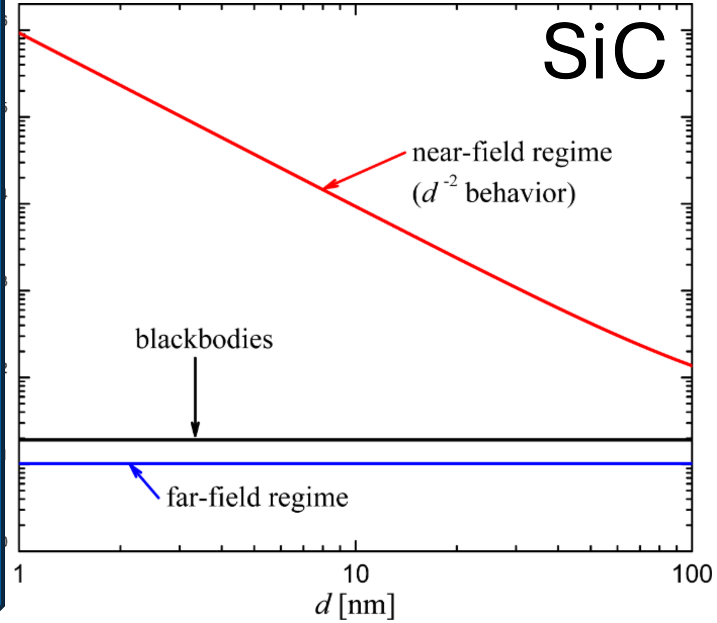
Near-field radiative heat transfer

$d \lesssim \lambda_{\text{th}}$ | electromagnetic waves | $T_A > T_B$



RHT can surpass the blackbody limit



Francoeur, *Handbook of Thermal Science and Engineering*, 1-43, 2017.

When present, SPhPs become the dominant type of mode contributing to NFRHT

Near-field radiative heat transfer is calculated via fluctuational electrodynamics

- Maxwell's equations (Rytov et al., *Principles of statistics radiophysics*, Springer-Verlag, 1989):

$$\nabla \times \mathbf{E}(\mathbf{r},\omega) = i\omega\mu_0\mathbf{H}(\mathbf{r},\omega)$$

$$\nabla \times \mathbf{H}(\mathbf{r},\omega) = -i\omega\varepsilon(\mathbf{r},\omega)\varepsilon_0\mathbf{E}(\mathbf{r},\omega) + \mathbf{J}^{(\mathrm{fl})}(\mathbf{r},\omega)$$

Fluctuating thermal current source

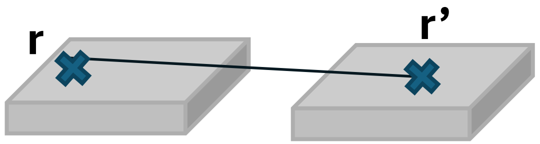
- Fluctuation-dissipation theorem:

$$\left\langle \mathbf{J}^{(\mathrm{fl})}(\mathbf{r},\omega)\mathbf{J}^{(\mathrm{fl})^{\dagger}}(\mathbf{r}',\omega') \right\rangle = 4\pi\omega\mathrm{Im}[\varepsilon(\mathbf{r},\omega)]\mathbf{\Theta}(\omega,T)\delta(\mathbf{r}-\mathbf{r}')\delta(\omega-\omega')\bar{\bar{\mathbf{I}}} \text{ where } \mathbf{\Theta}(\omega,T) = \frac{\hbar\omega}{\mathrm{e}^{\frac{\hbar\omega}{k_B T}}-1}$$

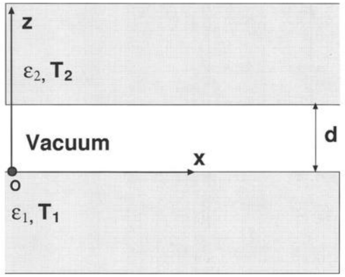
- Electric field is defined using the volume integral technique:

$$\mathbf{E}(\mathbf{r},\omega) = i\omega\mu_0 \int_{V_{\mathrm{therm}}} \bar{\bar{\mathbf{G}}}(\mathbf{r},\mathbf{r}',\omega)\mathbf{J}^{(\mathrm{fl})}(\mathbf{r}',\omega)d^3\mathbf{r}', \quad \mathbf{r} \in \Re^3$$

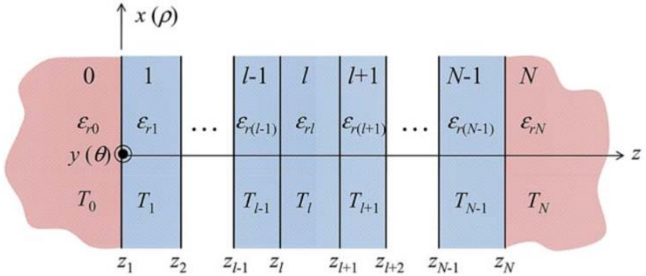
System Green's function



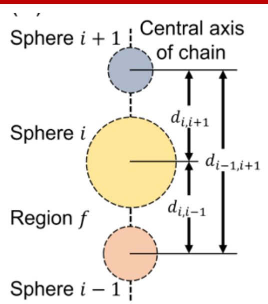
Most near-field radiative heat transfer (NFRHT) problems are solved analytically



Mulet et al., *Microscale Thermophys. Eng,* **6**, 209-222, 2002.

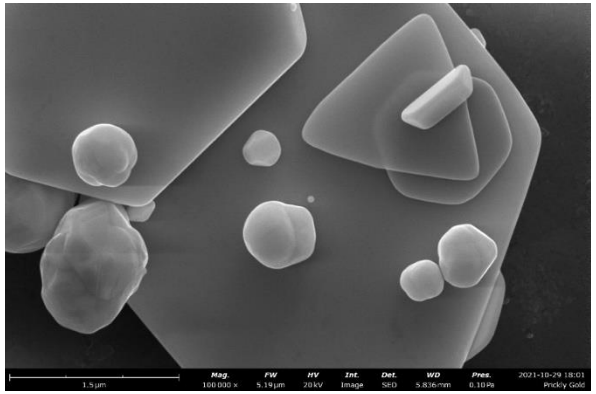


Francoeur et al., *JQSRT* **110**, 2002-2018, 2009.



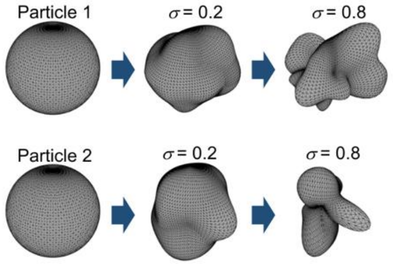
Czapla and Narayanaswamy, *JQSRT* **227**, 4-11, 2019.

Analytical solutions become intractable for complex geometries

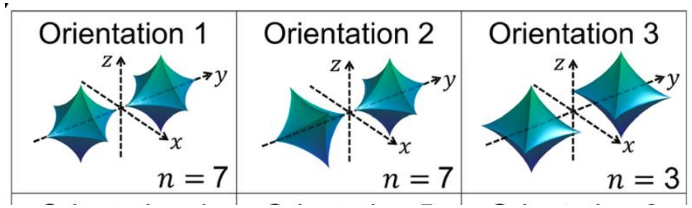


https://www.nanoscience.com/techniques/scanning-electron-microscopy /

We developed a numerical methodology based on FE for NFRHT between complex-shaped objects called the discrete system Green's function (DSGF)



Walter et al., *Physical Review B* **106**, 195417, 2022.



Walter and Francoeur, *Applied Physics Letters* **121**, 182206, 2022.

The DSGF solver computes numerically SGF from a linear system of equations

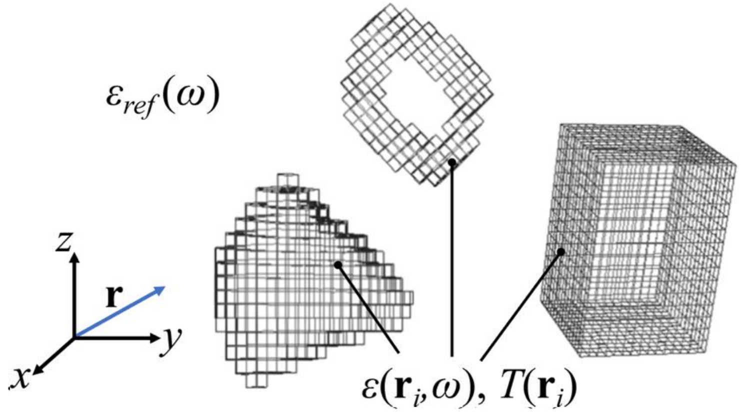
Walter et al., *Phys. Rev. B* **106**, *195417*, 2022.

Walter et al., *Light, Plasmonics and Particles, Chapter* 11, 2023.

- The system Green's function (SGF) equation:

$$\bar{\bar{\mathbf{G}}}^0(\mathbf{r},\mathbf{r}',\omega) = \bar{\bar{\mathbf{G}}}(\mathbf{r},\mathbf{r}',\omega) - k_0^2 \int_{V_{\text{therm}}} \bar{\bar{\mathbf{G}}}^0(\mathbf{r},\mathbf{r}'',\omega)\varepsilon_r(\mathbf{r}'',\omega)\bar{\bar{\mathbf{G}}}(\mathbf{r}'',\mathbf{r}',\omega)d^3\mathbf{r}''$$

- The thermal sources are discretized into cubical subvolumes:



Corrêa et al., *JQSRT* **328,** 109163, 2024.

https://github.com/Discrete-System-Greens-Function

$$\left\{\begin{bmatrix} \bar{\bar{\mathbf{I}}} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \bar{\bar{\mathbf{I}}} \end{bmatrix} - k_0^2 \begin{bmatrix} \bar{\bar{\mathbf{G}}}^0_{11} & \cdots & \bar{\bar{\mathbf{G}}}^0_{1N} \\ \vdots & \ddots & \vdots \\ \bar{\bar{\mathbf{G}}}^0_{N1} & \cdots & \bar{\bar{\mathbf{G}}}^0_{NN} \end{bmatrix} \begin{bmatrix} \alpha_1^{(0)} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \alpha_N^{(0)} \end{bmatrix}\right\} \begin{bmatrix} \bar{\bar{\mathbf{G}}}_{11} & \cdots & \bar{\bar{\mathbf{G}}}_{1N} \\ \vdots & \ddots & \vdots \\ \bar{\bar{\mathbf{G}}}_{N1} & \cdots & \bar{\bar{\mathbf{G}}}_{NN} \end{bmatrix} = \begin{bmatrix} \bar{\bar{\mathbf{G}}}^0_{11} & \cdots & \bar{\bar{\mathbf{G}}}^0_{1N} \\ \vdots & \ddots & \vdots \\ \bar{\bar{\mathbf{G}}}^0_{N1} & \cdots & \bar{\bar{\mathbf{G}}}^0_{NN} \end{bmatrix}$$

where $\boxed{\bar{\bar{\mathbf{G}}}_{ij}} = \begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix}$

$$\alpha_i^{(0)} = \Delta V_i \varepsilon_r(\mathbf{r}_i,\omega)$$

$9N^2$ terms to be calculated

or simply as

$$\bar{\bar{\mathbf{A}}}\bar{\bar{\mathbf{G}}} = \bar{\bar{\mathbf{G}}}^{\mathbf{0}}$$

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The Green's functions are directed applied to compute thermal quantities of interest

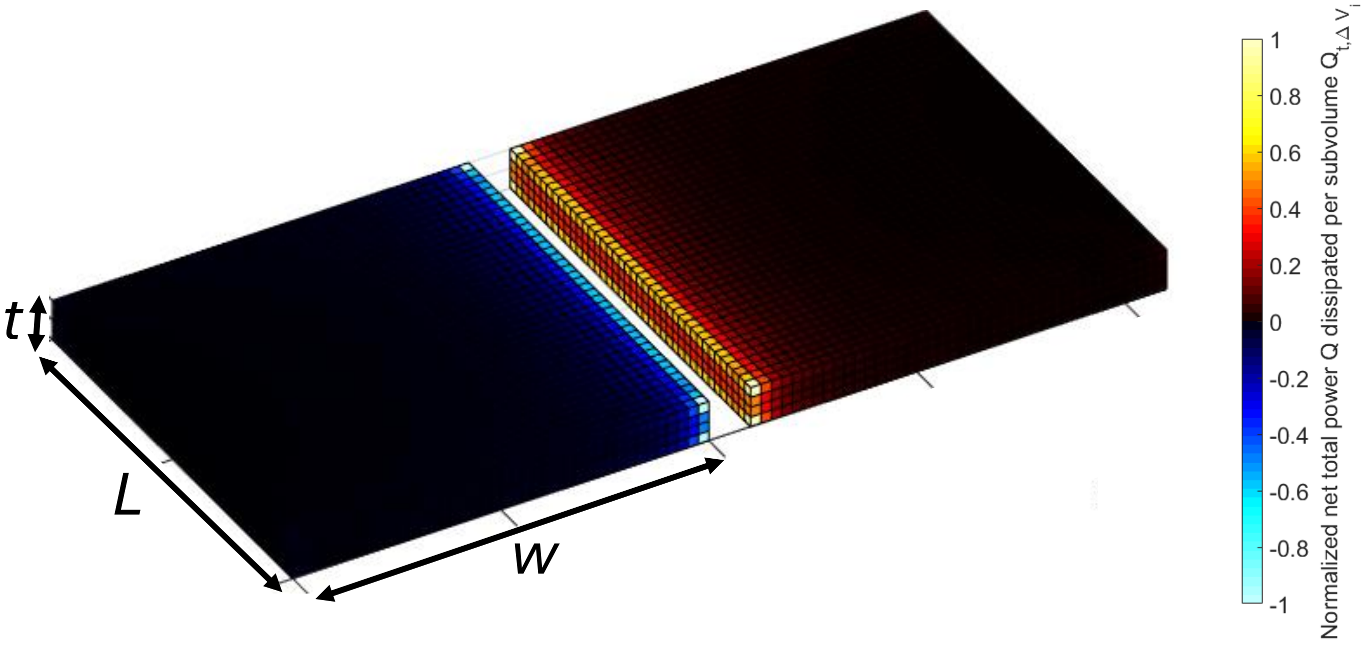
- Power dissipated between subvolumes:

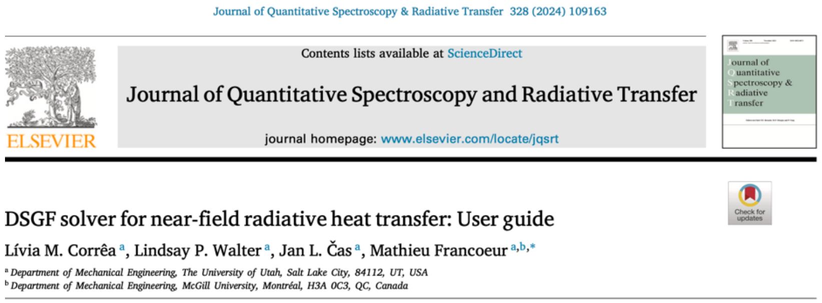
$$< \mathrm{Q}_{\Delta V_i}(t) >= \frac{1}{2\pi}\int_0^\infty \left\{ \sum_{\substack{j=1 \\ j\neq i}}^{N} [\Theta(\omega, T_j) - \Theta(\omega, T_i)] \boxed{\tau_{ij}(\omega)} \right\} d\omega,$$

- where $\tau_{ij}(\omega)$ is the transmission coefficient:

$$\boxed{\tau_{ij}(\omega)} = 4k_0^4 \Delta V_i \Delta V_j \mathrm{Im}[\varepsilon(\mathbf{r}_i, \omega)]\mathrm{Im}[\varepsilon(\mathbf{r}_j, \omega)]\boxed{\mathrm{Tr}[\bar{\bar{\mathbf{G}}}(\mathbf{r}_i, \mathbf{r}_j, \omega)\bar{\bar{\mathbf{G}}}^\dagger(\mathbf{r}_i, \mathbf{r}_j, \omega)]}$$

Multiscale simulation between SiC membranes, *t* = 100 nm, *w* = 1 μm, and *L* = 1 μm





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journal homepage: www.elsevier.com/locate/jqsrt

DSGF solver for near-field radiative heat transfer: User guide

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Corrêa et al., *JQSRT* **328,** 109163, 2024.

https://github.com/Discrete-System-Greens-Function

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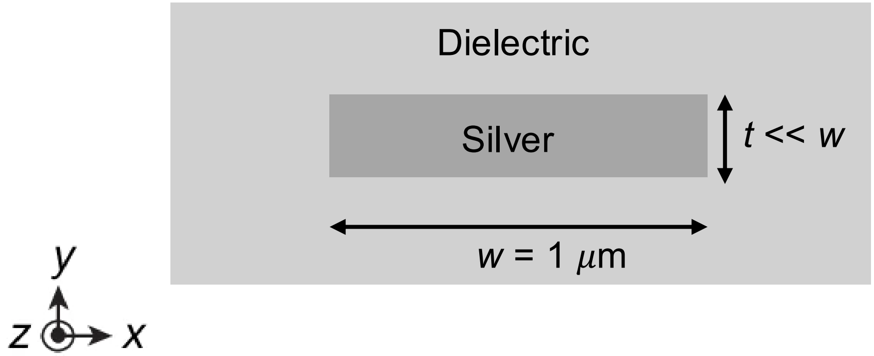
Motivation: How does EM corner and edge modes impact radiative heat transfer?

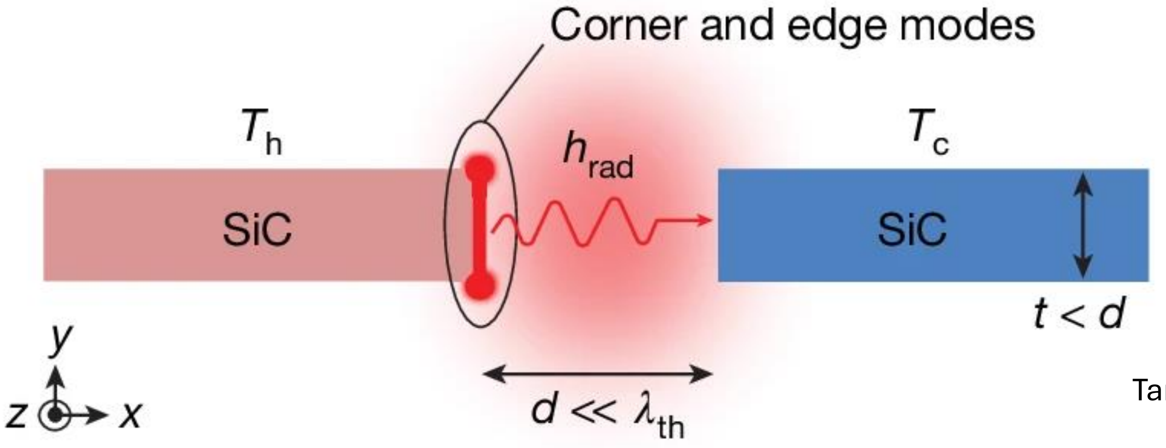


Coupled EM modes at the corners and edges of rectangular metallic membranes (non-thermal)

Berini, *Phys. Rev. B* **61**, 10494, 2000

Thermal nanophotonics in the

dual nanoscale regime: $t < d << \lambda_{\mathrm{th}}$



Tang, Corrêa et al., *Nature* **629**, 67-73, 2024

Key finding: *Near-field radiative heat transfer between SiC membranes in the dual nanoscale regime exceeds that between infinite surfaces*

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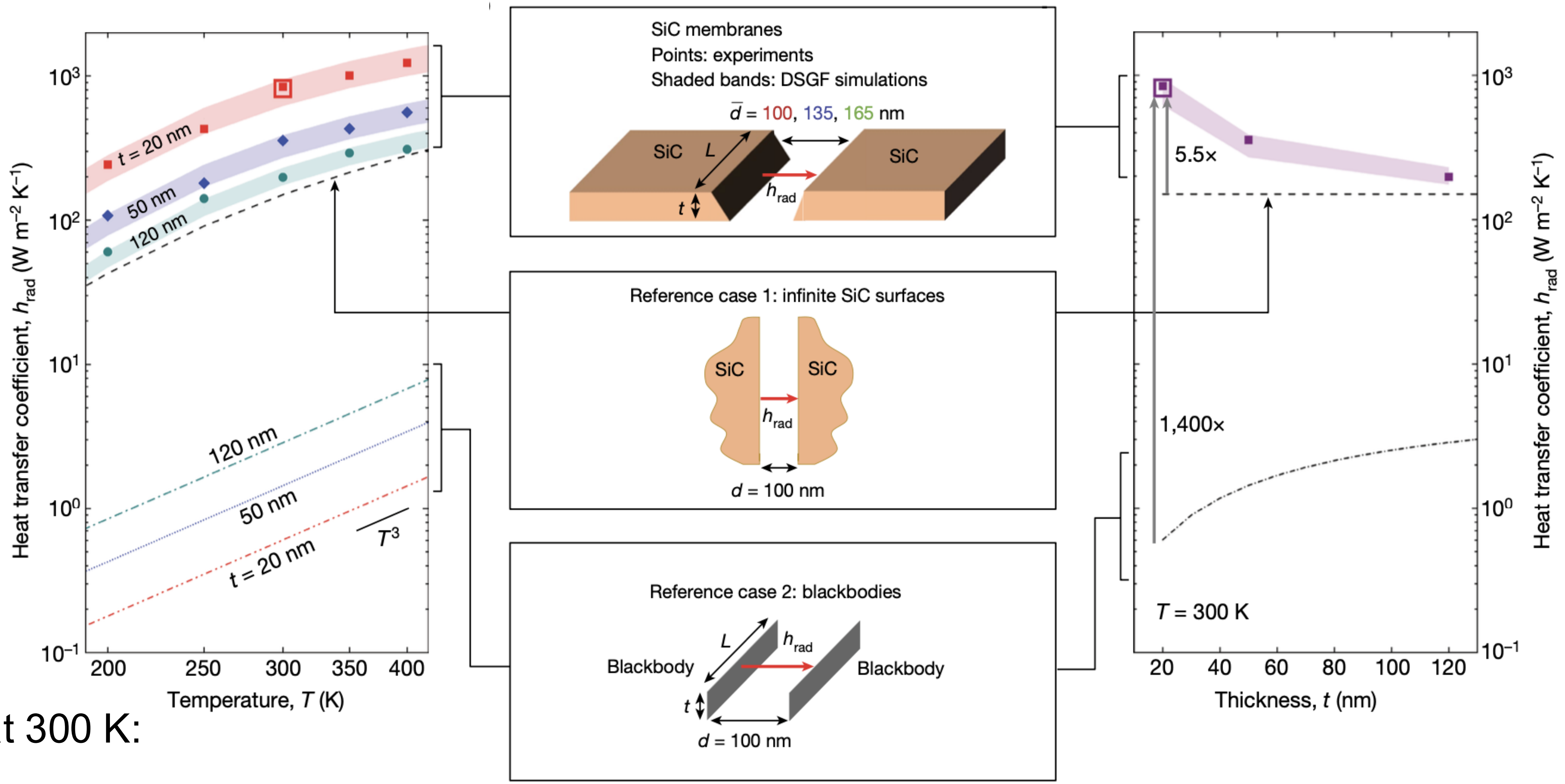
DSGF simulations showed good agreement against experimental results



t = 20 nm at 300 K:

- h_{rad} ~ 830 Wm^{-2}K^{-1}
- ~5.5 times larger than h_{rad} between SiC infinite surfaces
- ~1400 times larger than h_{rad} between blackbodies accounting for the view factor

Tang, Corrêa et al., *Nature* **629,** 67-73, 2024.

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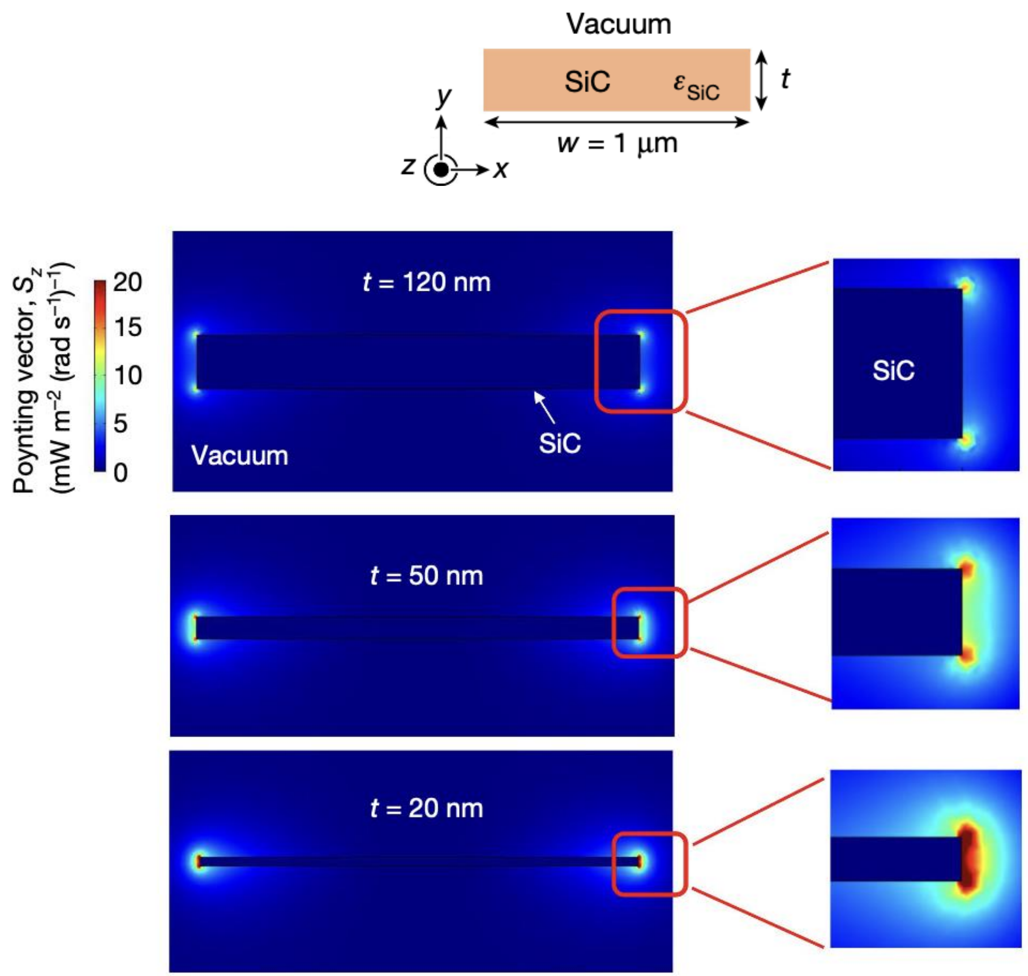
Coupling of corner and edge modes increases as *t* decreases

Modal analysis of a solitary SiC membrane using COMSOL Multiphysics:

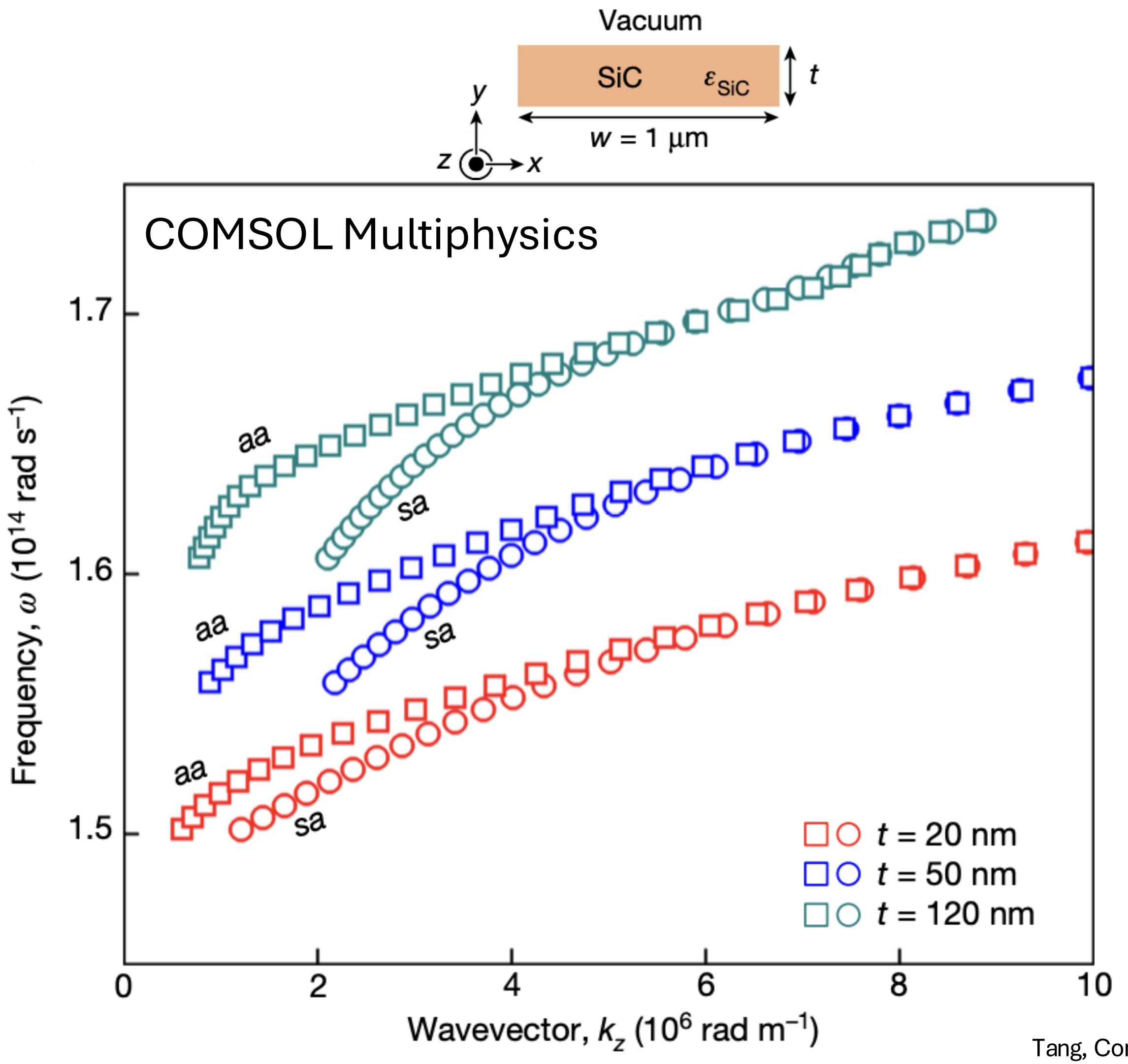


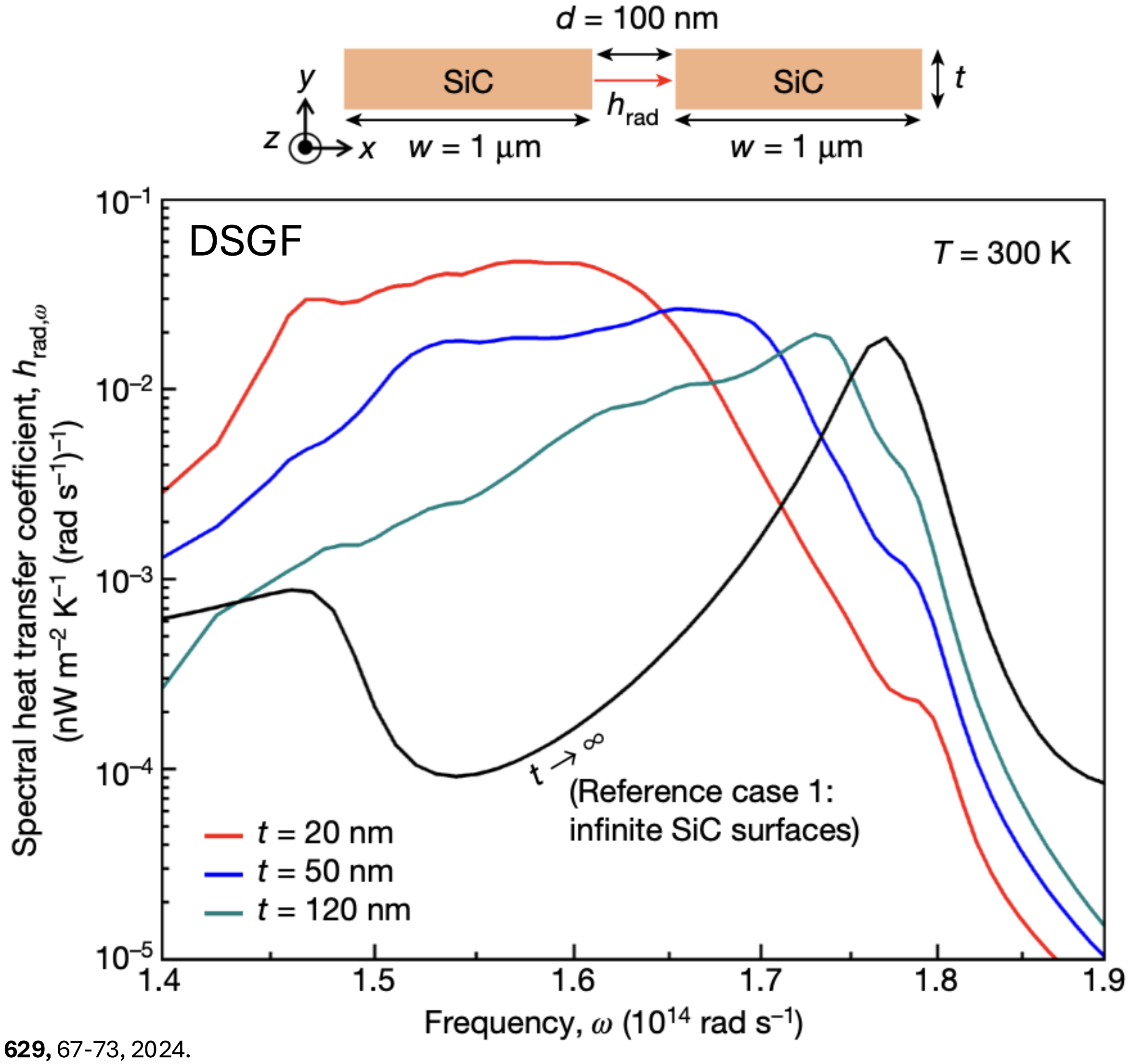
Tang, Corrêa et al., *Nature* **629,** 67-73, 2024.

Poynting vector along z-direction showing representative corner and edge modes

The dispersion curves indicate the resonance of the heat transfer coefficient

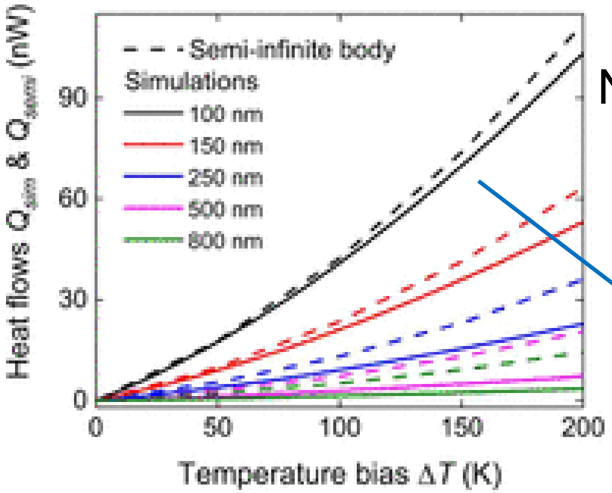
- The maximum contributing wavevector dominating NFRHT is estimated as ≈ d^{-1} ≈ 10^7 rad/m





Tang, Corrêa et al., *Nature* **629,** 67-73, 2024.

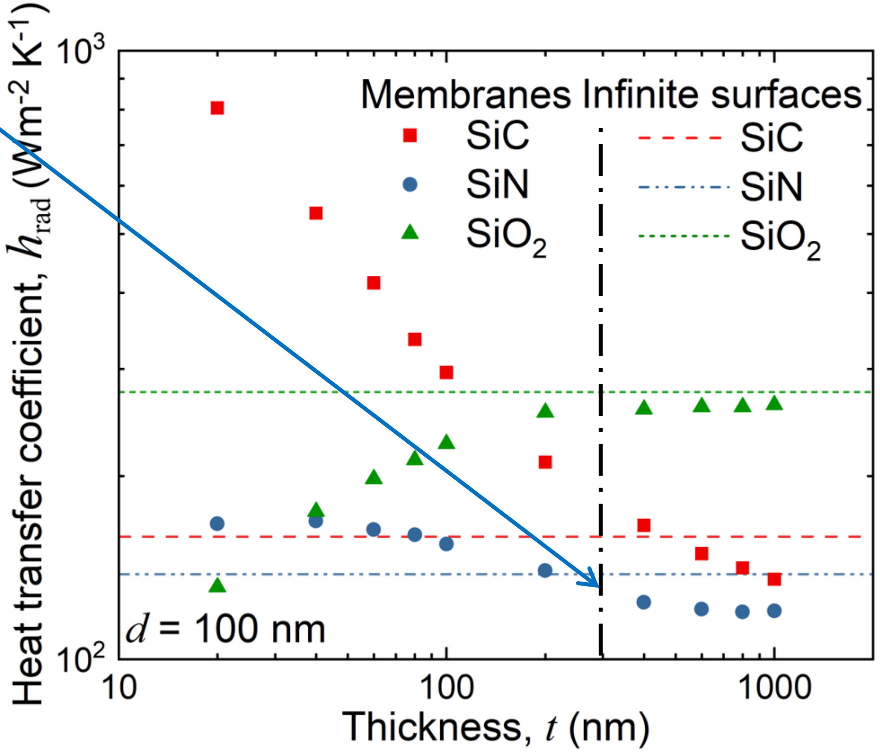
SiN with t = 300 nm

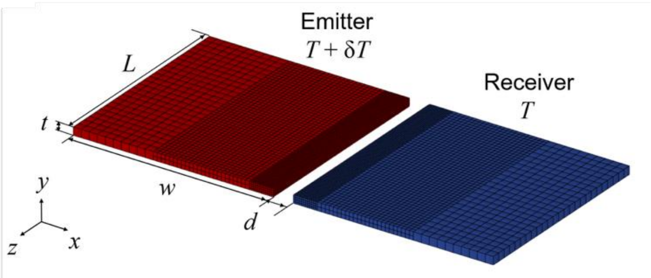


Luo et al., *Nano Lett.* **24**, 1502, 2024

Numerical simulations using the DSGF solver at T = 300 K

for w = 1 μm, L = 1 μm, and d = 100 nm.





McCormack et al., *Phys. Rev. Lett.* **136,** 146303, 2026.

***Key finding:** Material losses play a key role enhancing or attenuating near-field radiative heat transfer*

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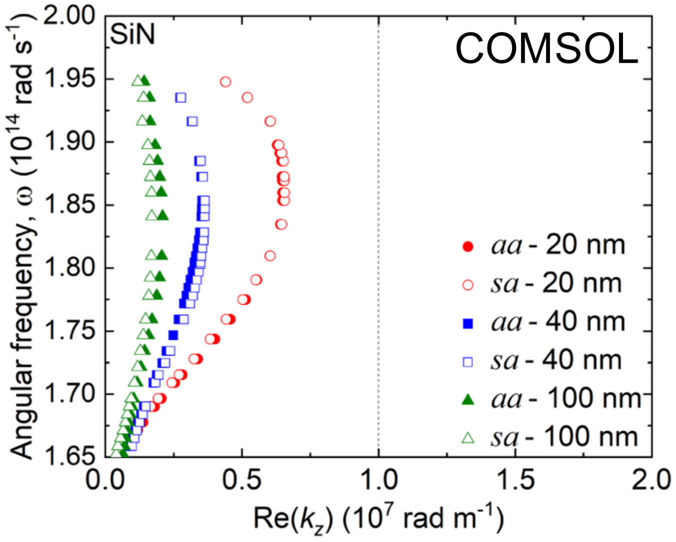
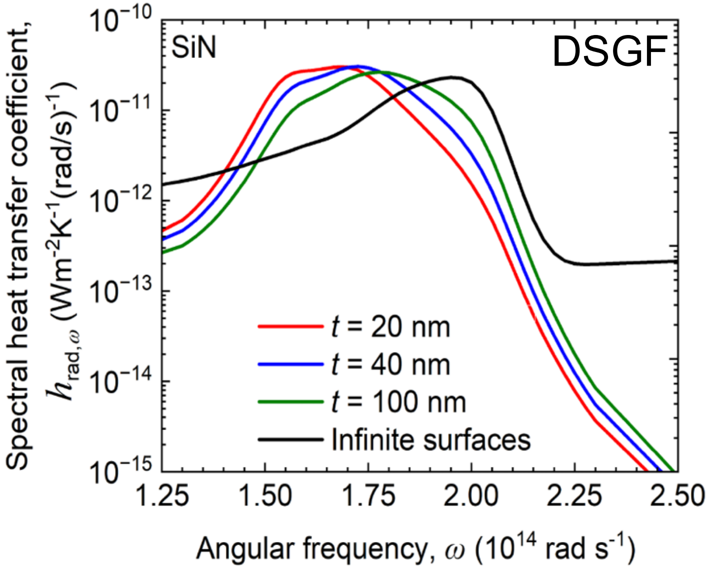
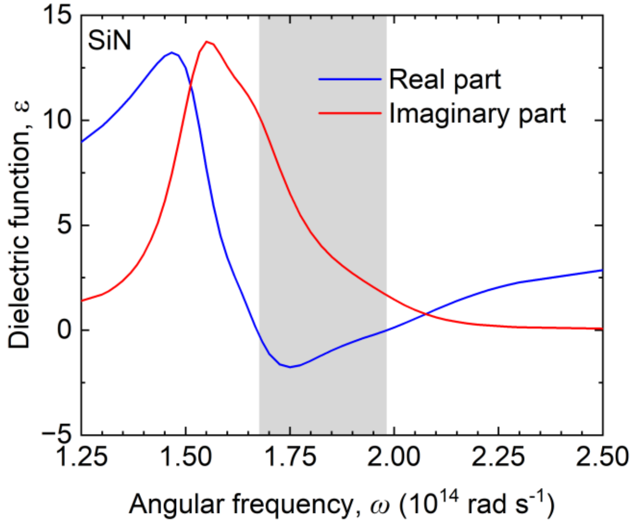
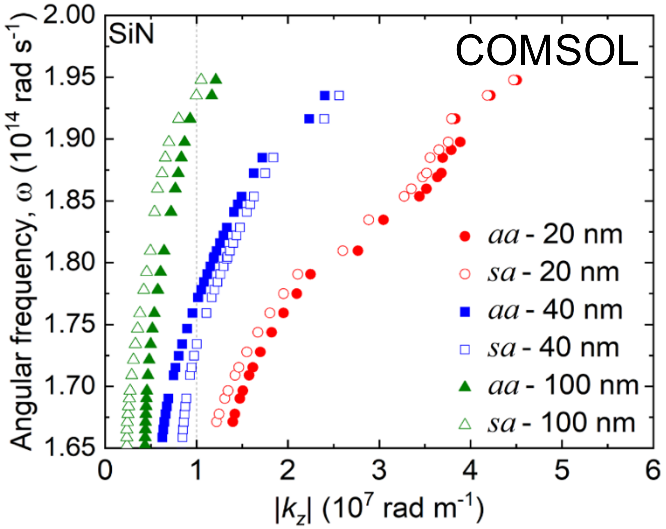
SiN: non-negligible losses reduce the available density of states





- The maximum contributing wavevector dominating NFRHT is estimated as ≈ d^{-1} ≈ 10^7 rad/m
- **Re ($k_{z,max}$)** occurs ~at the same frequency
- Corner and edge modes induce resonance **redshift**





- SiN presents **non-negligible** material losses along the Reststrahlen band
- **$|k_z|$** should be used to indicate resonance
- For d = 100 nm, $|k_{z,max}|$ ≈ 10^7 rad/m
- For t = 20 nm, **Re ($k_{z,max}$) ≈ 10^6 rad/m**
- **Re(k_z) << $|k_z|$**

McCormack et al., *Phys. Rev. Lett.* **136,** 146303, 2026.

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This research resulted in two publications

Article

Corner- and edge-mode enhancement of near-field radiative heat transfer

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Near-Field Radiative Heat Transfer in the Dual Nanoscale Regime between Polaritonic Membranes

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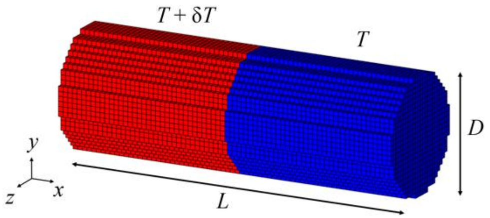
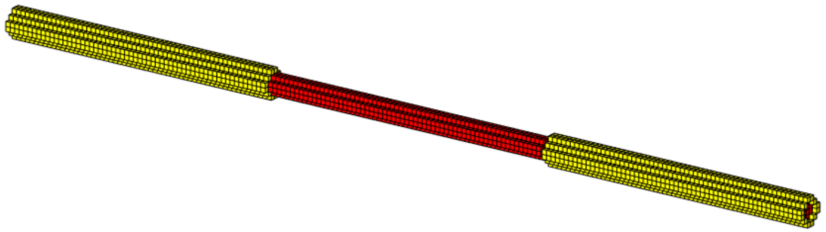
The DSGF method enables rigorous prediction of radiation conduction in nanostructures





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Thank you!
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