Phonon-polariton mediated heat transfer in nanostructures

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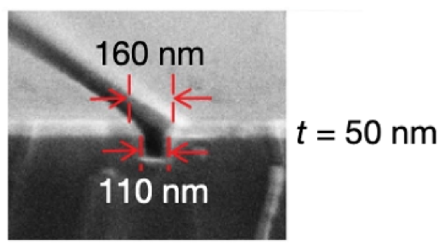
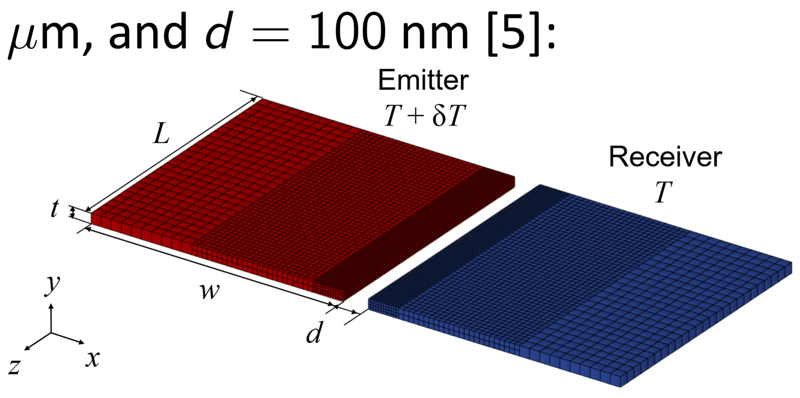
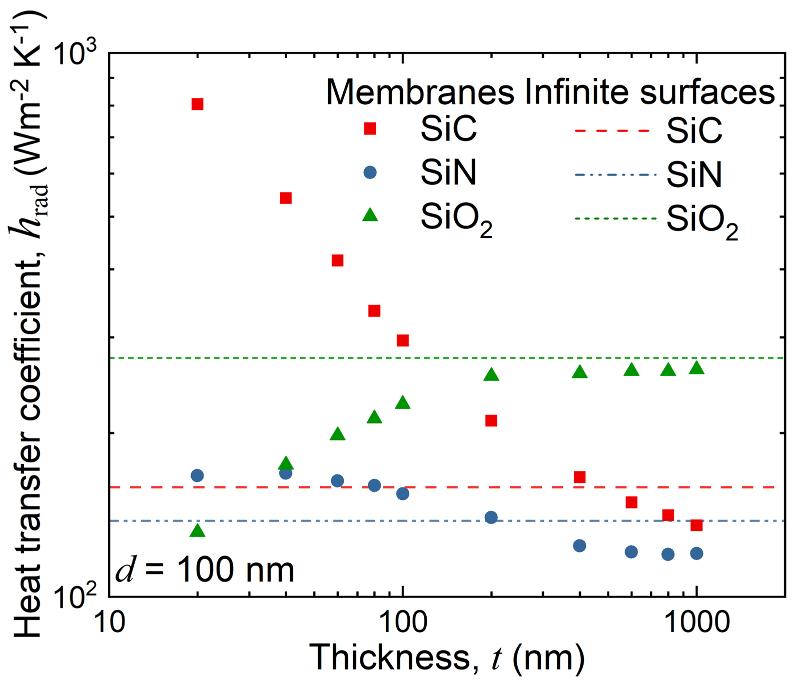
Radiative heat transfer in the dual nanoscale regime

Different polaritonic materials with similar EM responses display opposite trends in the dual nanoscale regime of near-field radiative heat transfer (NFRHT) [1, 2].



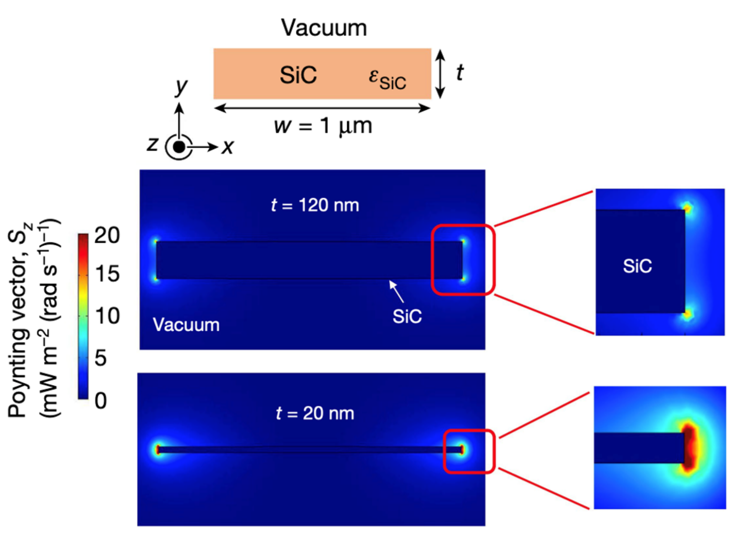
Using numerically-exact discrete system Green's function (DSGF) simulations [3, 4], the NFRHT coefficient is predicted between membranes with $w = L = 1$ μm, and $d = 100$ nm [5]:





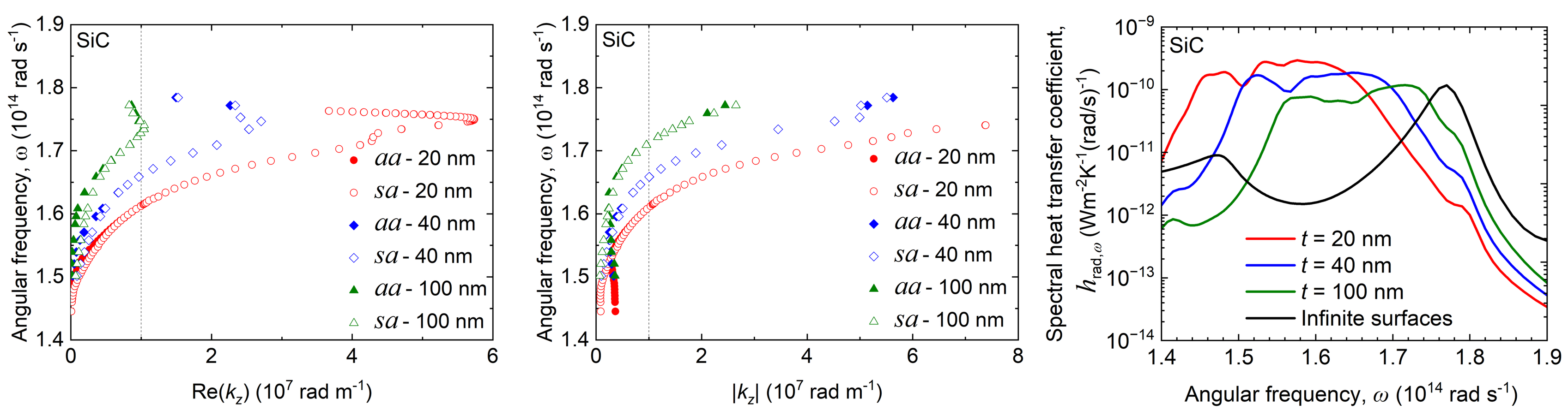
$$h_{rad}(T) = \int_0^\infty \frac{1}{2\pi A_c}\left[\sum_{i\in V_E}\sum_{j\in V_R}\mathcal{T}_{ij}(\omega)\right]\left[\frac{\partial\Theta(\omega,T')}{\partial T}\right]_{T'=T} d\omega,$$

where Θ is the mean energy of an EM state, and $\mathcal{T}_{ij}$ is the transmission coefficient.
Modal analyses show that all membranes support **EM corner and edge modes** [6], which induce spectral redshift.
Material losses (i.e., Im(ε)) play a key role in the dual nanoscale regime.



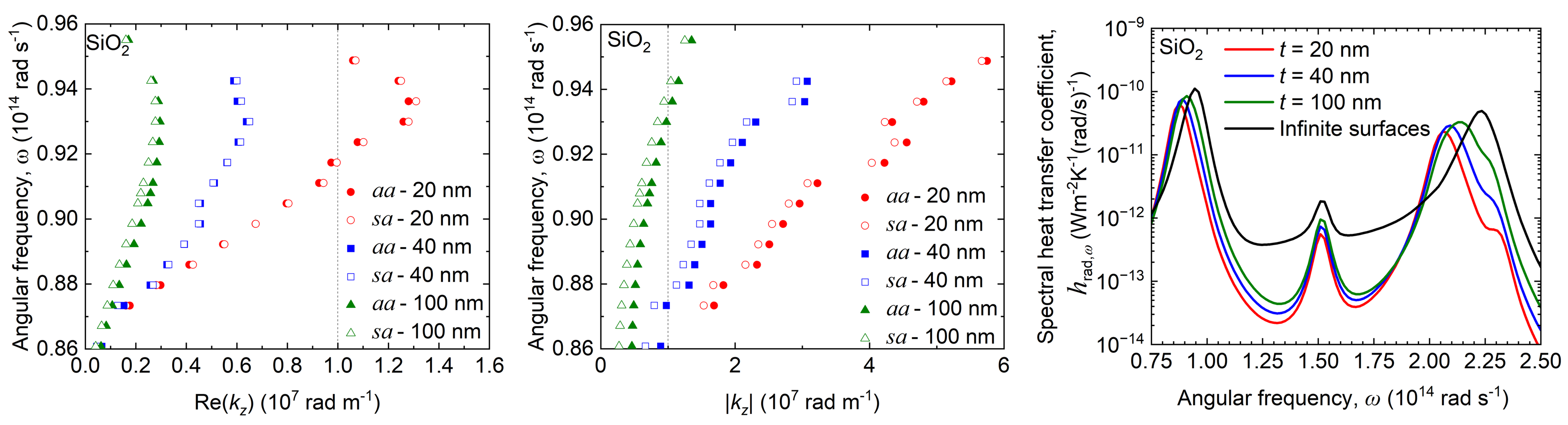
SiC:

- Losses are mostly negligible, Re(k_z) $\gg$ Im(k_z).
- Either Re(k_z) or $|k_z|$ can predict $h_{rad,\omega}$ resonances.
- Strong SPhP coupling is promoted, **enhancing** NFRHT.



SiN and SiO_2:

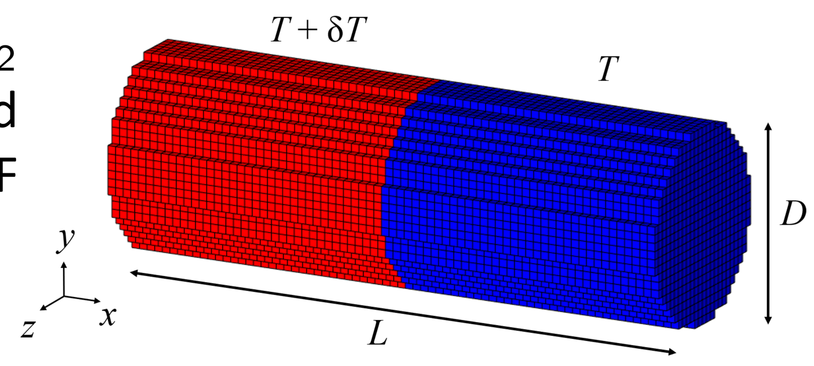
- Losses are non-negligible.
- $|k_z|$ should be used to predict resonance redshift.
- Losses reduce the maximum Re(k_z) tunneled between the membranes.
- For SiO_2, NFRHT is **attenuated** with decreasing membrane thicknesses.



Application: localized radiative cooling.

Radiation-conduction in nanowires

The radiative conductivity in SiO_2 nanowires with $D = 66$ nm and $L = 200$ nm is predicted using the DSGF method [3, 7]:



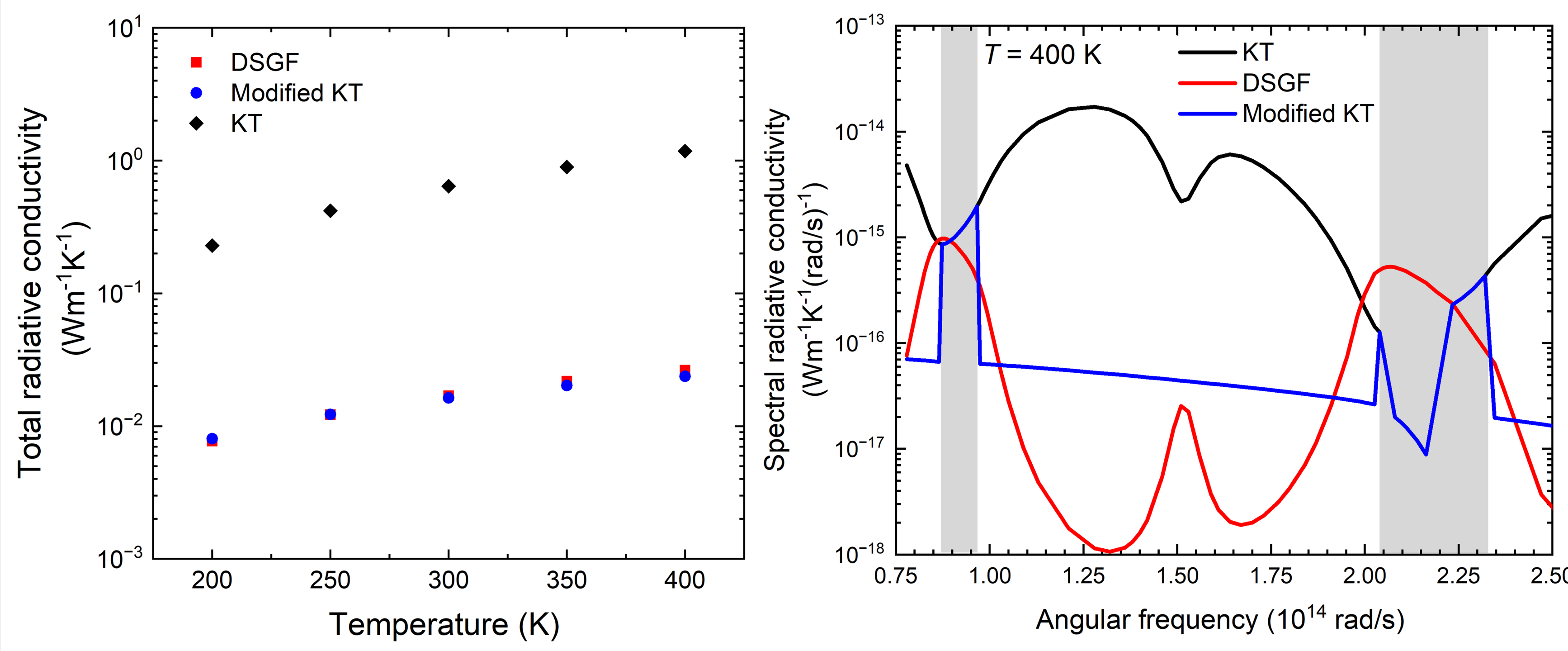
$$\kappa(T) = \int_0^\infty \frac{1}{2\pi A_c}\left[\sum_{i\in V_A}\sum_{j\in V_B}\mathcal{T}_{ij}(\omega)(\mathbf{r}_j - \mathbf{r}_i)\cdot\hat{\mathbf{x}}\right]\left[\frac{\partial\Theta(\omega,T')}{\partial T}\right]_{T'=T} d\omega.$$

The radiative conductivity is typically calculated using kinetic theory (KT) as [8]:

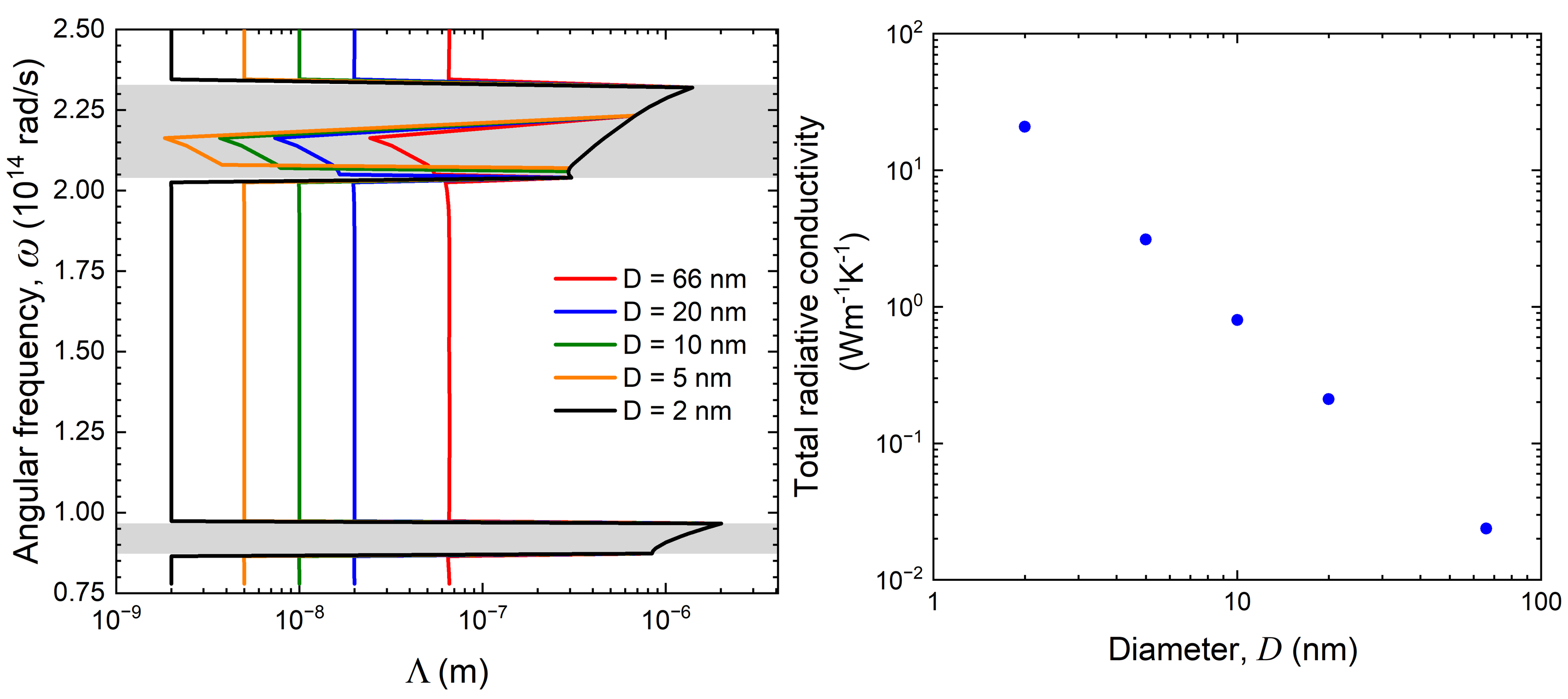
$$\kappa(T) = \int_0^\infty \frac{1}{\pi A_c}\hbar\omega\Lambda\frac{\partial f_0}{\partial T}d\omega,$$

where the mean free path Λ is calculated using dispersion relations for an infinite cylinder.
Assuming Λ as the propagation length $L_p = (2\text{Im}(k))^{-1}$ is not valid over the whole spectrum.
We propose a modified KT where

- Inside Reststrahlen bands: $\Lambda = L_p$.
  SPhPs are dominant and do not undergo size effect.
- Outside Reststrahlen bands: $\Lambda = \Lambda_{wire}\left(\frac{1}{\text{Kn}} - \frac{1}{4\text{Kn}^2}\right)$,
  where $\Lambda_{wire} = L_p$ and Kn = Λ_{wire}/D.
  Photons experience **size effect** due to boundary scattering.



Radiation-conduction can exceed the bulk phonon conductivity when SiO_2 nanowires are thinner than 10 nm.



Application: thermal management of solid-state devices.

References

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