Fundamentals of Near-Field Thermal Radiation

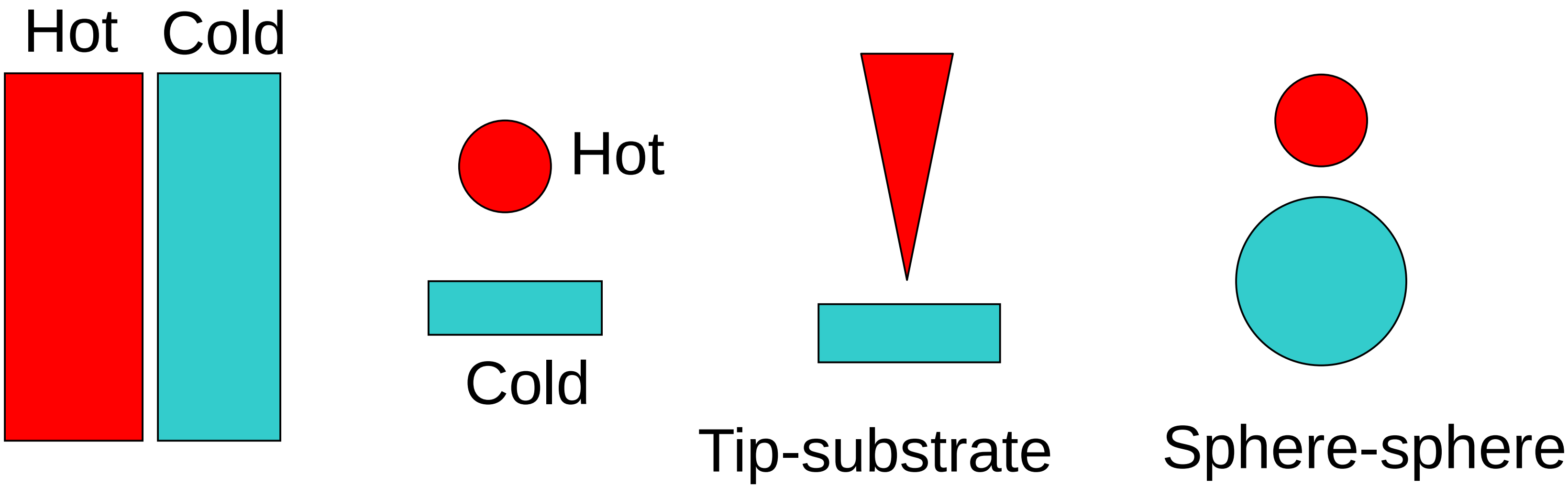
Zhuomin Zhang, Ph.D.
J. Erskine Love, Jr. Professor
George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology, Atlanta, Georgia

Presented at **KITP, UC Santa Barbara**
Emerging Regimes and Implications of Quantum and Thermal Fluctuational Electrodynamics, June 20-August 4, 2022
June 21, 2022

Outline

- Introduction and background
- Experimental demonstrations
- Fluctuational electrodynamics
- Predicted near-field radiative heat transfer
- Summary and open questions

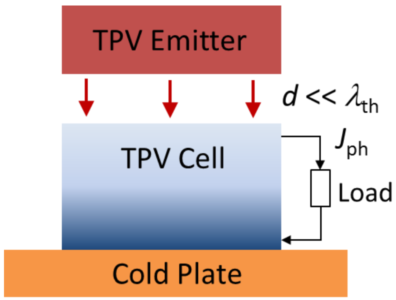
Near-Field Radiative Heat Transfer between Closely-Spaced Objects



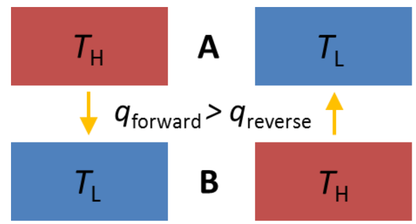
- When the separation is at a distance comparable to the characteristic wavelength, radiative energy transfer can be greatly enhanced (recently demonstrated by several groups).
- Professor Chang-Lin Tien’s group at UC Berkeley performed some very first analytical and experimental studies in late 1960s and early 1970s.
- Professor Gang Chen’s group demonstrated heat flux exceeding blackbody at room temperature in 2008.

Why Does Near-Field Radiation Matter?

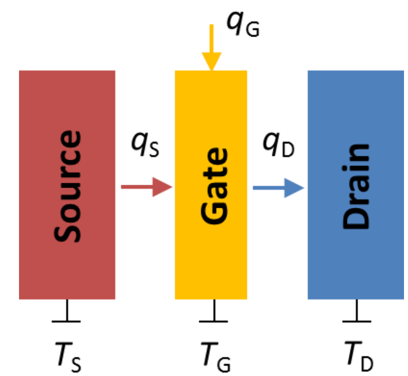
Near-field thermophotovoltaics



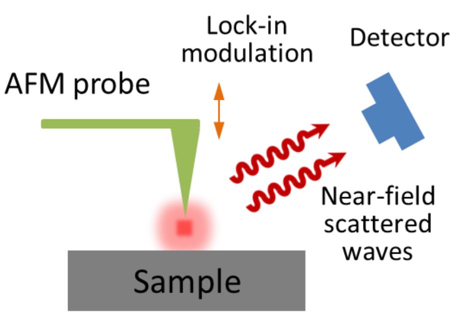
Contactless thermal rectifier



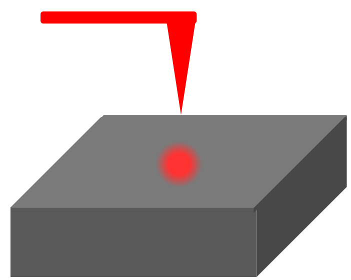
Thermal transistors



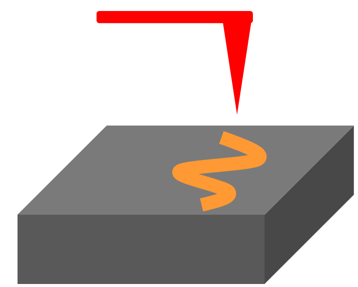
Thermal imaging beyond the diffraction limit



Local heating/cooling



Nanofabrication
Heat-assisted magnetic recording

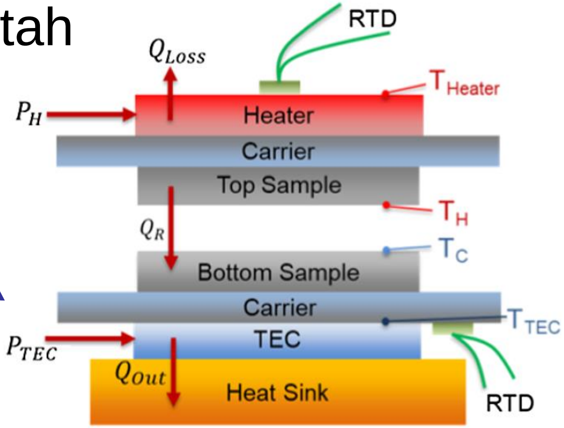


See **Liu, Wang, and Zhang, 2015,** *Nanoscale Microscale Thermophys. Eng.*

Measurements of Near-Field Radiation

Plate-Plate Geometry:

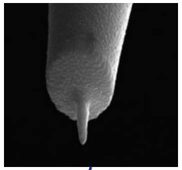
- Tien, Berkeley (1970)
- Hargreaves, Philips Res Lab
- Chen, MIT (2008)
- Tanner, U. Florida
- Kralik, ASCR (Czech Rep)
- Lipson, Columbia U.
- Ito et al., U. Tokyo
- Lee, KAIST
- Zhang, Georgia Tech
- Francoeur, U. Utah
- Jacob, Purdue
- Park, U. Utah

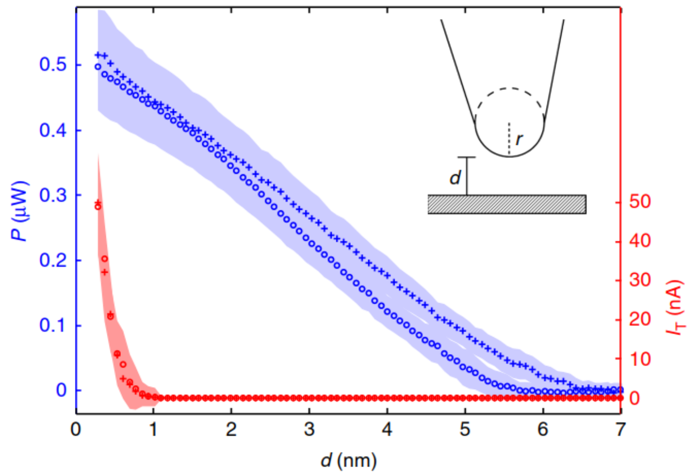


PRL (2018)

Tip(sphere)-Plate Geometry:

- Kittel, U. Oldenburg
- Greffet, CNRS (2009)
- Chevrier, CNRS
- Chen, MIT (2009)
- Shen, CMU
- Reddy, U. Michigan





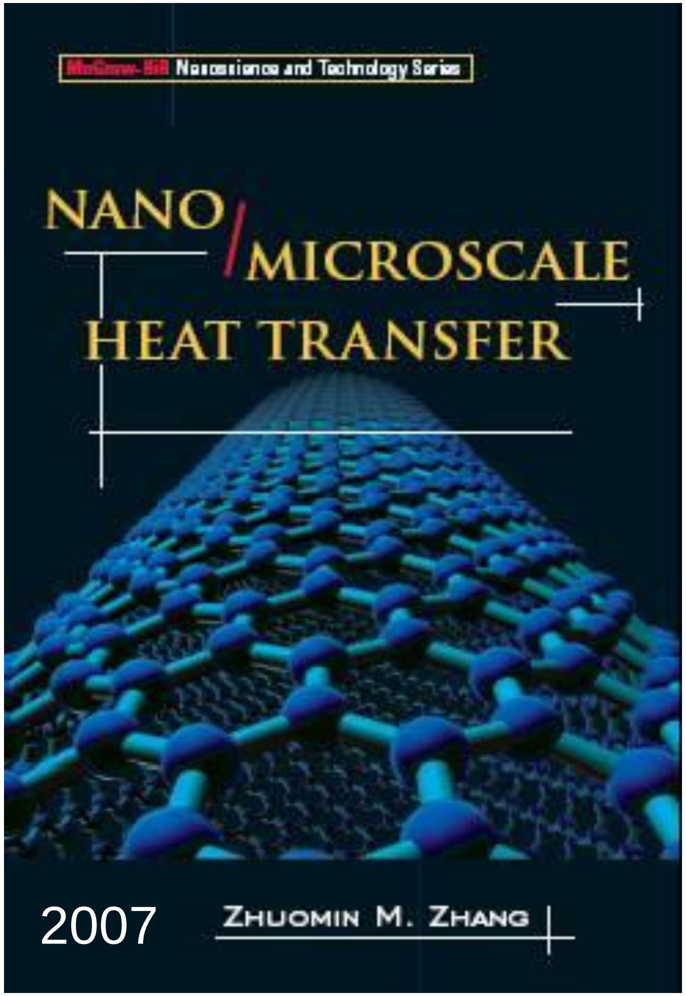
Nat. Commun. (2017)

The number of publications has increased quickly since 2018.

Micro/Nanoscale Thermal Radiation

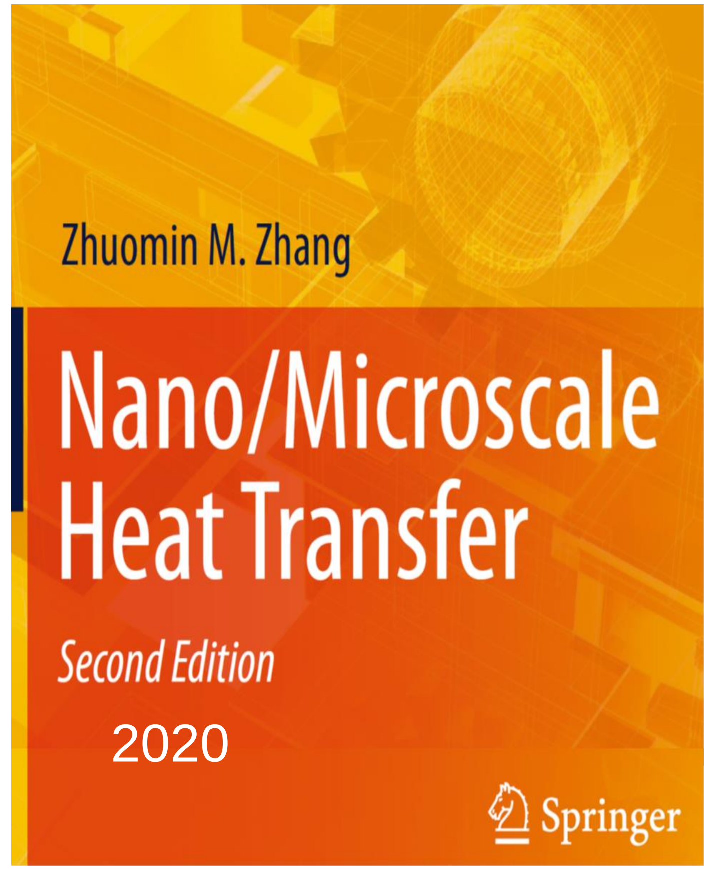
- Micro/nanoscale thermal radiation concerns both near-field radiative heat transfer (NFRHT) between closely spaced objects and the interaction of electromagnetic waves with micro/nanostructured materials that could potentially modify the far-field radiative properties.
- Examples of micro/nanostructures, gratings, nanowires, nanotubes, multilayers, nanoparticles and clusters, graphene and 2D materials, graphene ribbons, etc.
- New international workshops and funding opportunities have been surging to support research in these areas.

Nano/Microscale Heat Transfer



First Edition 479 pages

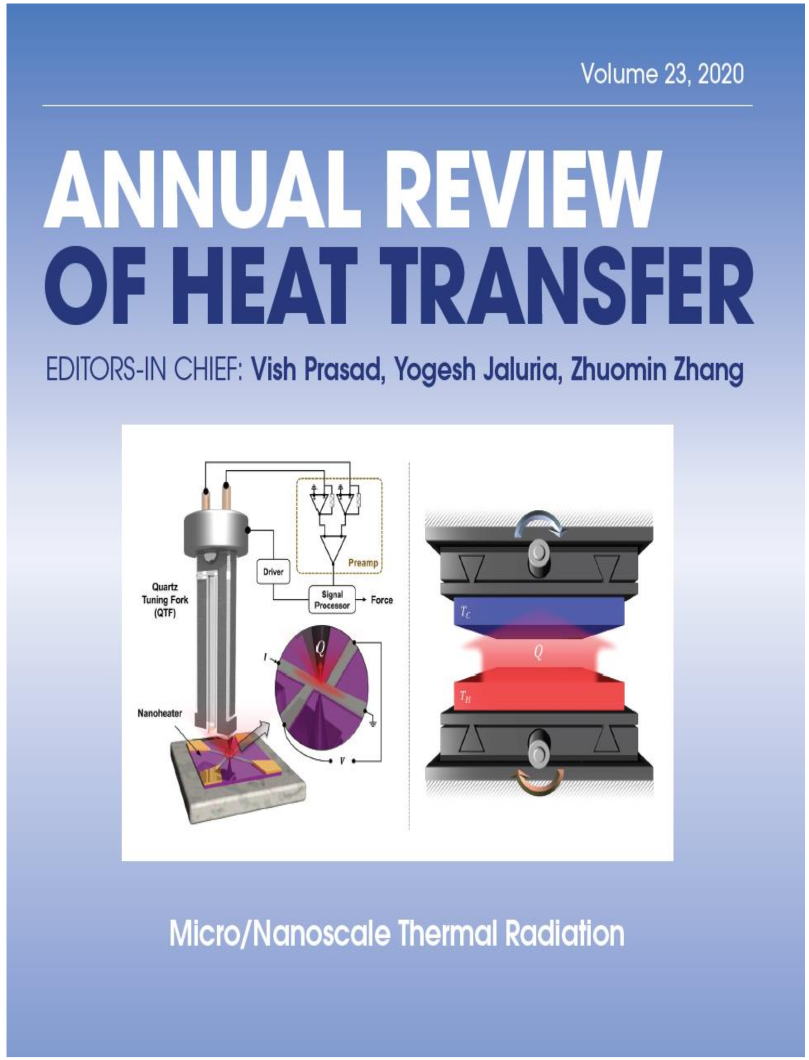
https://link.springer.com/book/10.1007/978-3-030-45039-7



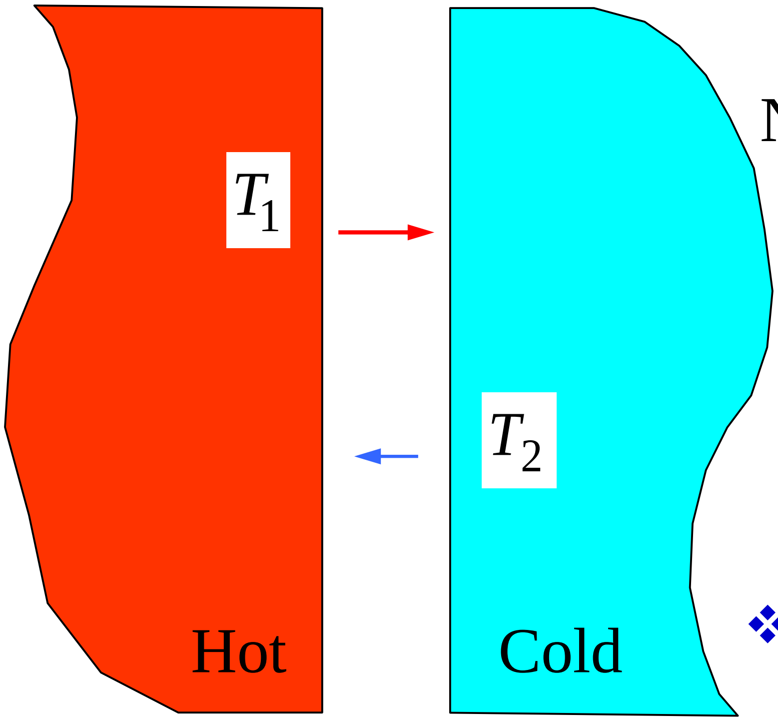
Second Edition 761 pages

Micro/Nanoscale Thermal Radiation

Vol. 23 (2020)



Radiative Heat Transfer between Two Blackbodies



Vacuum Gap

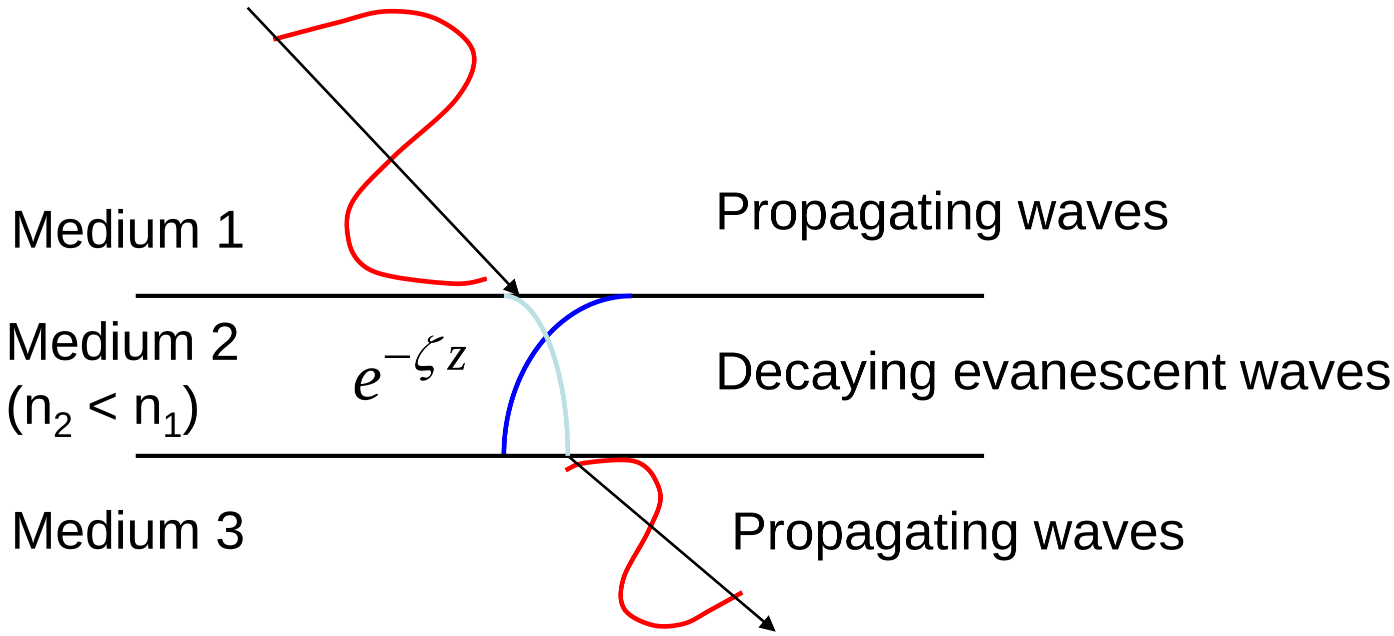
Net radiation heat flux from 1 to 2:

$$\boxed{q''_{12} = \sigma T_1^4 - \sigma T_2^4}$$

Due to Stefan-Boltzmann law (1885).

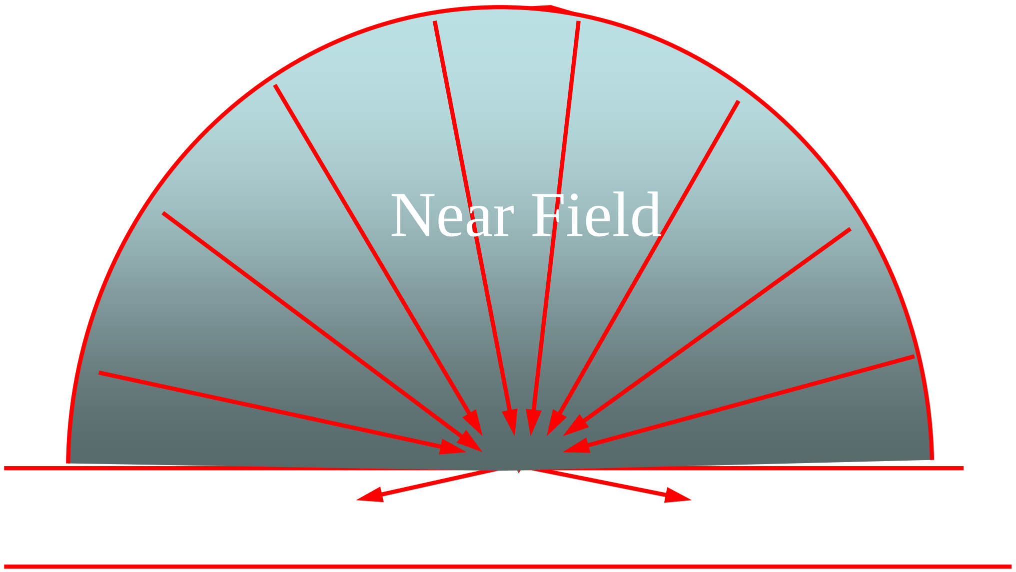
- ***Can heat transfer by radiation exceeds the limit set for blackbodies?***
- ***If so, when will it become important and what are the applications?***

Photon Tunneling or Radiation Tunneling



When the distance is small enough (near field), photons can tunnel through even though the incidence angle is greater than the critical angle. See for example, Cravalho, Tien, and Caren, *J. Heat Transfer* (1967).

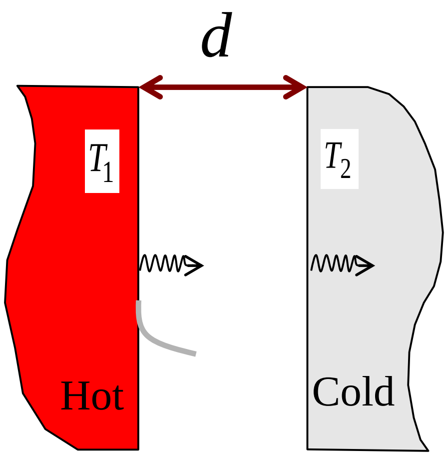
Far-Field V.S. Near-Field Radiation



In the near field, interference effects become important as well as photon tunneling. There are more energy transfer channels or modes (wave vectors). For dielectric media, it is limited to frustrated modes.

Thermal Radiation: Far Field vs. Near Field

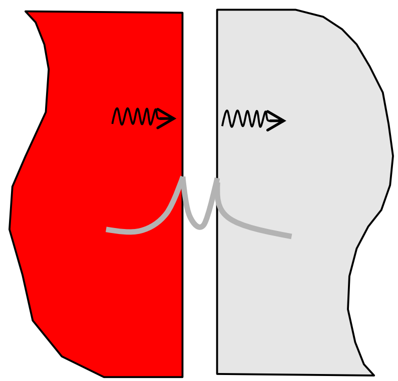
$d >> \lambda_{\text{th}}$



The Stefan-Boltzmann law (1885), the upper limit for propagating modes:

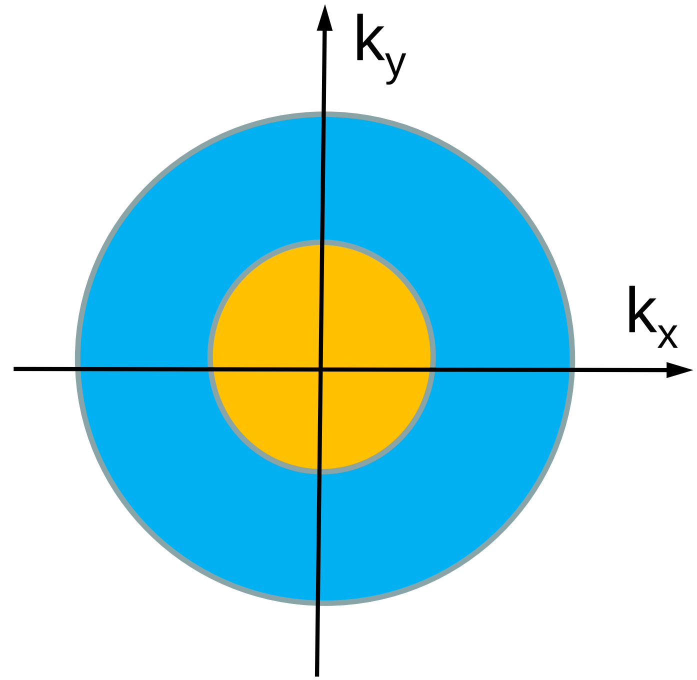
$$q_{\text{BB}} = \sigma_{\text{SB}}\left(T_1^4 - T_2^4\right)$$

$d << \lambda_{\text{th}}$



Heat flux exceeds the blackbody limit by orders of magnitude due to tunneling of evanescent waves.

From the point view of wavevector space



The inner and outer circle denotes propagating and evanescent modes, respectively.

Near-Field Radiative Heat Transfer

$$q_{\omega,1-2} = \frac{\Theta(\omega,T_1)}{8\pi^3} \iint_{k_x,k_y} \xi(\omega,k_x,k_y) dk_x dk_y$$

$$= \frac{\Theta(\omega,T_1)}{8\pi^3} \int_0^{2\pi} \int_0^{\infty} \xi(\omega,\beta,\phi)\beta d\beta d\phi \ , \quad \text{where } 0 \le \xi \le 1$$

Energy transmission coefficient or transmission factor; *photon tunneling probability* (for evanescent waves)

Isotropic: $$q_{\omega,1-2} = \frac{\Theta(\omega,T_1)}{4\pi^2} \int_0^{\infty} \xi(\omega,\beta)\beta d\beta$$

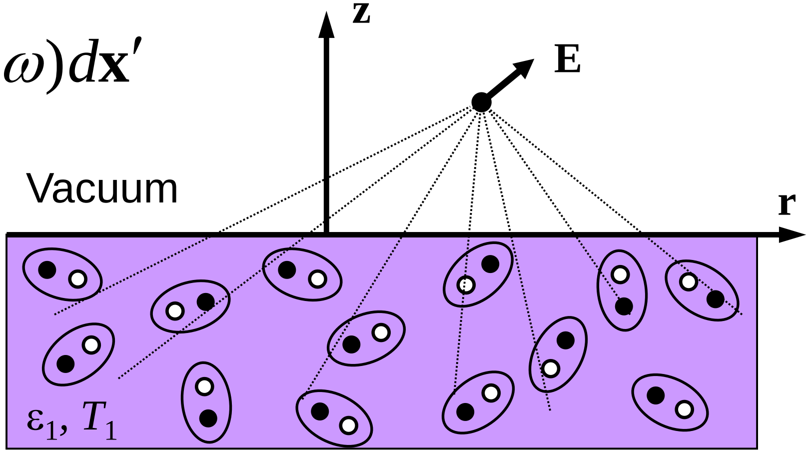
$$q_{\text{net}} = \int_0^{\infty} \left(q''_{\omega,1-2} - q''_{\omega,2-1} \right) d\omega$$

Also notice that ξ is a function of d (vacuum spacing) !

Fluctuation-Dissipation Theorem

$$\mathbf{E}(\mathbf{x},\omega) = i\omega\mu_0 \int_V \bar{\bar{\mathbf{G}}}(\mathbf{x},\mathbf{x}',\omega)\cdot \mathbf{j}(\mathbf{x}',\omega)d\mathbf{x}'$$

$$\mathbf{H}(\mathbf{x},\omega) = \frac{1}{i\omega\mu_0}\nabla\times\mathbf{E}(\mathbf{x},\omega)$$



Power flux: $\langle \mathbf{S}(\mathbf{x},\omega)\rangle = \frac{1}{2}\left\langle \mathrm{Re}[\mathbf{E}(\mathbf{x},\omega)\times\mathbf{H}^*(\mathbf{x},\omega)]\right\rangle$

Energy density is very high near the surface!

Electromagnetic field is produced by the induced dipoles of random thermal fluctuation of charges!

Fluctuational Electrodynamics

Correlation function for fluctuating currents:

$$\left\langle j_m(\mathbf{x}',\omega)\, j_n^*(\mathbf{x}'',\omega')\right\rangle = \frac{4\omega\varepsilon_0 \operatorname{Im}(\varepsilon)}{\pi}\Theta(\omega,T)\delta_{mn}\delta(\mathbf{x}'-\mathbf{x}'')\delta(\omega-\omega')$$

This is for isotropic medium and Θ is the mean energy of a Planck oscillator. Im(ε) is the imaginary part of the (relative) permittivity or dielectric function. A similar expression can be obtained for magnetic materials on the fluctuating magnetic current $\mathbf{M}^{(r)}$. Hence,

Maxwell's (1st and 2nd) equations in frequency domain:

$$\nabla\times\mathbf{H}(\mathbf{x},\omega) = -\mathrm{i}\omega\varepsilon_0\varepsilon\mathbf{E}(\mathbf{x},\omega) + \mathbf{J}^{(\mathrm{r})}(\mathbf{x},\omega) \qquad \text{(Ampere's law)}$$

$$\nabla\times\mathbf{E}(\mathbf{x},\omega) = \mathrm{i}\omega\mu_0\mu\mathbf{H}(\mathbf{x},\omega) - \mathbf{M}^{(\mathrm{r})}(\mathbf{x},\omega) \qquad \text{(Faraday's law)}$$

The key is to determine the dyadic Green's functions as mentioned previously!

Semi-infinite or Multilayer Structures

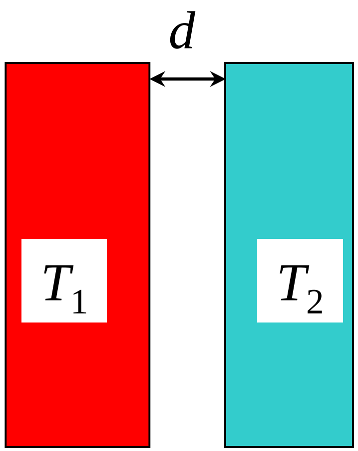
$$\overline{\overline{\mathbf{G}}}(\mathbf{x},\mathbf{x}',\omega)=\frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\overline{\overline{\mathbf{g}}}(\beta,z,z',\omega)\mathrm{e}^{\mathrm{i}\beta(r-r')}dk_x dk_y$$

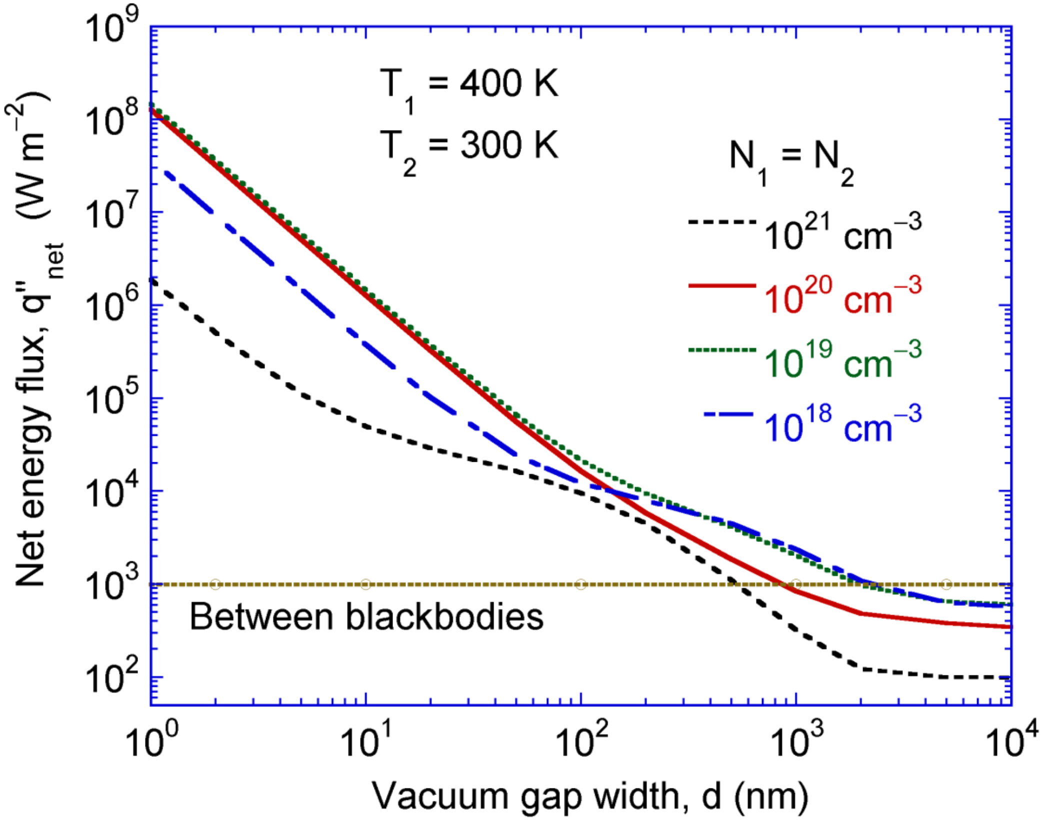
By using a Fourier transform, the spatial integration with respect to *x*-*y* plane becomes an integration in the wavevector space k_x-k_y. The integration over *z'* may be numerically solved by considering multilayers. For an isotropic, nonmagnetic medium, we obtain the previous formulation for NFRHT between two media:

$$q_{\text{net}}=\frac{1}{8\pi^3}\int_0^{\infty}\left[\int_0^{2\pi}\int_0^{\infty}\xi(\omega,\beta,\phi)\beta d\beta d\phi\right]\left[\Theta(\omega,T_1)-\Theta(\omega,T_2)\right]d\omega$$

In the far-field limit, the integration over β is limited to propagating waves only: $\beta < k_0 = \omega/c$.

Radiative Heat Transfer between Heavily Doped Silicon

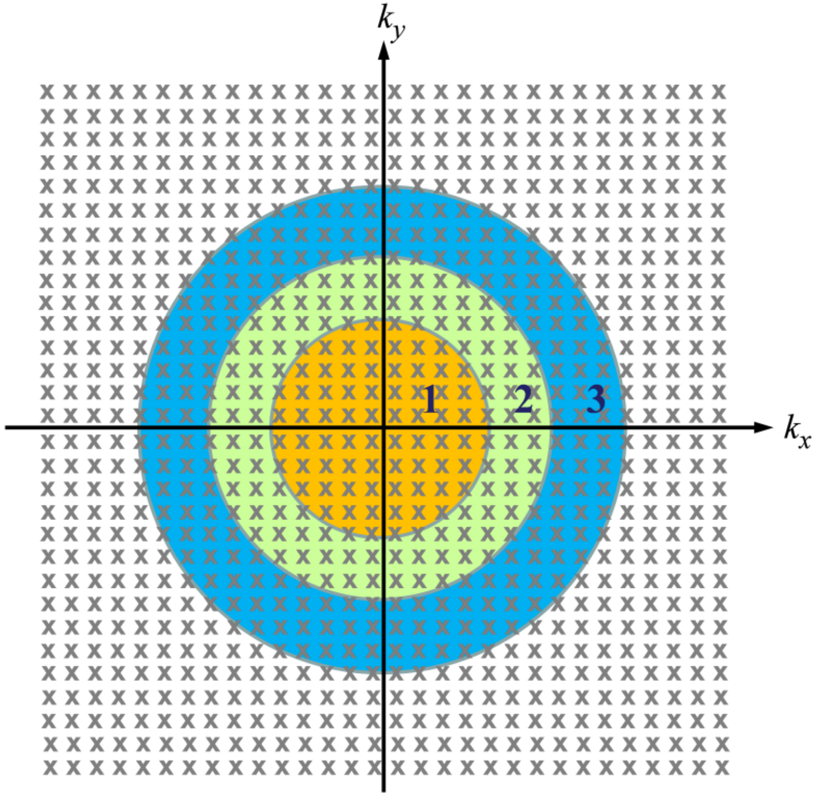




Basu, Lee, and Zhang, *J. Heat Transfer* (2010).

Also see Fu and Zhang, *Int. J. Heat Mass Transfer* (2006).

Wavevector Space

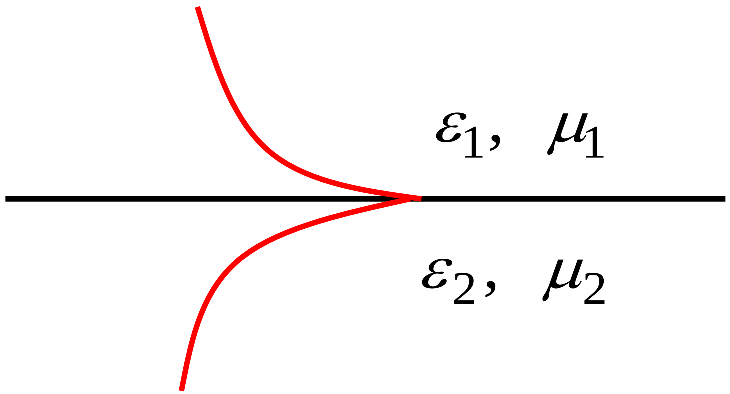


1. Propagating waves ($\beta < k_0$)

2. Frustrated modes ($k_0 < \beta < nk_0$)

3. Surface modes

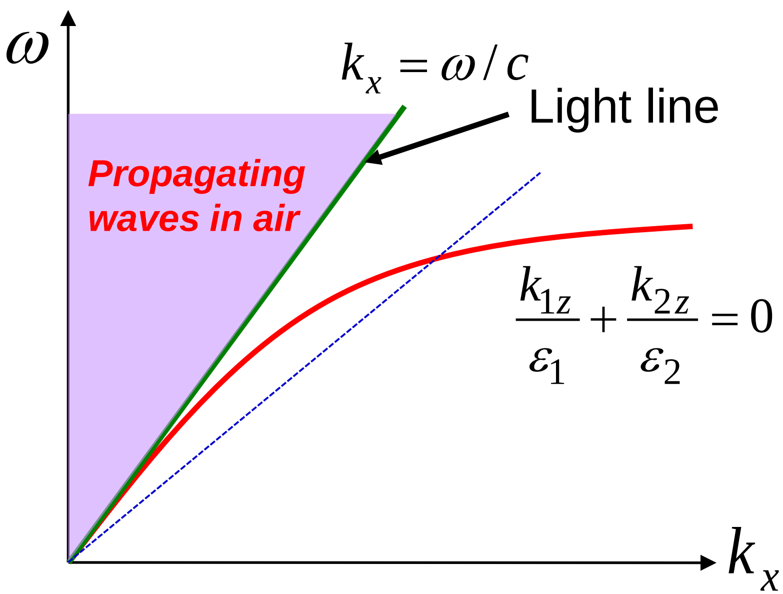
SPP or SPhP Dispersion Relations



Dispersion relation

$$\frac{k_{1z}}{\varepsilon_1} + \frac{k_{2z}}{\varepsilon_2} = 0$$ TM waves

$$\frac{k_{1z}}{\mu_1} + \frac{k_{2z}}{\mu_2} = 0$$ TE waves



To excite surface waves, one needs a coupler

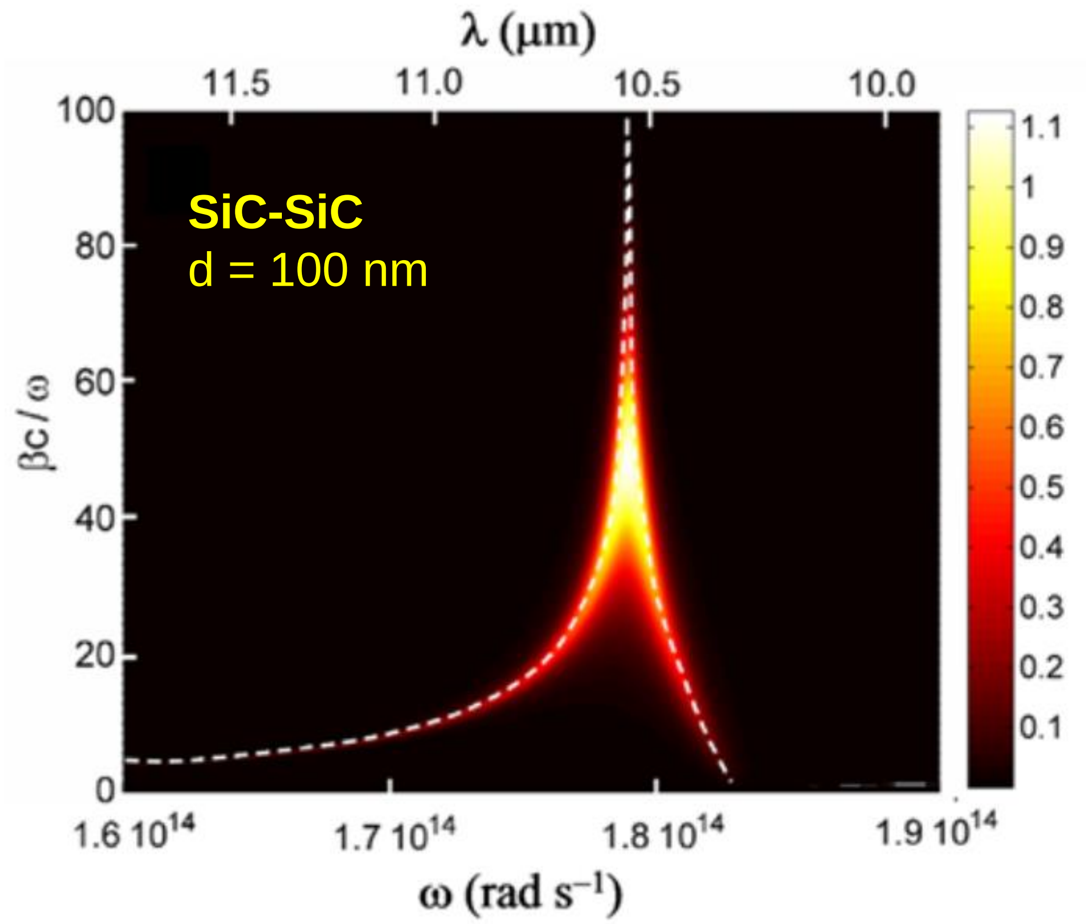
(1) Prism (ATR configuration)

(2) Grating, photonic crystals, etc.

(3) Near field even for flat surfaces!!!

Surface plasmon polariton (SPP) or surface phonon polariton (SPhP)

Effect of Surface Waves

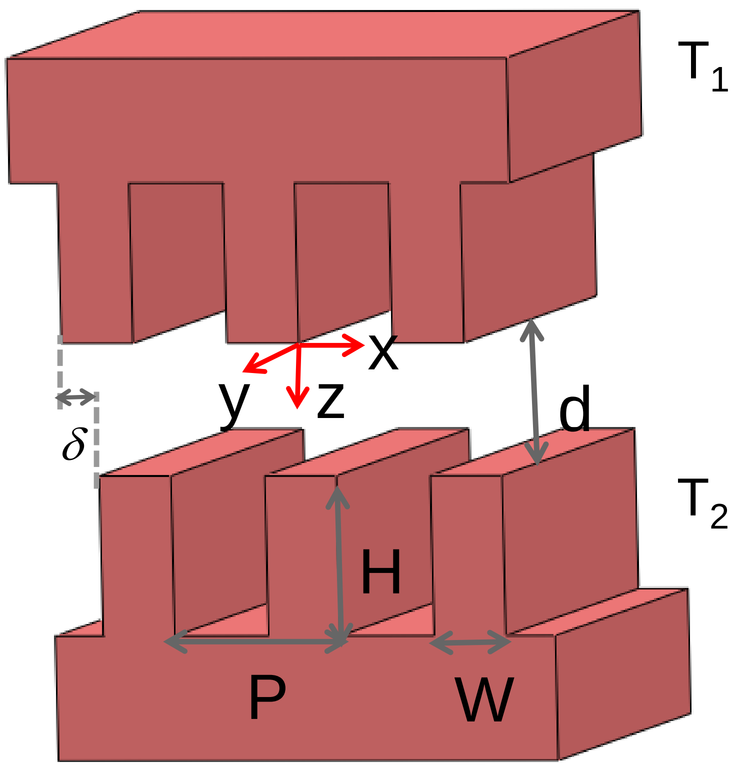


Color contour is proportional to $\xi\beta$

Basu et al., Int. J. Energy Res. (2009);
Park and Zhang, Front. Heat Mass Transfer (2013)

Near-Field Radiative Transfer between Nanostructures

$$q = \frac{1}{8\pi^3}\int_0^\infty \left[\int_{-\pi/P}^{\pi/P}\int_{-\infty}^{\infty} \xi(\omega,k_x,k_y)dk_x dk_y\right]\left[\Theta(\omega,T_1)-\Theta(\omega,T_2)\right]d\omega$$



$$\xi(\omega,k_x,k_y) = \mathrm{Tr}\left(\mathbf{D}\mathbf{W}_1\mathbf{D}^\dagger\mathbf{W}_2\right)$$

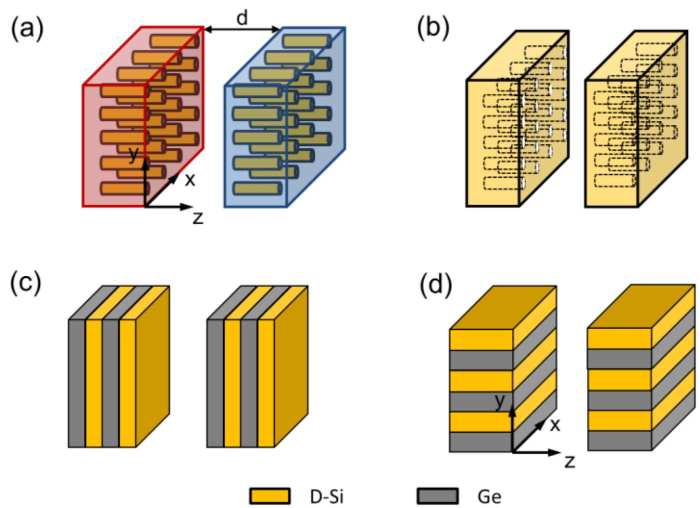
$$\mathbf{D} = \left(\mathbf{I}-\mathbf{S}_1\mathbf{S}_2\right)^{-1}$$

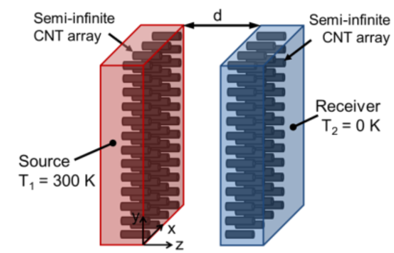
$$\mathbf{W}_1 = \sum\nolimits_{-1}^{\mathrm{pw}} - \mathbf{S}_1\sum\nolimits_{-1}^{\mathrm{pw}}\mathbf{S}_1^\dagger + \mathbf{S}_1\sum\nolimits_{-1}^{\mathrm{ew}} - \sum\nolimits_{-1}^{\mathrm{ew}}\mathbf{S}_1^\dagger$$

$$\mathbf{W}_2 = \sum\nolimits_{1}^{\mathrm{pw}} - \mathbf{S}_2^\dagger\sum\nolimits_{1}^{\mathrm{pw}}\mathbf{S}_2 + \mathbf{S}_2^\dagger\sum\nolimits_{1}^{\mathrm{ew}} - \sum\nolimits_{1}^{\mathrm{ew}}\mathbf{S}_2$$

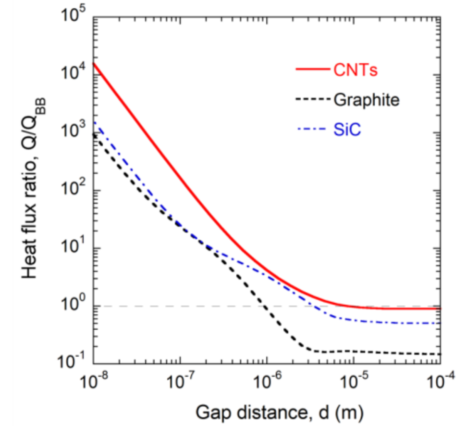
S is the scattering matrix, and can be solved by rigorous coupled-wave analysis (RCWA).

Nanostructure Effects and 2D Materials

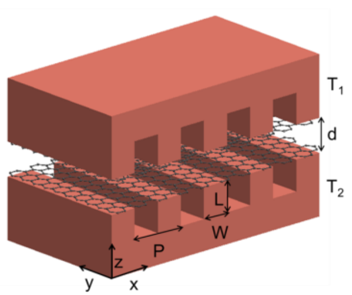




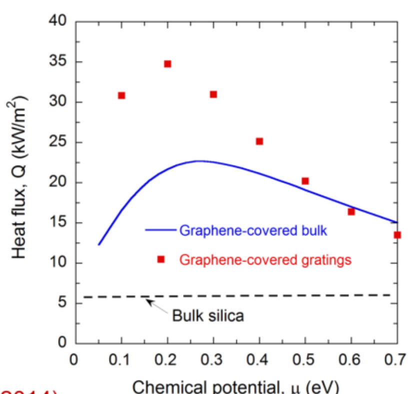
Due to hyperbolic dispersion, the near-field heat flux for CNT arrays can be an order of magnitude higher than that for SiC.



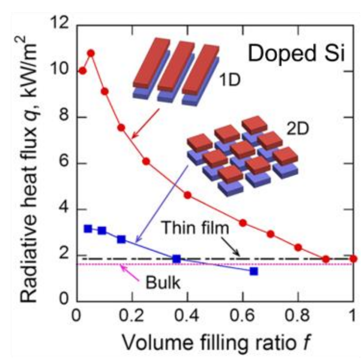
Liu, Zhang, and Zhang, APL (2013)



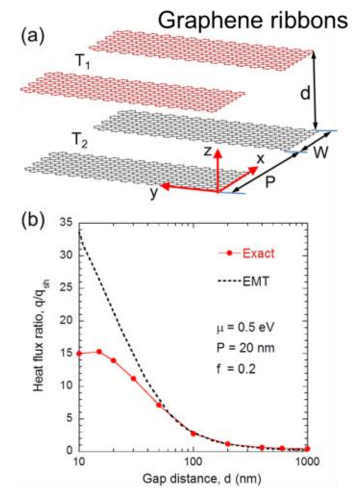
$T_1 = 310$ K, $T_2 = 290$ K
d = 100 nm



Liu and Zhang, *Appl. Phys. Lett.* (2014)
Liu et al., *Phys. Rev. A* (2015)



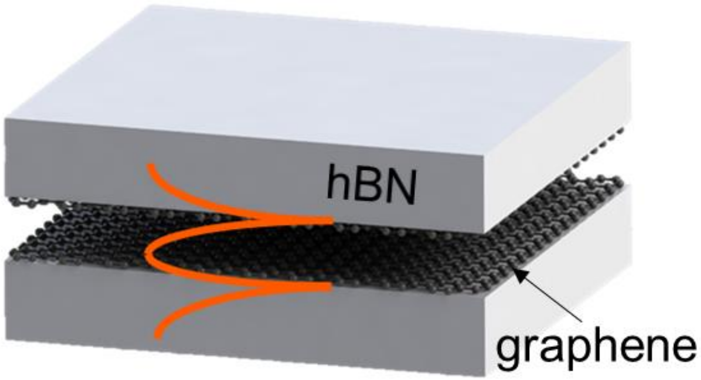
Liu and Zhang, 2015, *ACS Photonics*
(We have used used both scattering theory and FDTD)



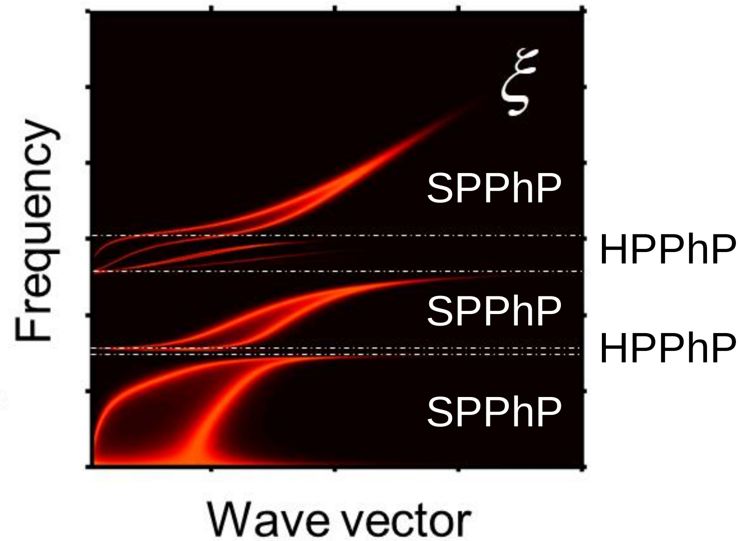
Liu and Zhang, 2015, *Appl. Phys. Lett.*

Also hBN, Black Phosphorus, $MoSe_2$, etc.

Hybrid Modes: Graphene on hBN



Hexagonal boron-nitride (hBN)

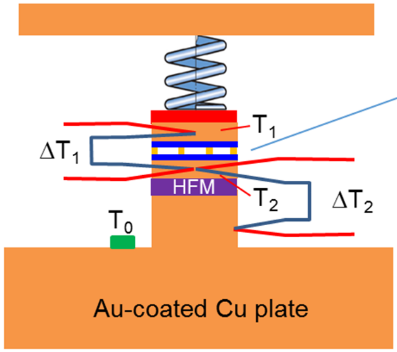


Surface plasmon (SP) in graphene are coupled with the hyperbolic phonon polariton (HPhP) in hBN to form hybrid modes:

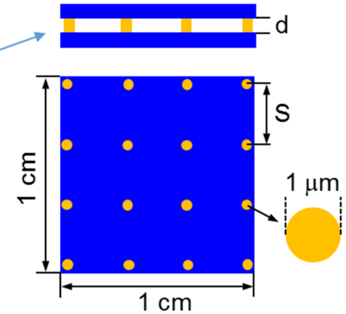
- Surface Plasmon-Phonon Polariton (SPPhP)
- Hyperbolic Plasmon-Phonon Polariton (HPPhP)

Zhao and Zhang, *J. Heat Transfer* **139** (2017) 022701.
Zhao et al., *Phys. Rev. B* **95** (2017) 245437.

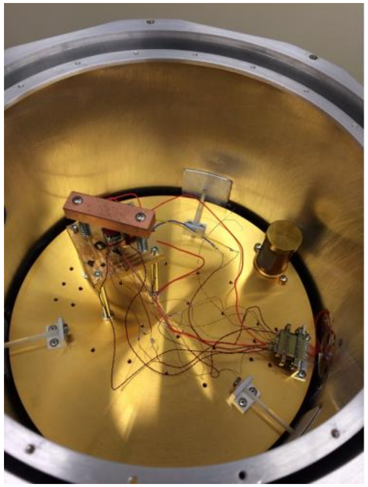
A Measurement Example

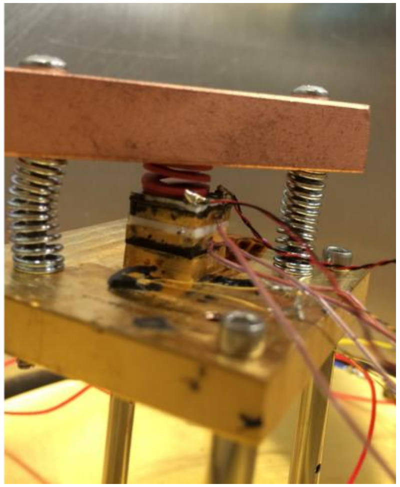


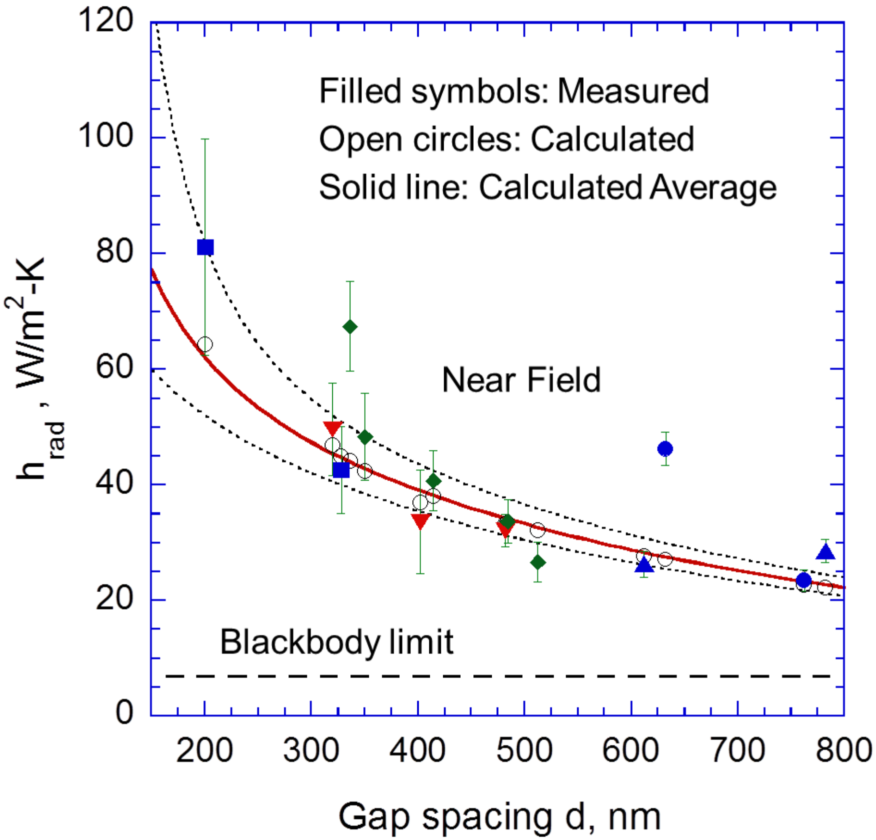
(a) Experimental setup



(b) Sample schematic







Watjen, Zhao, and Zhang, *Appl. Phys. Lett.* **109**, 203112 (2016).

Summary

- Much has been done on the modeling and simulation of near-field radiative transfer with planar and nanostructured materials, including metamaterials and metasurfaces
- Many groups have successfully measured near-field radiative transfer, even demonstrated devices
- Outstanding questions remain as in the extreme near field, photon-phonon coupling, energy transfer versus momentum transfer, etc.