Application of Near-Field thermal Radiation in Thermal Rectifiers

Shizheng WEN

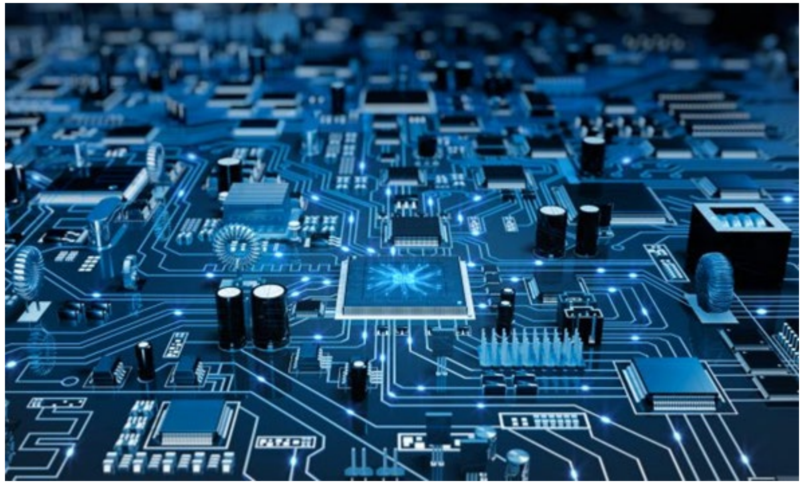
Personal Academic Site: https://www.shizheng-wen.com/

College of Energy and Power Engineering

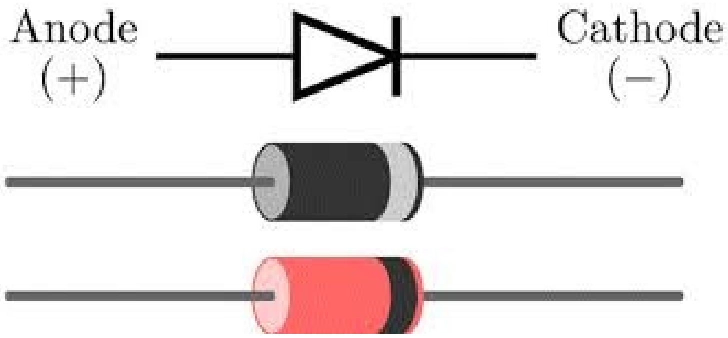
Nanjing University of Aeronautics and Astronautics

Supervisors:
Xianglei Liu (NUAA)

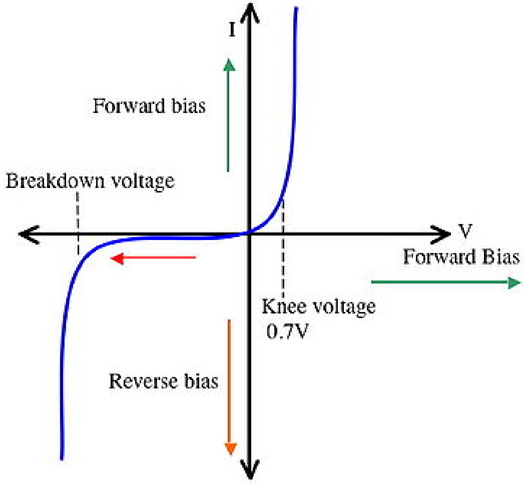
Backgrounds



Electric technology



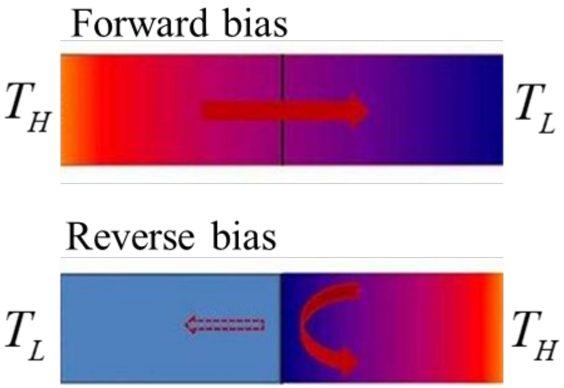
Electric Diode



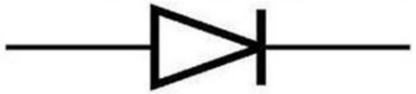
Rectification of electrons flow

Controlling the heat flow may provide alternative ways to process information at harsh conditions

Thermal Rectification

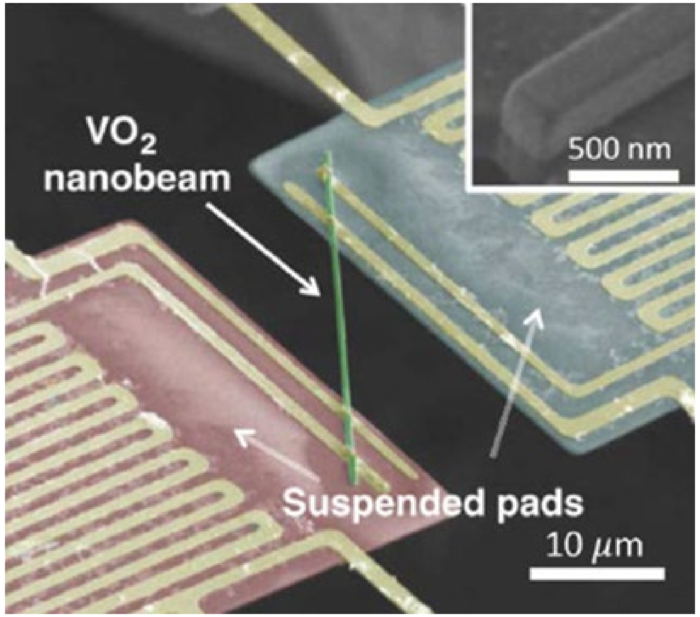


Thermal Diode
Thermal Rectifier



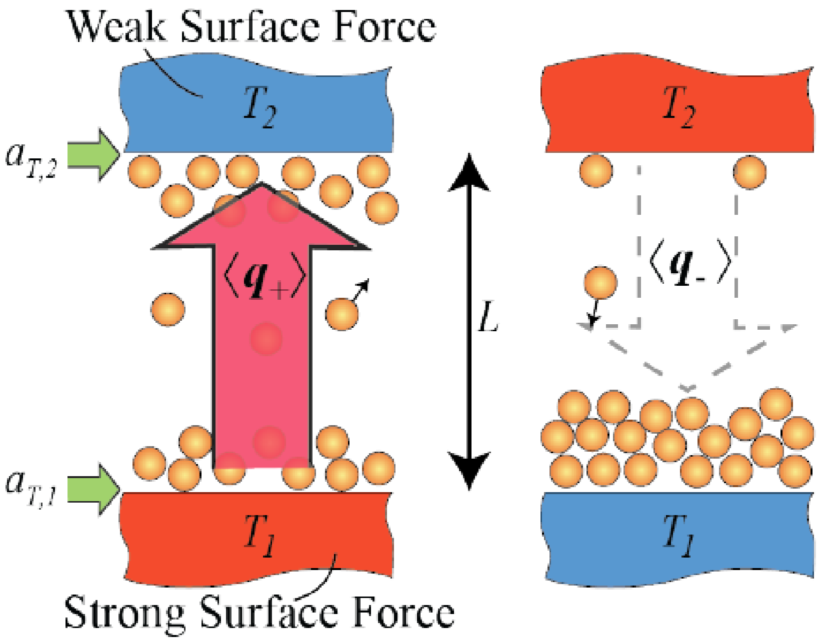
Backgrounds

Heat flow can by realized by three approaches: **Conduction | Convection | Radiation**



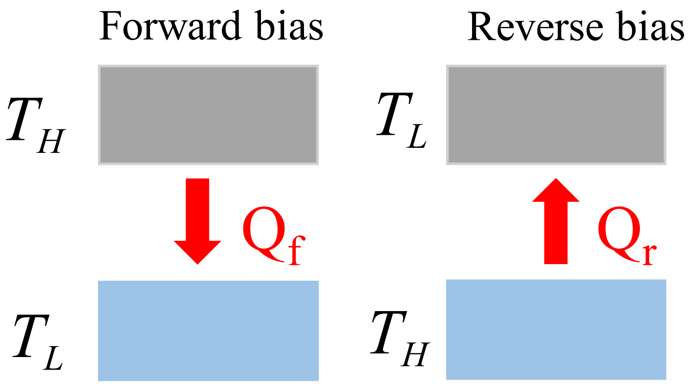
Conduction-based thermal rectifier

Chang et al. *Science* 2006, Vol. 314, 1121-1124



Convection-based thermal rectifier

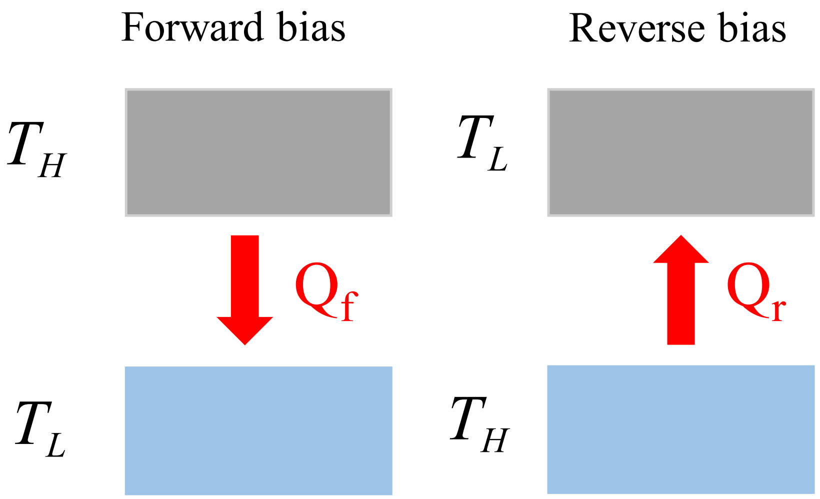
Avanessian and Hwang, *ICNMM2015 - 48508*



Radiation-based thermal rectifier

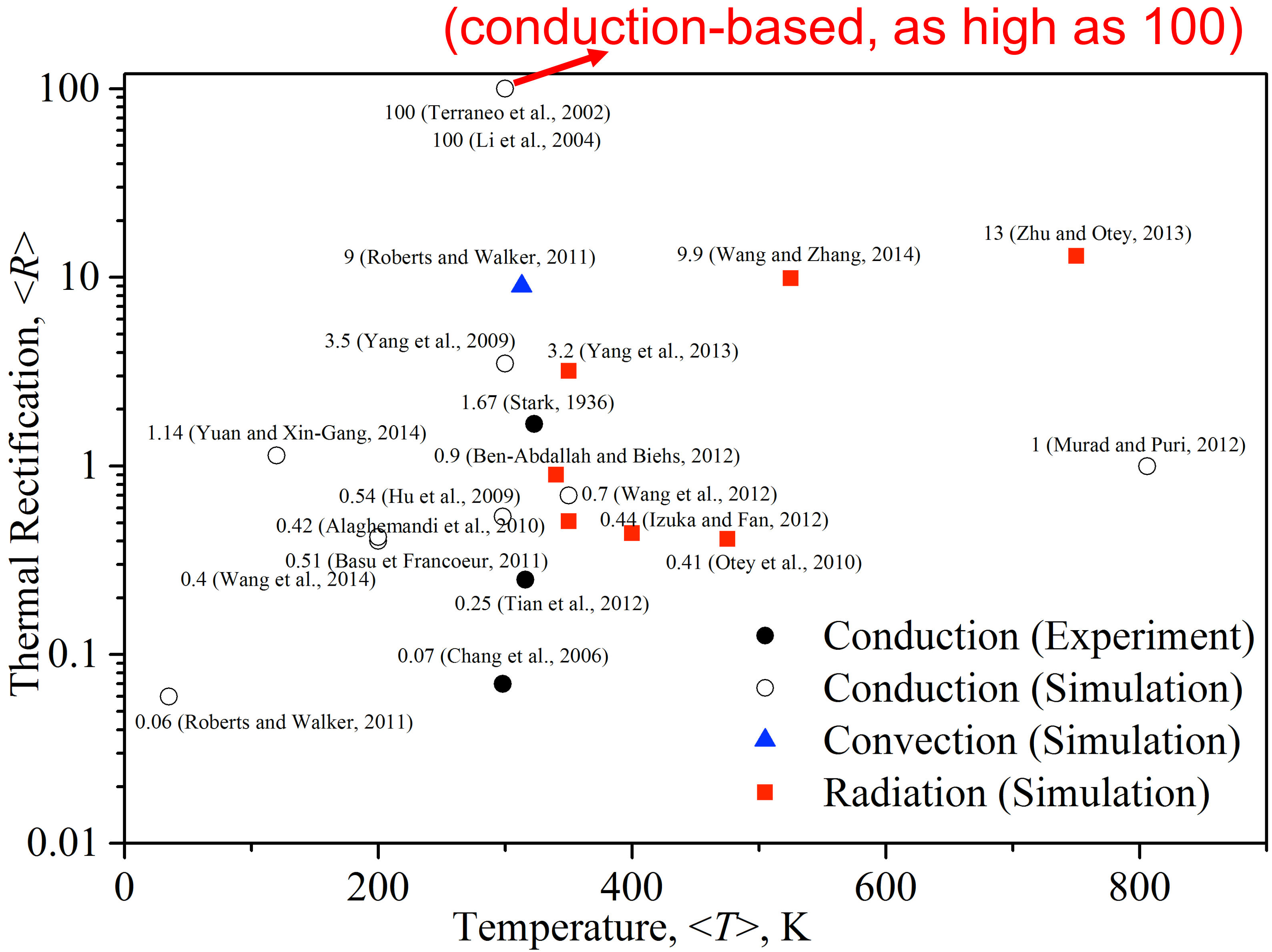
Merits: avoid contact and intrusion

Problem



Thermal rectification ratio:

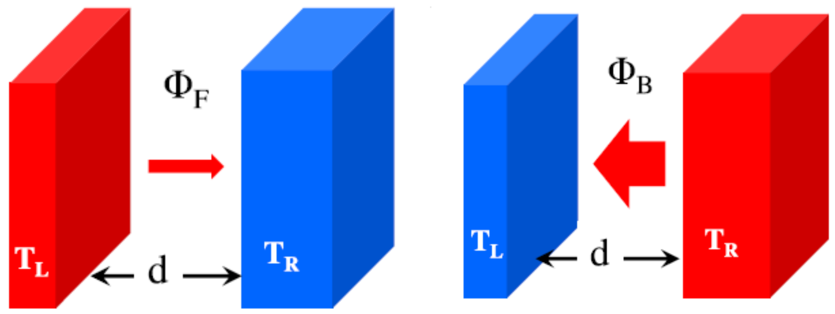
$$R_{\text{ratio}} = \frac{Q_f}{Q_r} - 1$$



Avanessian and Hwang, *ICNMM2015 - 48508*

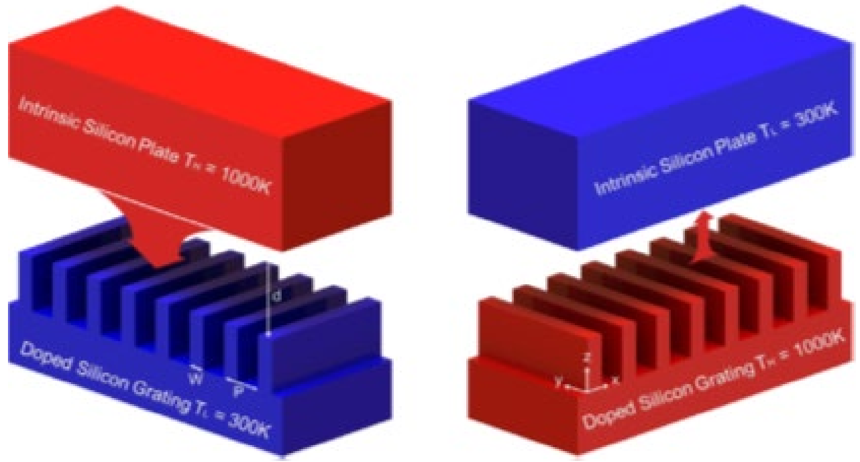
Method

Flat-plate



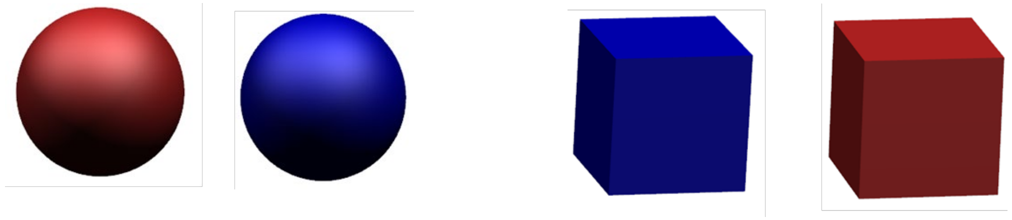
Ben-Abdallah et al. *AIP ADVANCES* **5**, 053502 (2015)

Plate with nanostructures



Shen et al. *JQSRT*, Vol. 211, 1-8 (2018)

Nanoparticles-based rectifier in my work



Calculating Near-field thermal radiation:

1.Two spheres: spectral poynting vector $E(r_1,\omega)\times H(r_1,\omega)$

$$\langle E_{i\omega}(r_1,\omega) H^*_{j\omega}(r_1,\omega)\rangle = i\omega\mu_0 \int_V d^3r' \left\{ \overline{\overline{G}}_E(r_1,r,\omega)\, \overline{\overline{G}}^{*}_H(r_1,r,\omega) \langle J_l(r,\omega) J^*_m(r',\omega)\rangle \right\}$$

$$\left.\begin{matrix} \overline{\overline{G}}_E(r_1,r,\omega) \\ \overline{\overline{G}}_H(r_1,r,\omega) \end{matrix}\right\}$$

Dyadic Green's functions (DGFs) are obtained by using partial-wave

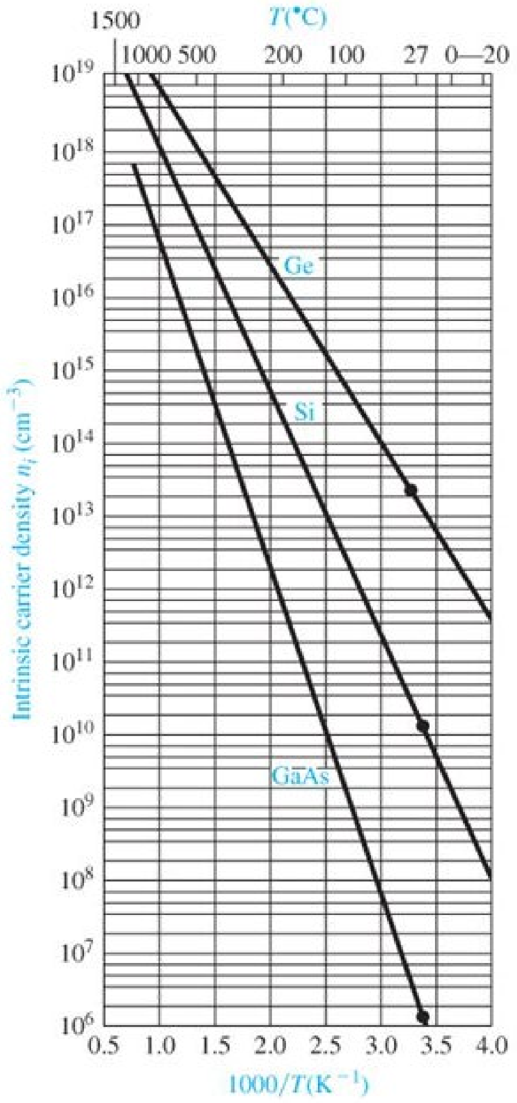
2. Nanoparticles with irregular shapes:

Thermal discrete dipole approximation method (TDDA):
The emitter and absorber are discretized into electric dipoles with the number of N_e and N_a

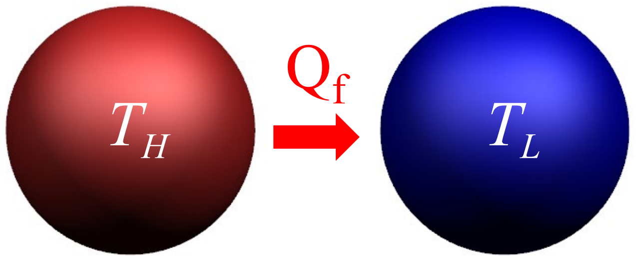
$$Q_\omega = \frac{\omega}{2} \sum_{i=N_e+1}^{N_e+N_a} \left(\mathrm{Im}\left[\left(\alpha_i^{-1}\right)^* \right] \frac{2}{3} k_0^2 \right) tr\left(\overline{\overline{R}}_{p_i p_i} \right)$$

Method

Electrons of silicon will be excited at high temperatures



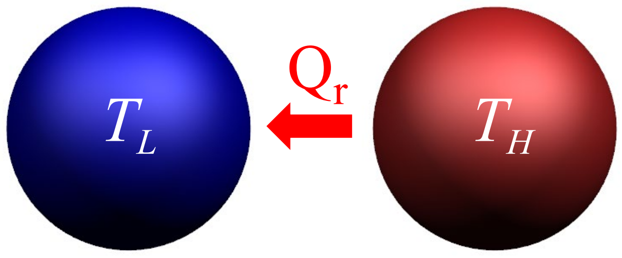
forward bias



intrinsic Si | dissimilar material

Electrons will be excited at high temperatures, which gives rise to the enhancement of radiative heat transfer

reverse bias



intrinsic Si | dissimilar material

Electrons won't be excited, which give rise to the constraint of radiative heat transfer

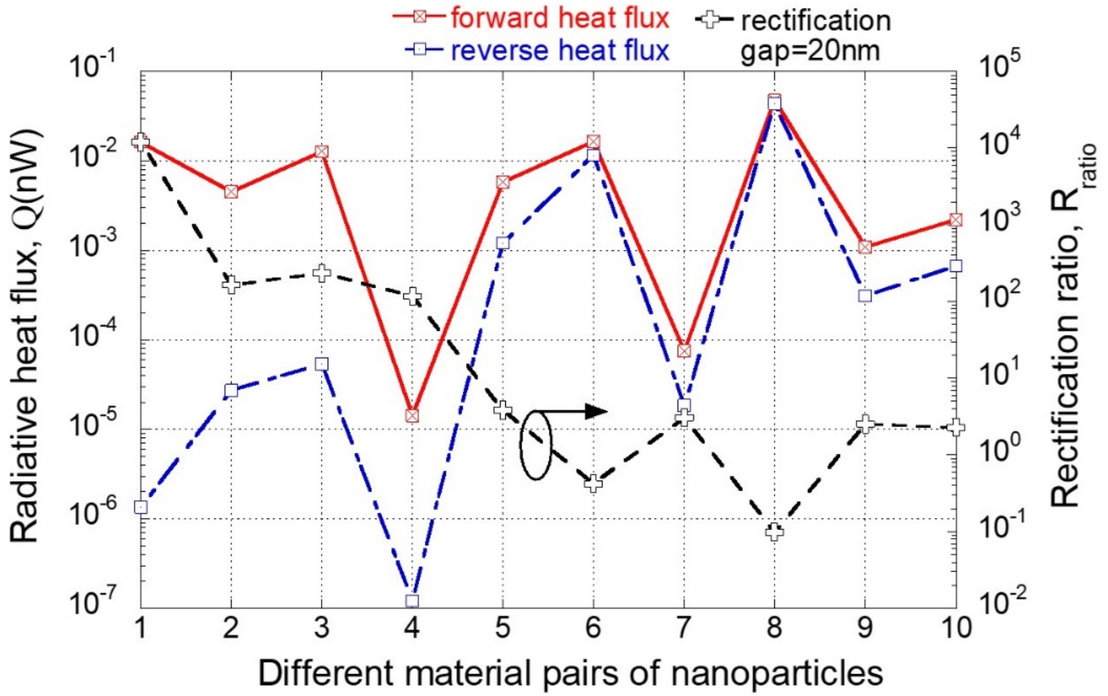
High rectification ratio

- The temperature-dependent dielectric function of silicon is obtained from Fu and Zhang.

Fu et al. *International Journal of Heat and Mass Transfer* **2006,** Vol. 49,1703-1718

Results

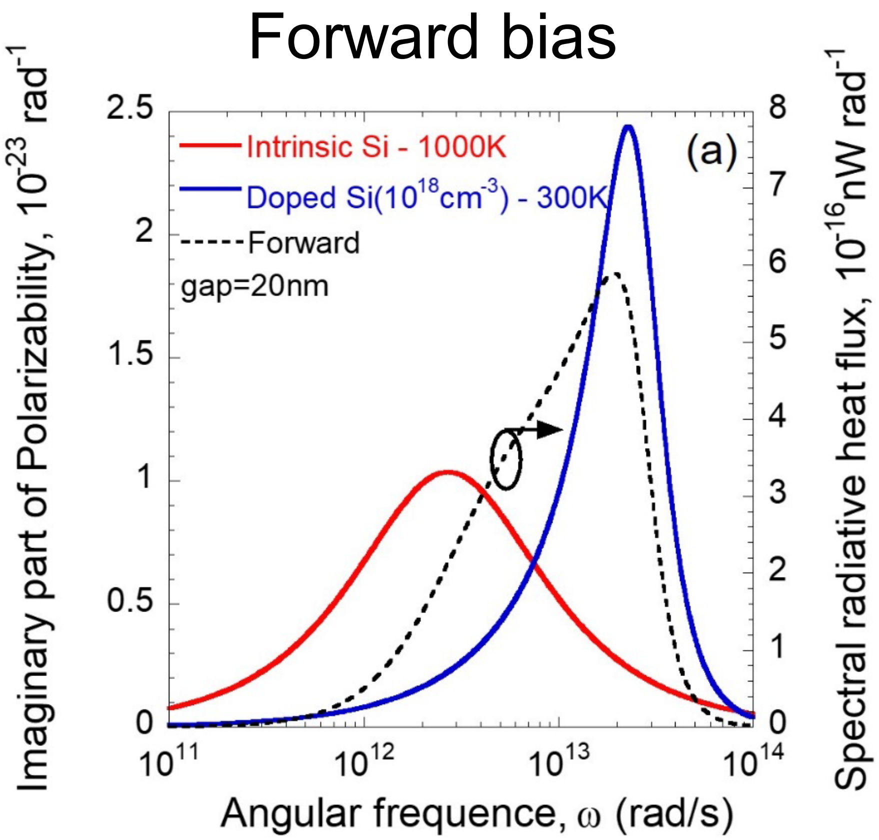
Numbers	Material Pairs	Numbers	Material Pairs
1	Intrinsic Si - Doped Si (10^{18} cm^{-3})	6	Doped Si(10^{18} cm^{-3}) - SiO_2
2	Intrinsic Si - 3C-SiC	7	Doped Si(10^{18} cm^{-3}) - Au
3	Intrinsic Si - SiO_2	8	3C-SiC - SiO_2
4	Intrinsic Si - Au	9	3C-SiC - Au
5	Doped Si(10^{18} cm^{-3}) - 3C-SiC	10	SiO_2 - Au

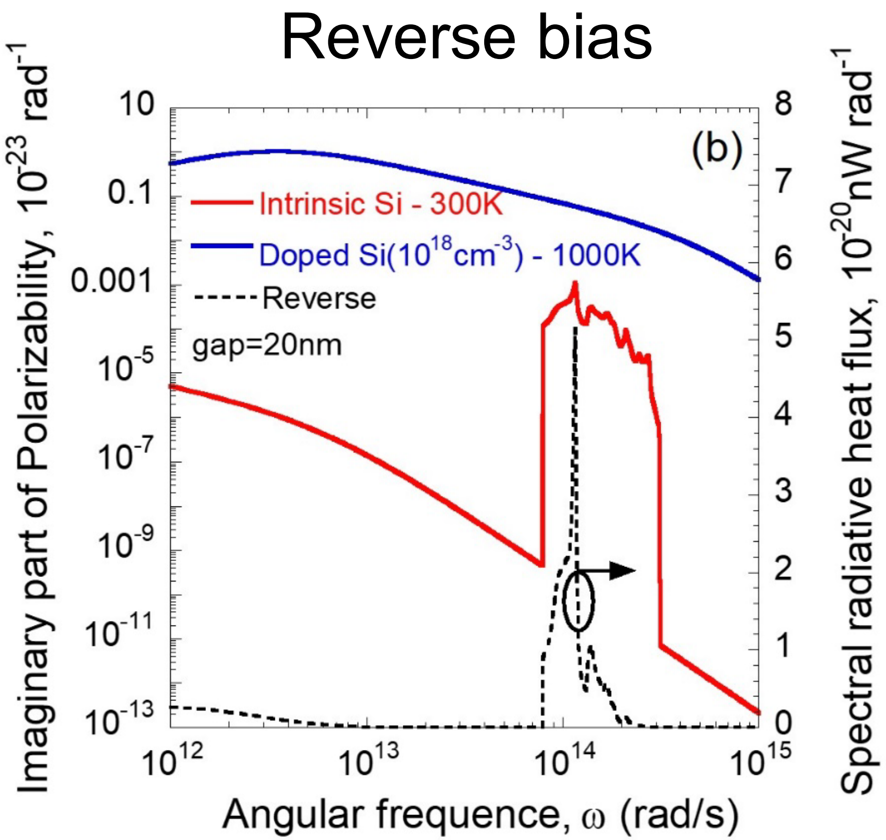


Near-field radiative heat flux and rectification ratio of the proposed diode for different material pairs

- Rectification ratios are all above 100 when intrinsic Si is included in the material pair (See number 1 2 3 4).
- Rectification ratios are less than 5 when intrinsic Si is not included in the material pair (See number 5 6 7 8 9 10).
- A record-high rectification ratio of more than 10^4 is theoretically achieved when the material pair is intrinsic Si and dope Si (10^{18} cm^{-3})

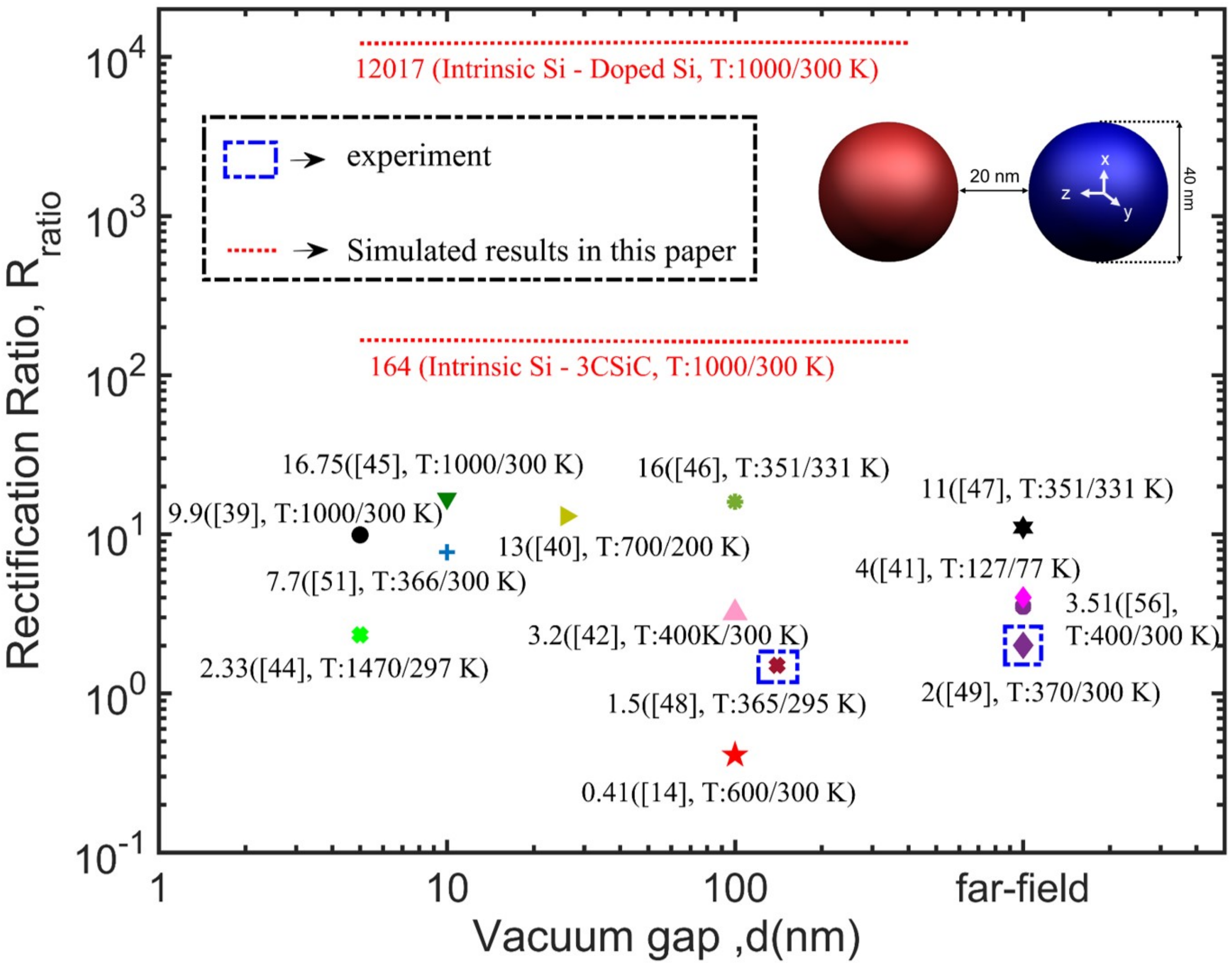
Results





- In forward biased case, the carrier concentration of intrinsic Si at 1000 K will have nearly the same value as that in doped Si (10^{18} cm^{-3}) at 300 K. Polarizability of two material will have a strong match
- In the reverse biased case, polarizability for doped Si at 1000 K will merely match the peak induced by absorption of lattice vibration for intrinsic Si at 300 K.

Conclusions



- A highly efficient radiative thermal rectifier consisting of two nanoparticles, i.e., intrinsic Si nanoparticle and a dissimilar nanoparticle, is proposed. Due to the thermal excitation of intrinsic Si at high temperature, rectification ratios can reach more than 100.
- Particularly, for the nanoparticles comprising by intrinsic Si and doped Si (10^{18} cm^{-3}), the rectification ratio can reach a record-high value of more than 10^4 due to the strong match of polarizability.
- Effects of gap distances and configurations of nanoparticles on the rectification ratio can be found in my paper.

Shizheng Wen, Xianglei liu, Sheng Cheng, Zhoubing Wang, Shenghao Zhang, Chunzhuo Dang, "Ultrahigh thermal rectification based on near-field thermal radiation between dissimilar nanoparticles", *J. Quant. Spectrosc. Radiat. Transfer* **234,** 1-9 (2019)

Outline

Thank you for listening!

Acknowledgement

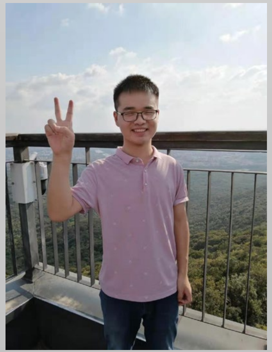

Xianglei Liu


Jiadong Shen


Yiming Xuan


Yannan Yang


Yapeng Hu


Hang Yu