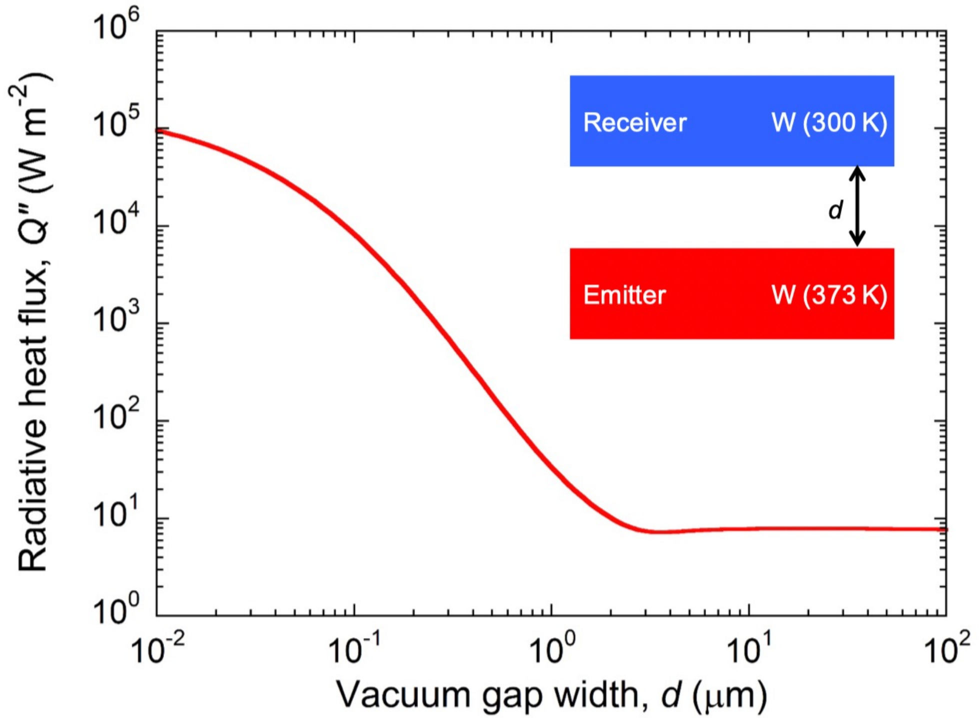
KITP Conference
Quantum and Thermal Electrodynamic Fluctuations in the Presence of Matter: Progress and Challenges
July 11, 2022

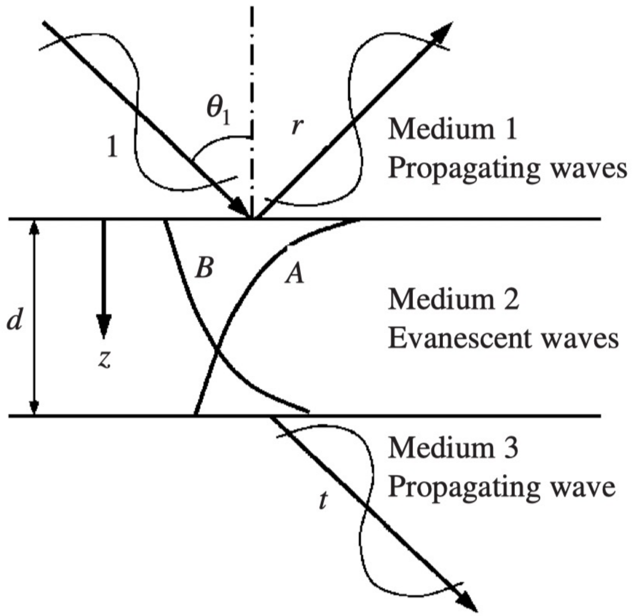
Experiments of Near-Field Thermal Radiation and Energy Conversion

Bong Jae Lee, Ph.D.

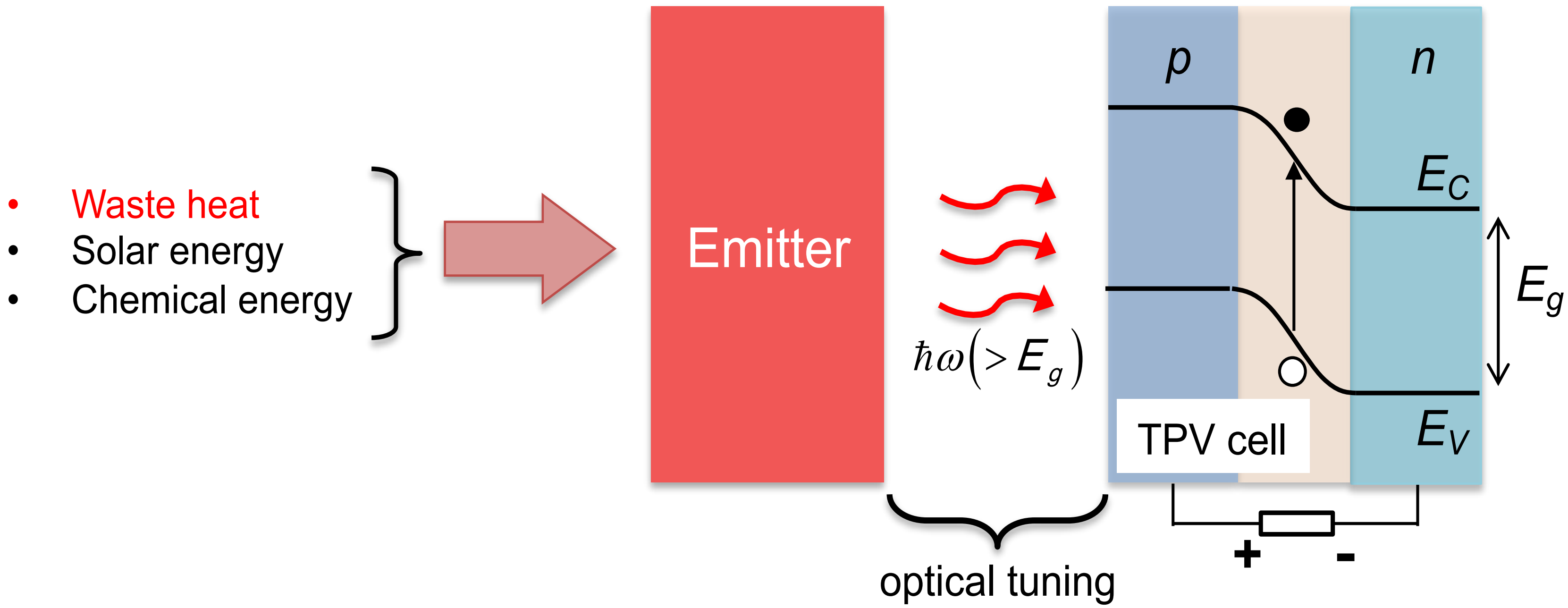
Department of Mechanical Engineering
KAIST, South Korea

Near-Field Thermal Radiation





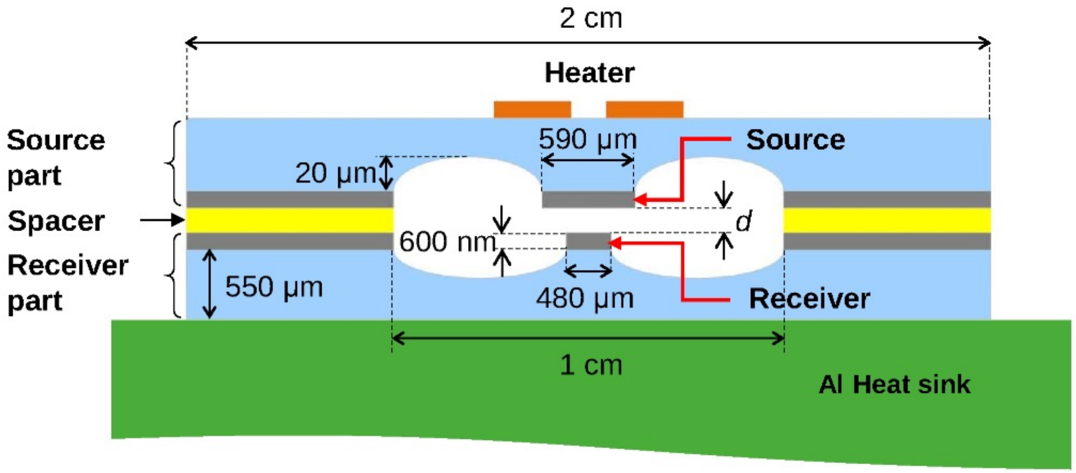
Motivation: Near-Field TPV Device

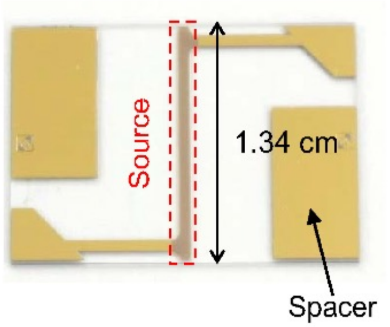


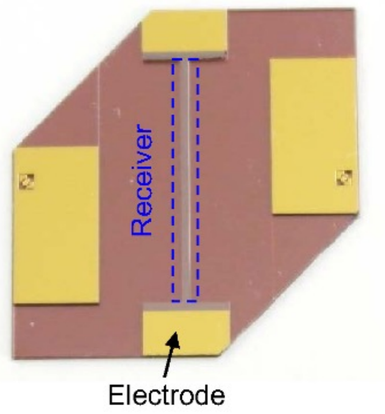
For realizing NF-TPV device, we need

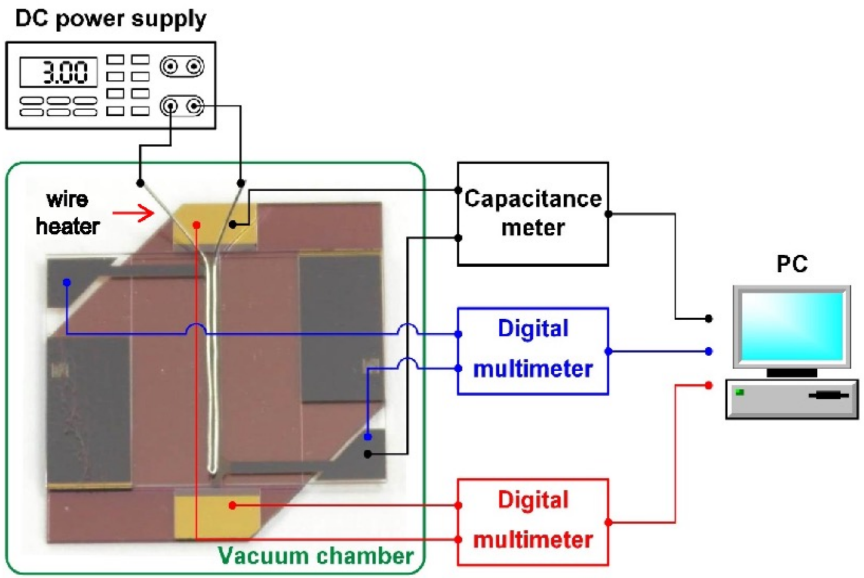
- source temperature to be as high as possible
- vacuum gap to be as small as possible
- surface area to be as wide as possible

MEMS-Based Platform for NFRHT Experiments





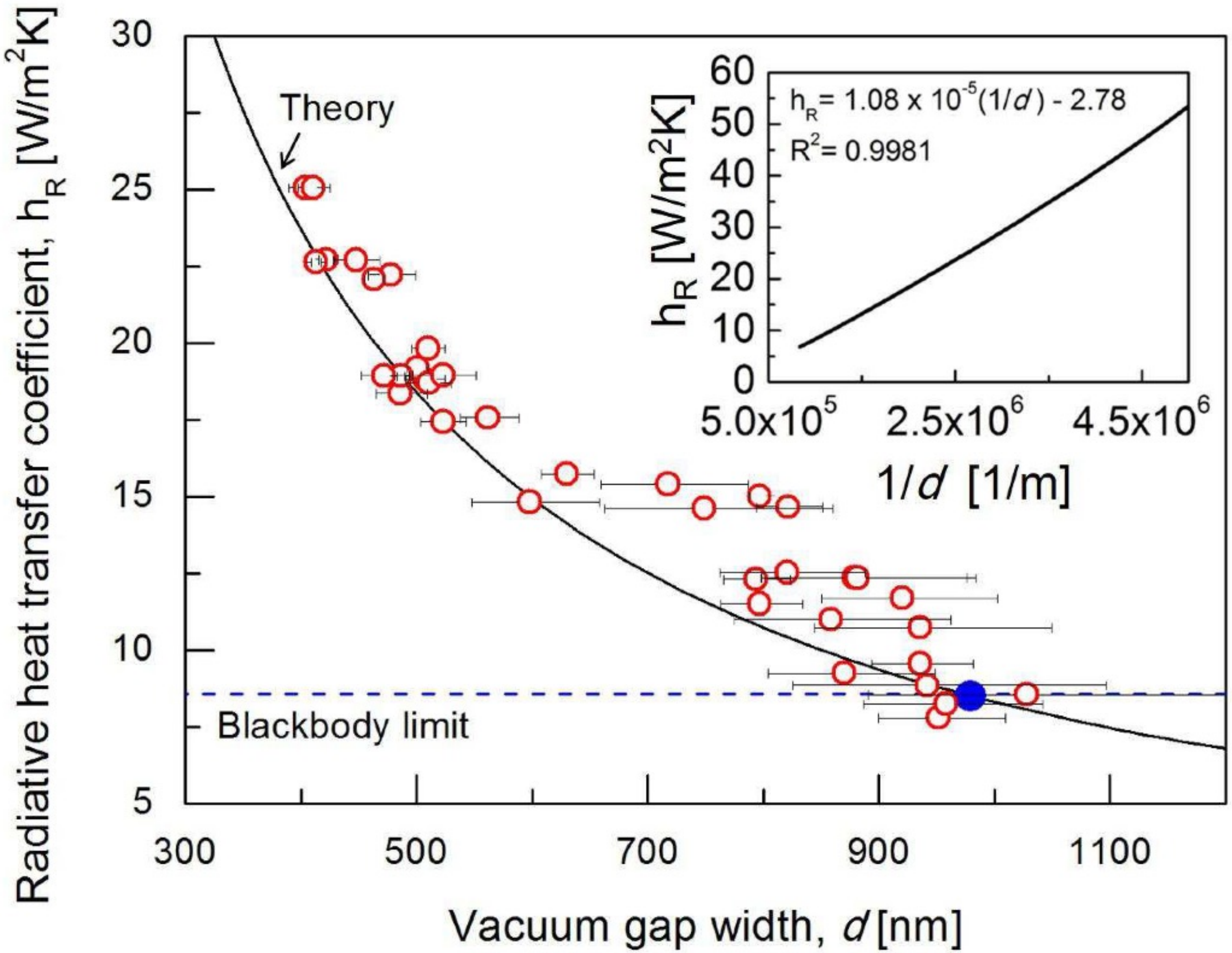




M. Lim, S.S. Lee, and B.J. Lee, *Physical Review B* 91, 195136, 2015.

Center for Extreme Thermal Physics and Manufacturing

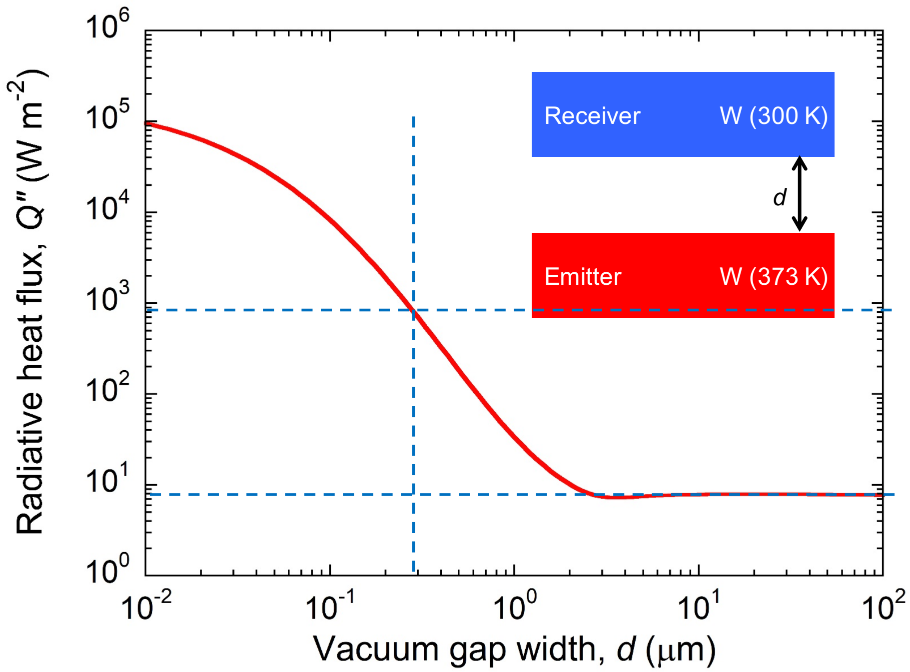
Measured NFRHT



M. Lim, S.S. Lee, and B.J. Lee, *Physical Review B* 91, 195136, 2015.

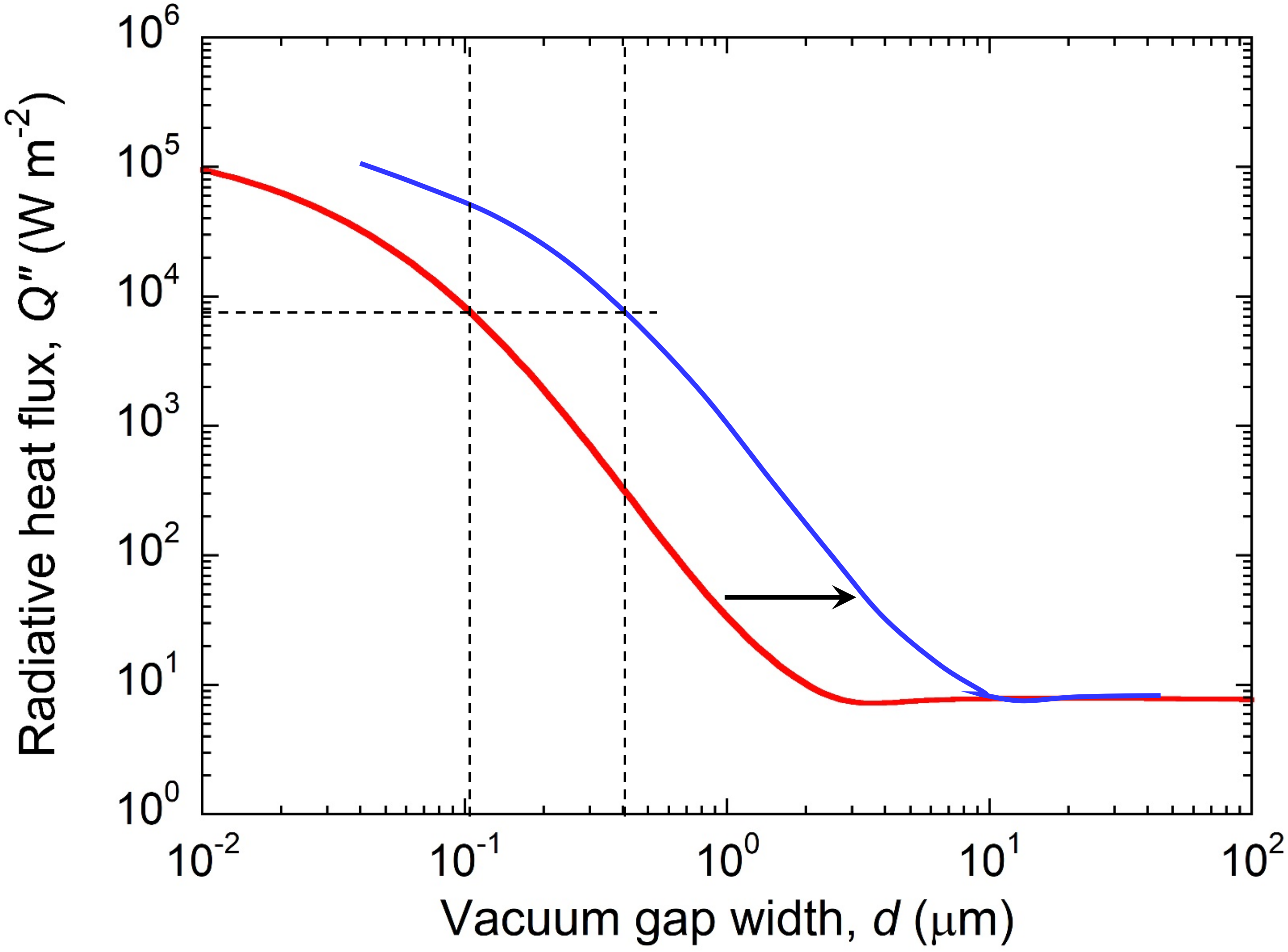
Challenge & Opportunity

- Near-field enhancement of radiative heat transfer becomes significant when the vacuum gap distance between parallel plates is less than 200 nm. But maintaining such a small gap distance between parallel plates (**with wide surface area**) is extremely challenging.

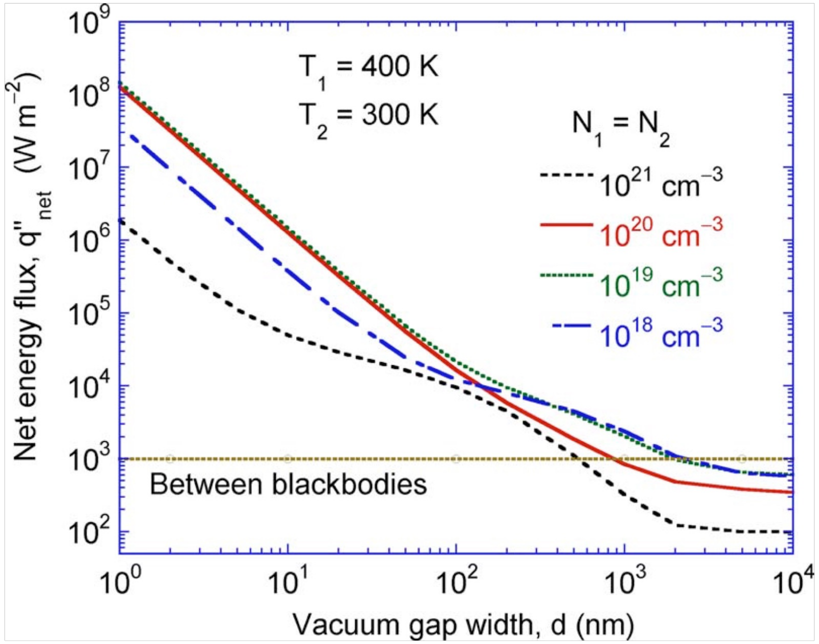


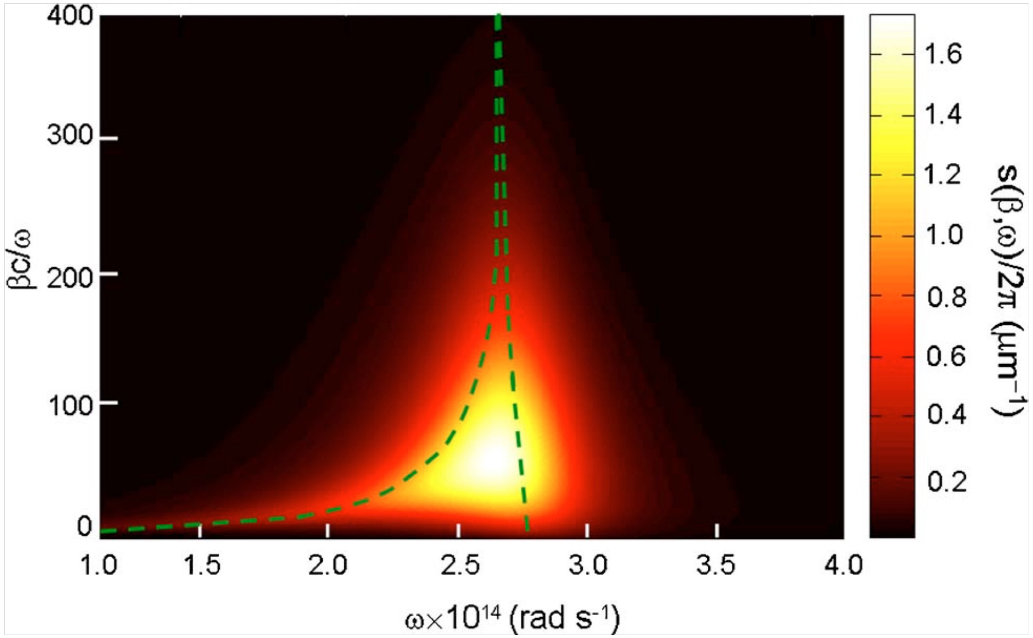
- We may also need to seek alternatives. For instance, we can modify surface conditions using optical metamaterials including graphene in order to further enhance the near-field thermal radiation at achievable vacuum gap distance (~ 200 nm).

Challenge & Opportunity – cont'd



SPP-Meditated NFRHT

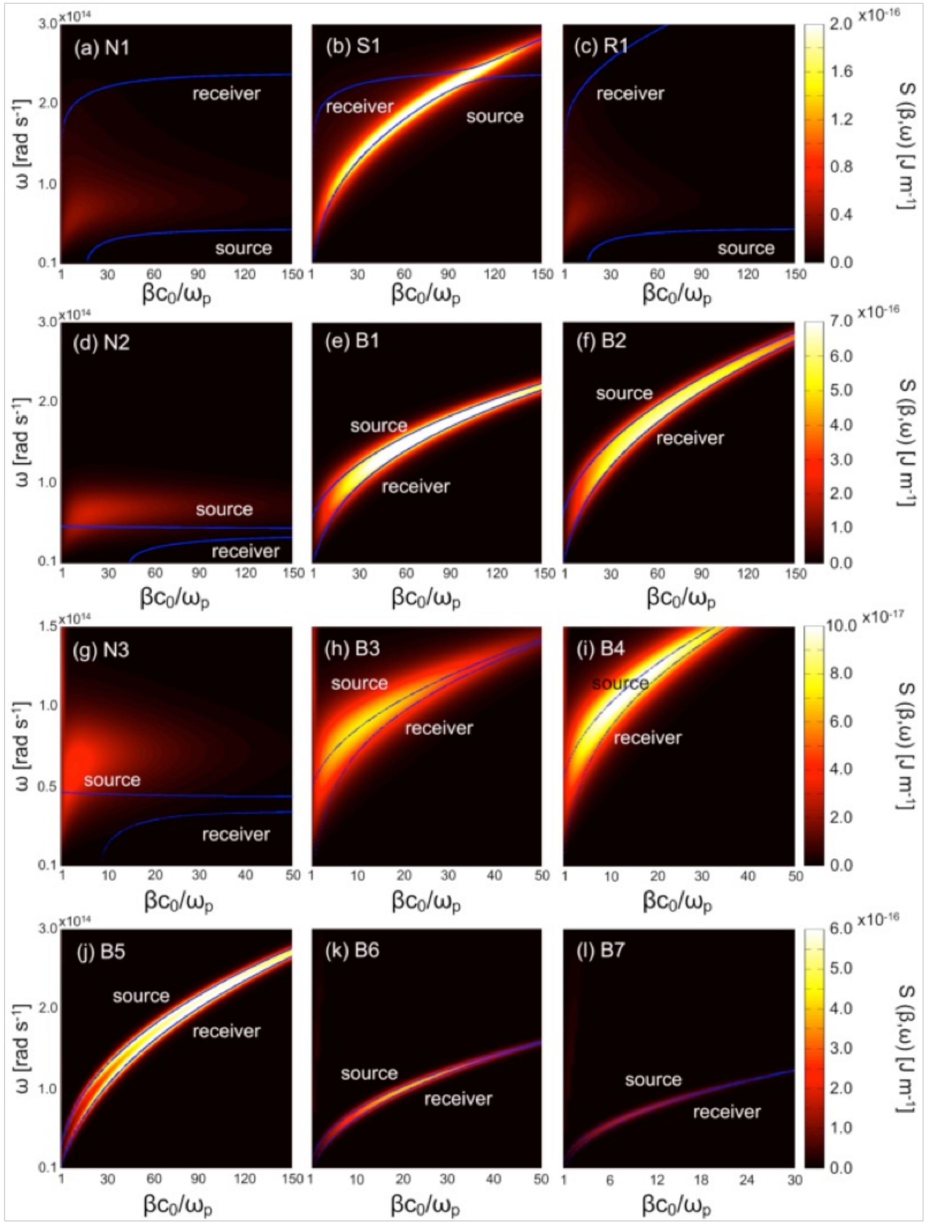


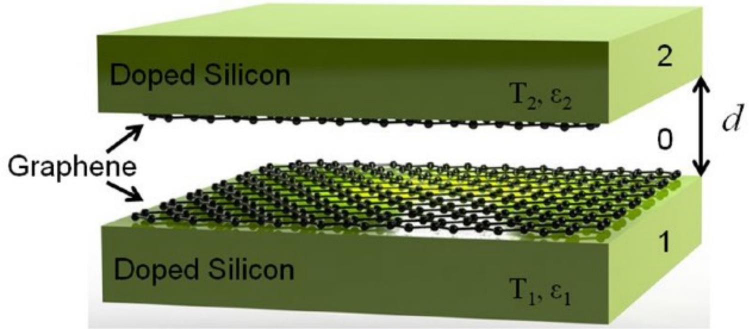


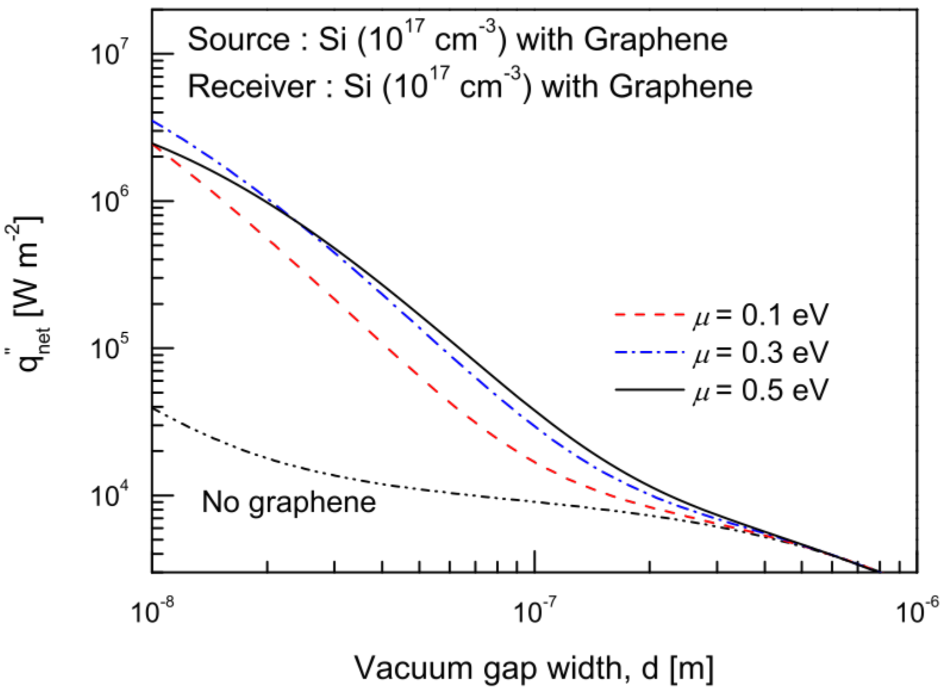
S. Basu, B.J. Lee, and Z.M. Zhang, *Journal of Heat Transfer* 132, 021005, 2010.

→ Since evanescent waves associated with the SPPs dominantly contribute to the near-field radiative heat transfer, tailoring the SPP dispersion curves in the ω–$k_{\parallel}$ domain using surface nanostructures will eventually lead to tune the near-field radiation at a given vacuum gap.

Spectral Control of NFRHT using Graphene

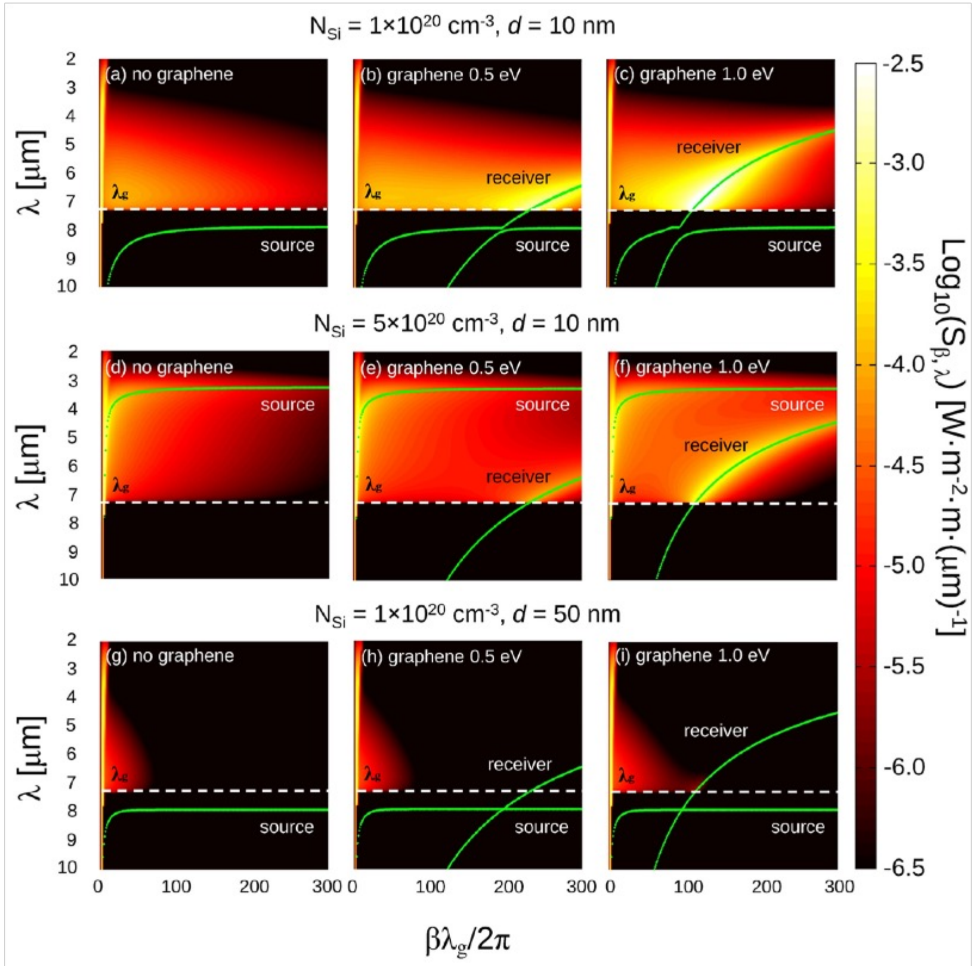


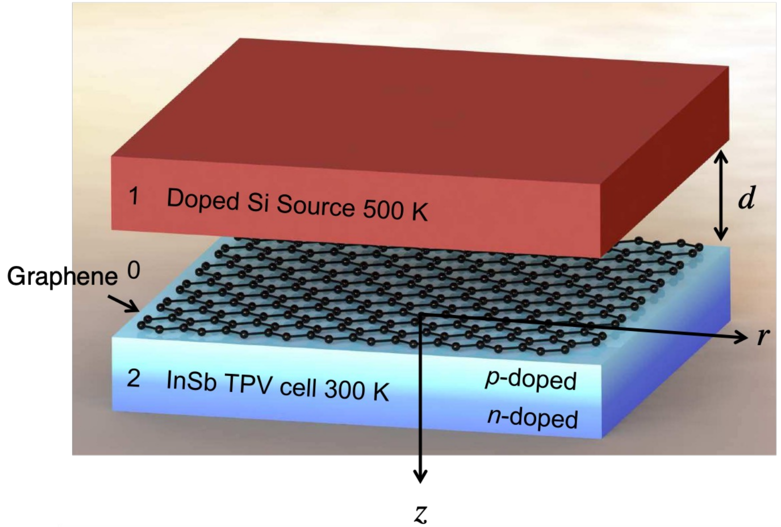


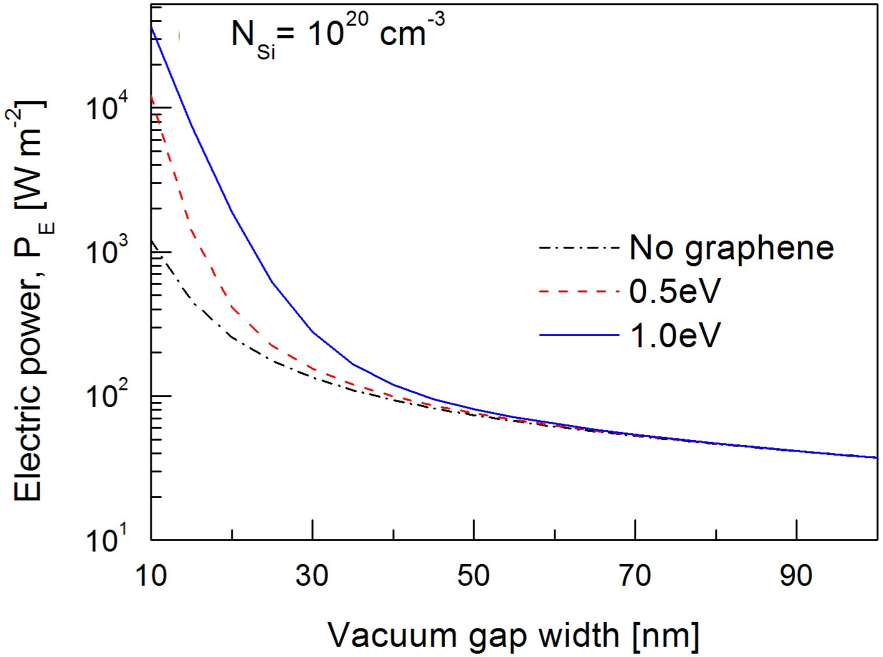


M. Lim, S.S. Lee, and B.J. Lee, *Optics Express* 21, 22173–22185, 2013.

Graphene-Assisted NF-TPV System

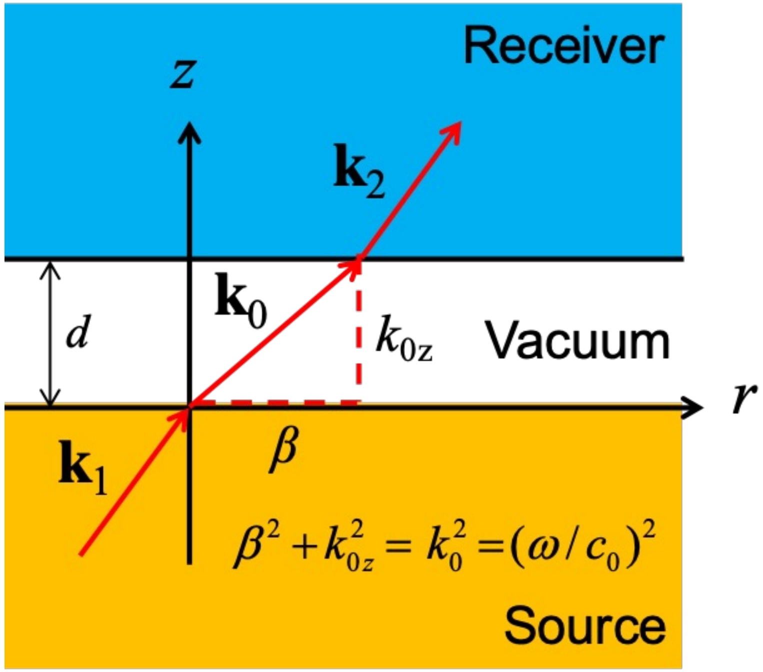






M. Lim, S.M. Jin, S.S. Lee, and B.J. Lee, *Optics Express* 23, A240-A253, 2015.

Tunneling of Evanescent Waves



$$k_i = \sqrt{\varepsilon_i \omega^2 / c_0^2}$$

ε_i Permittivity of medium i

If $\beta >> \omega / c_0$,

$$k_{0z} = \sqrt{\omega^2 / c_0^2 - \beta^2} \approx i\beta$$

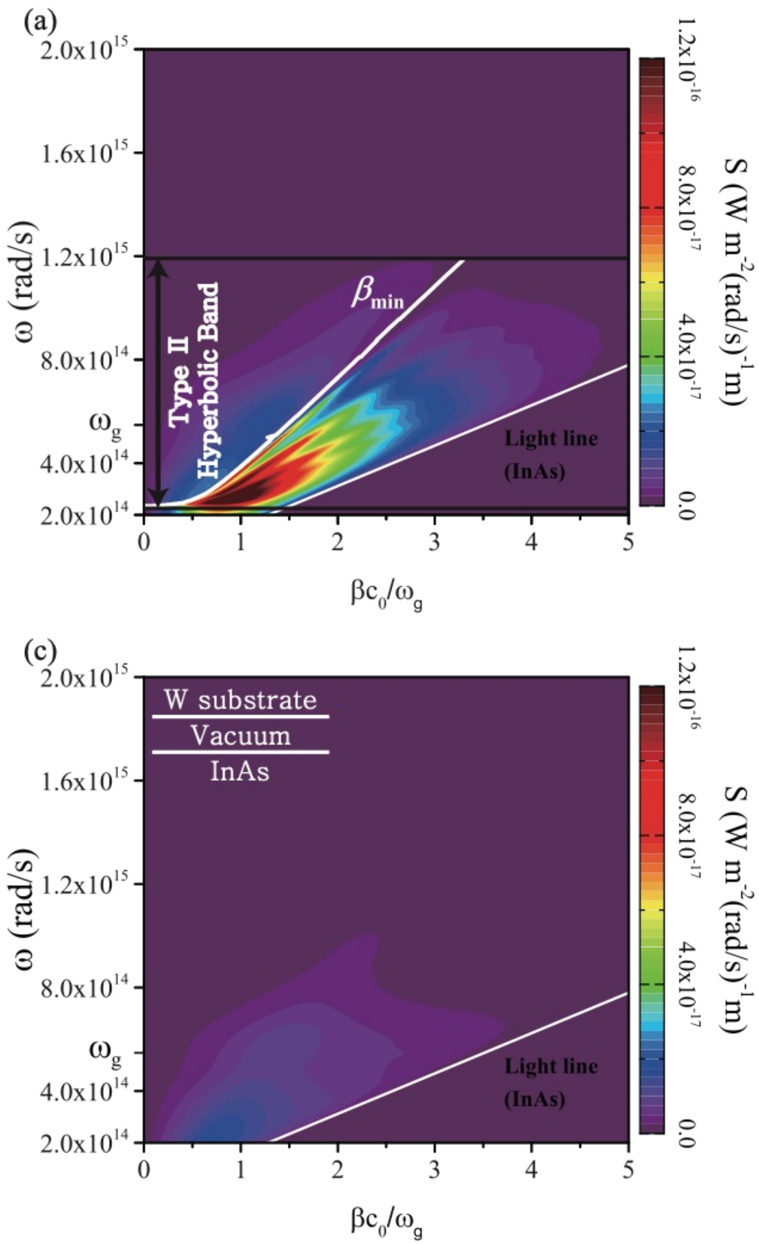
The amplitude of evanescent wave decay with the factor of

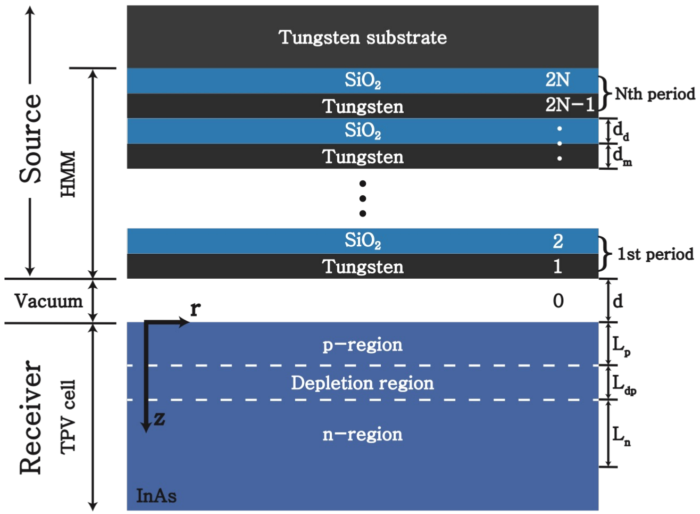
$$e^{ik_{0z}z} \approx e^{-\beta z}$$

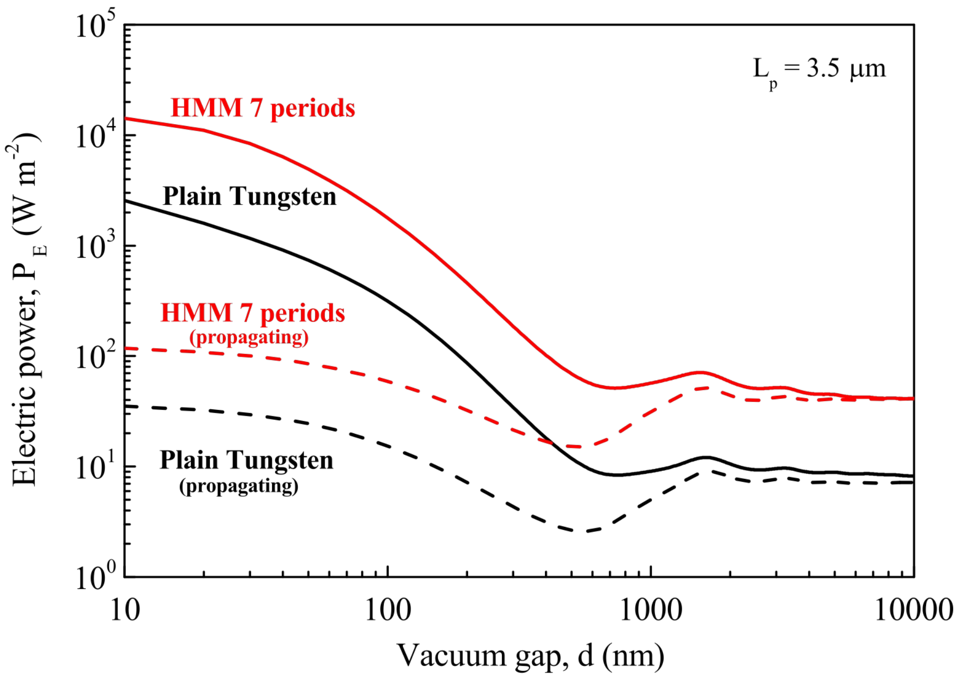
Larger β rarely contribute to the heat transfer when vacuum gap width becomes larger

→ SPP dispersion curves should be close to the vacuum light line

HMM-Assisted NF-TPV System

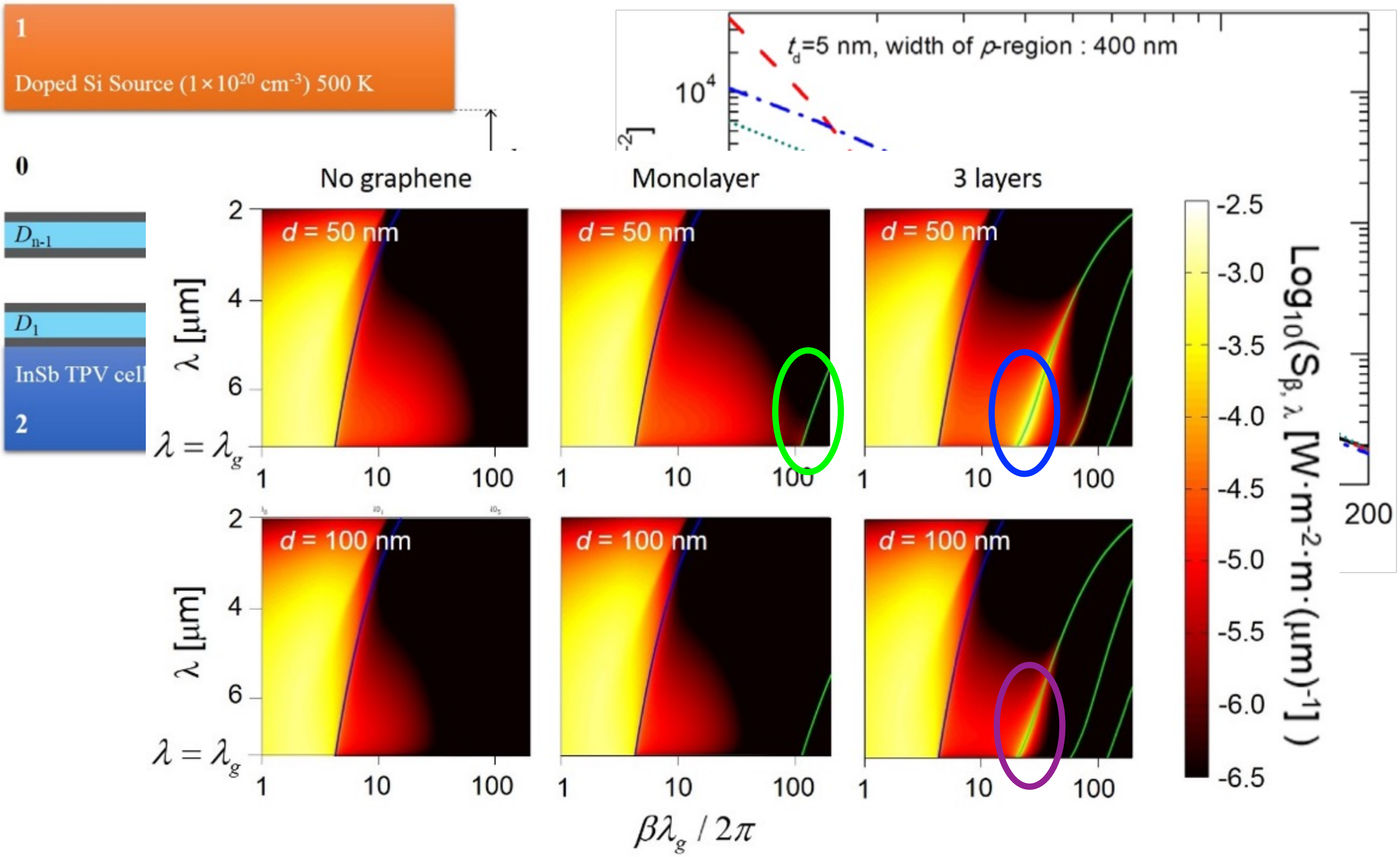






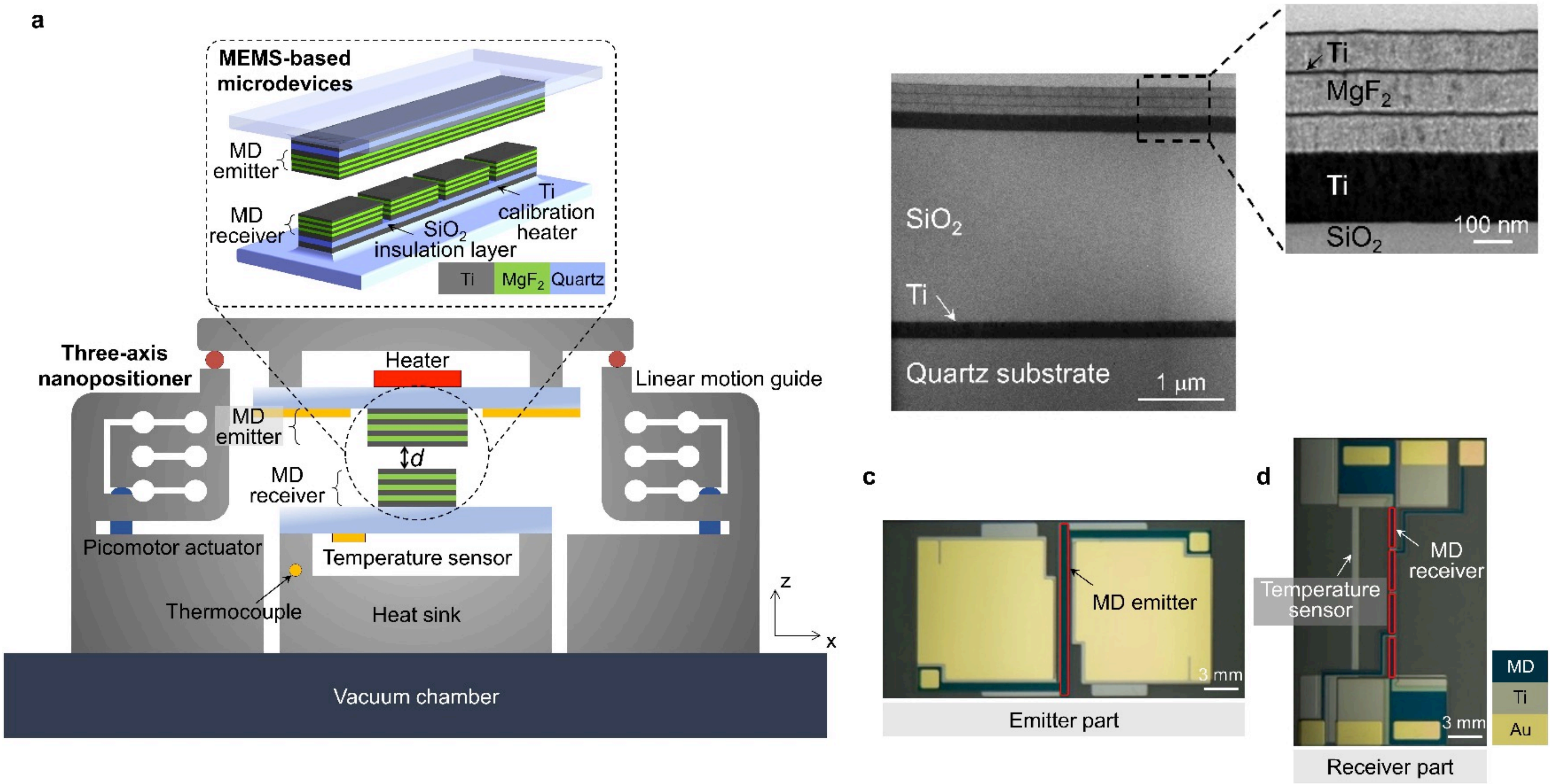
S.M. Jin, M. Lim, S.S. Lee, and B.J. Lee, *Optics Express* 24, A635-A649, 2016.

Challenge & Opportunity



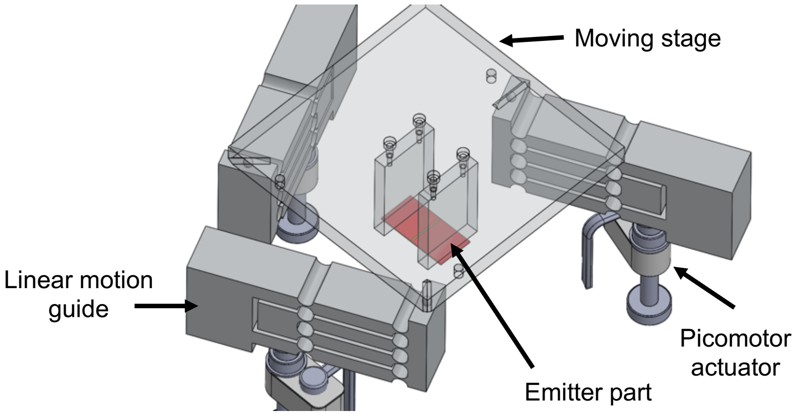
M. Lim, S.S. Lee, and B.J. Lee, *Journal of Quantitative Spectroscopy & Radiative Transfer* 197, 84-94, 2017.

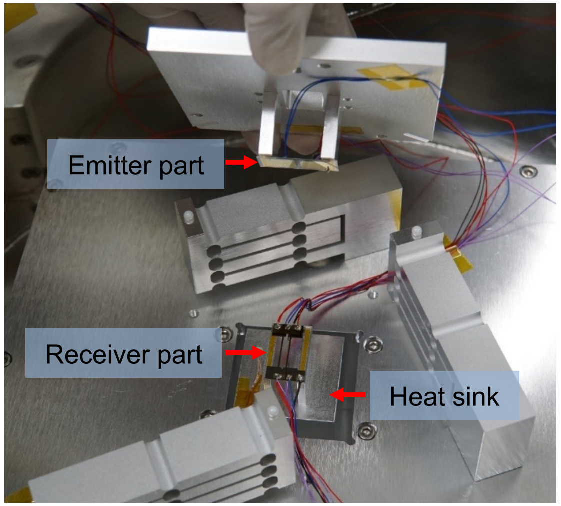
Control of NFRHT

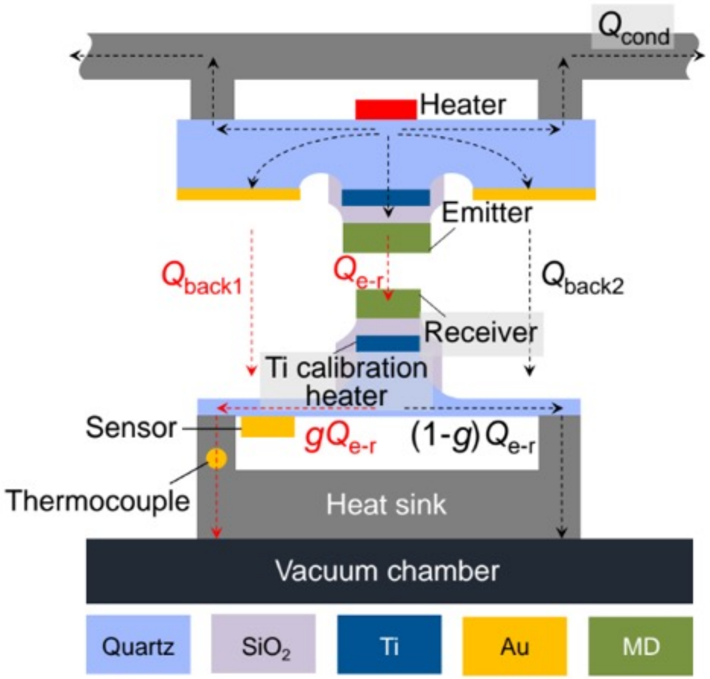


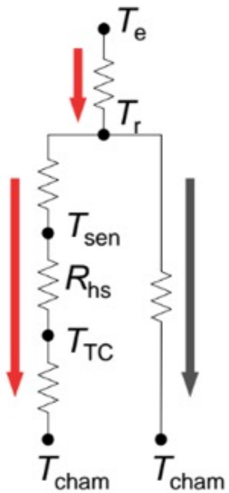
M. Lim, J. Song, S.S. Lee, and B.J. Lee, *Nature Communications* 9, 4302, 2018.

Control of NFRHT – cont'd

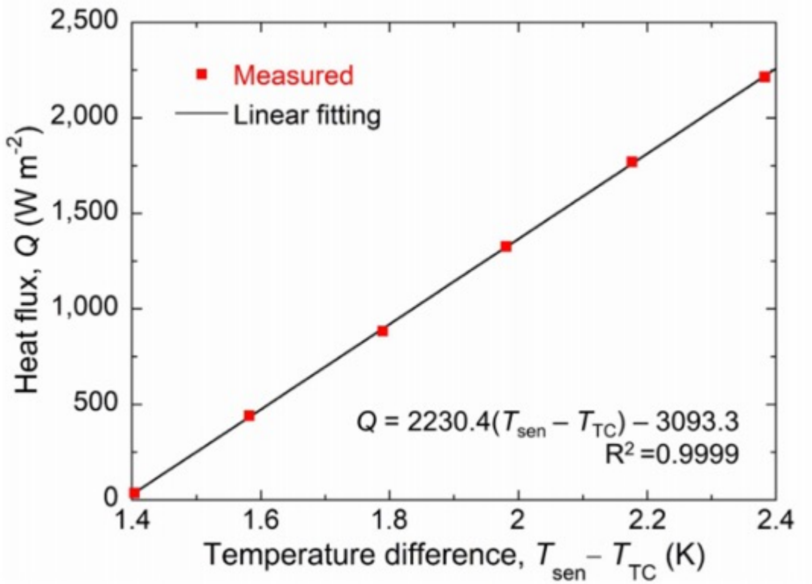






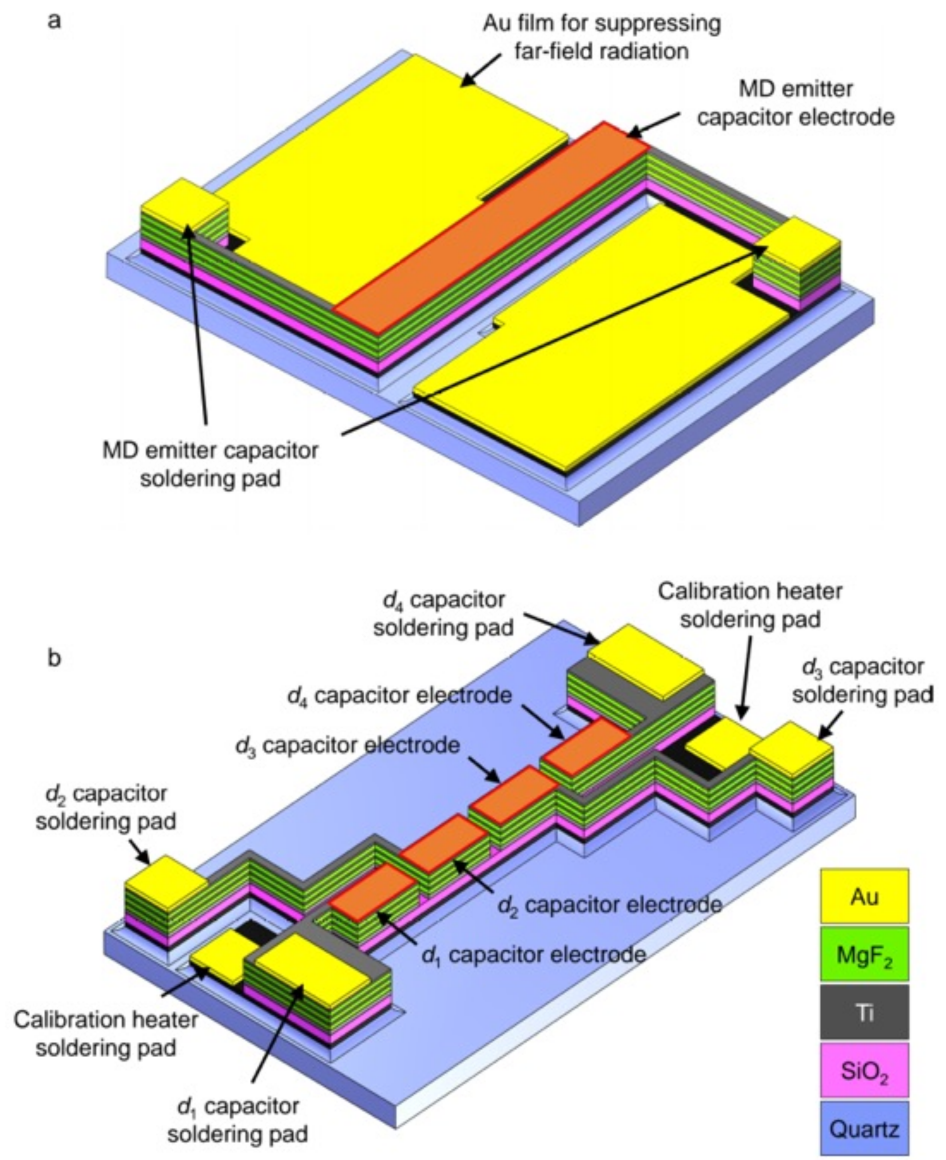


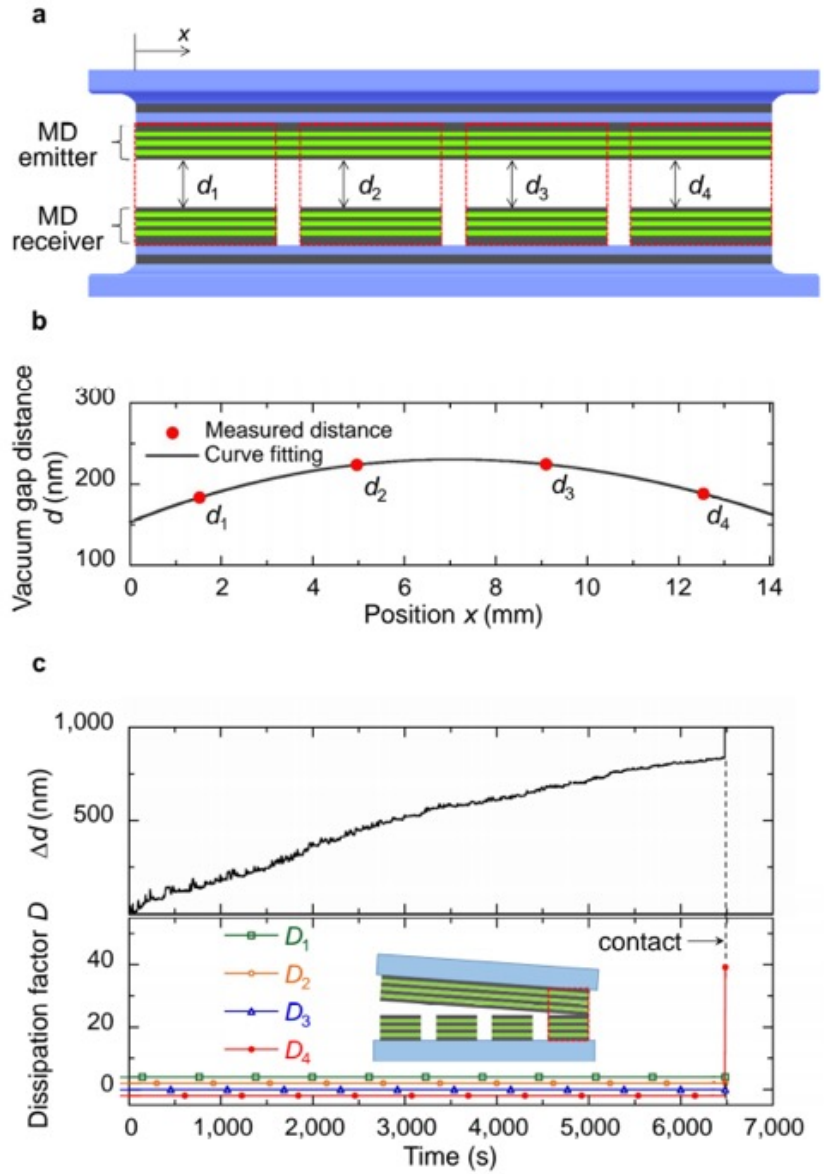
$$Q_{e\to r} = (T_{sen} - T_{TC})/(gR_{hs}) - Q_{back,1}/g$$



$$gQ_{e\to r} + Q_{back,1} = (T_{sen} - T_{TC})/R_{hs}$$

Control of NFRHT – cont'd





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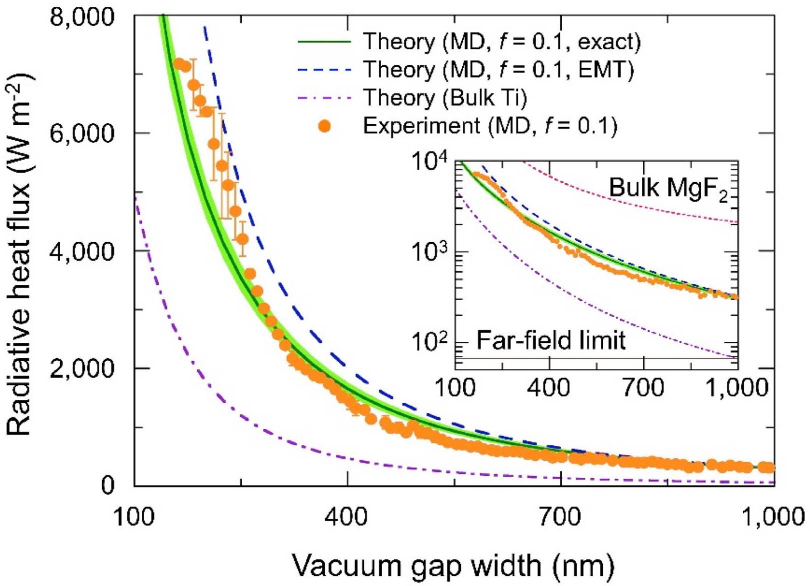
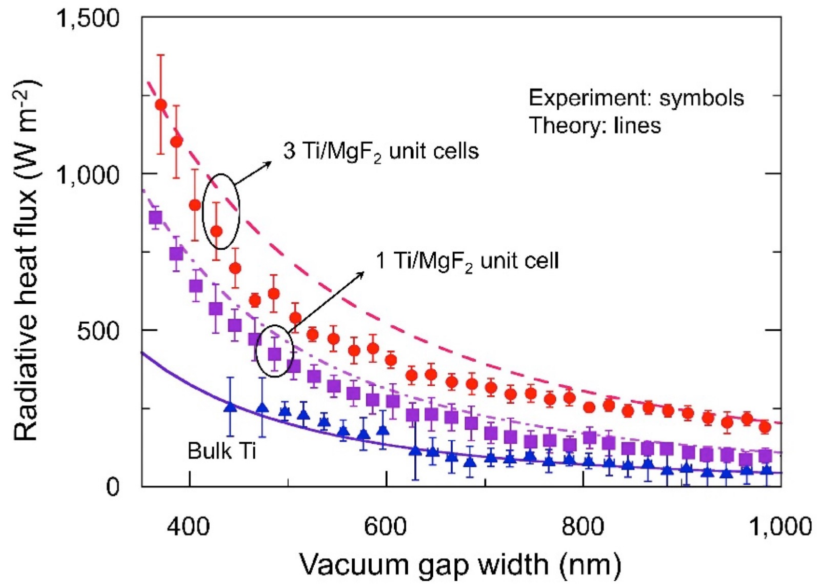
Control of NFRHT – cont'd



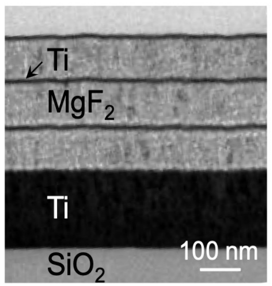


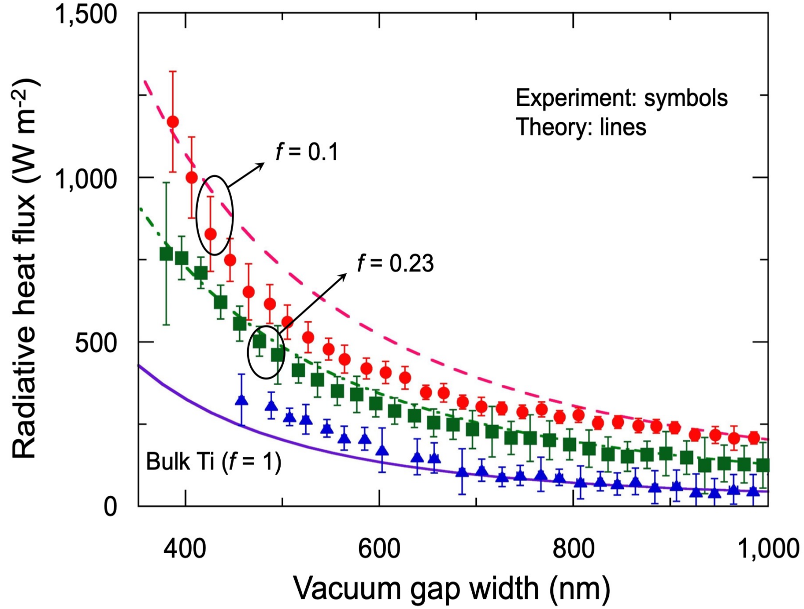
Volume filling ratio (f)

$$f = \frac{t_m}{t_m + t_d}$$

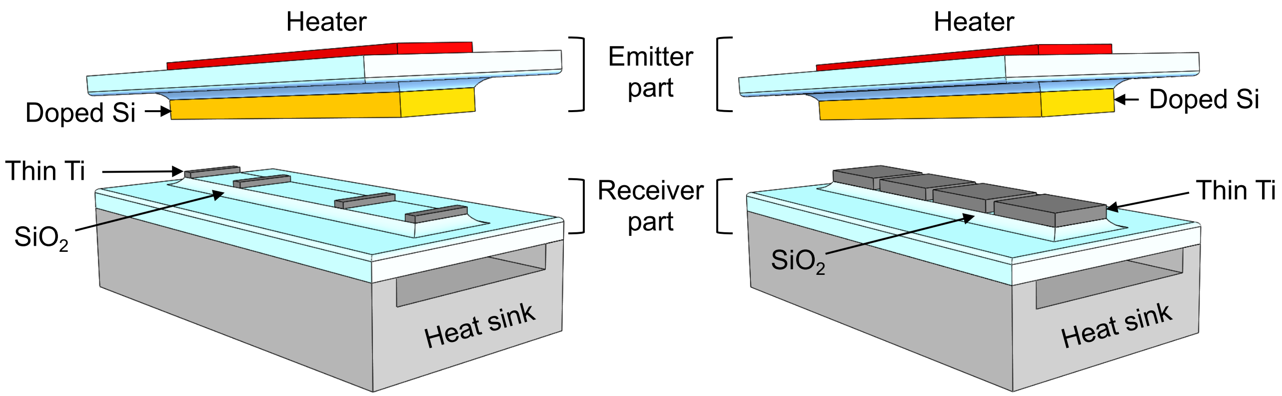
t_m : thickness of Ti layer

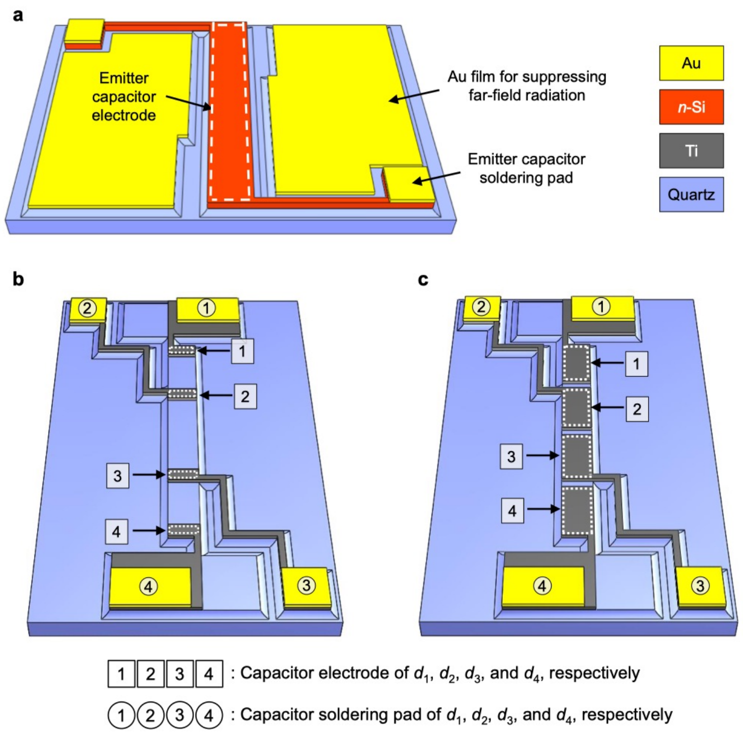
t_d : thickness of MgF_2 layer

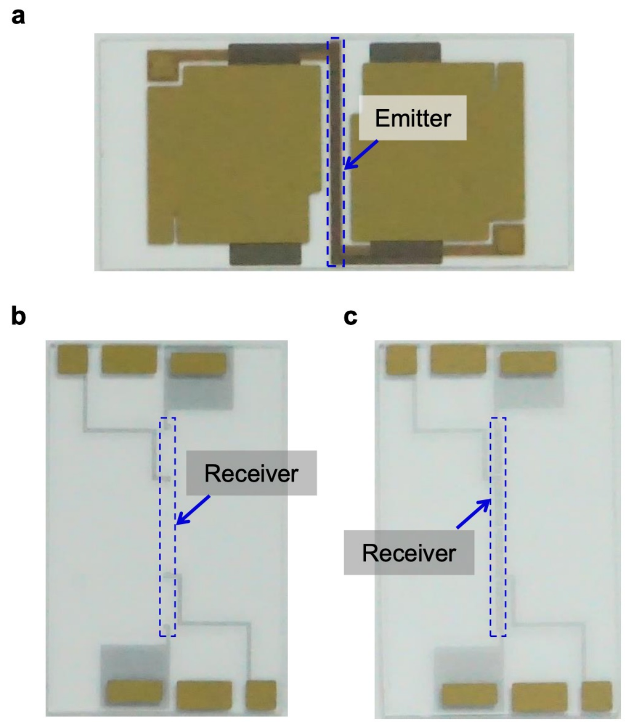




Coupling in Asymmetric Configuration

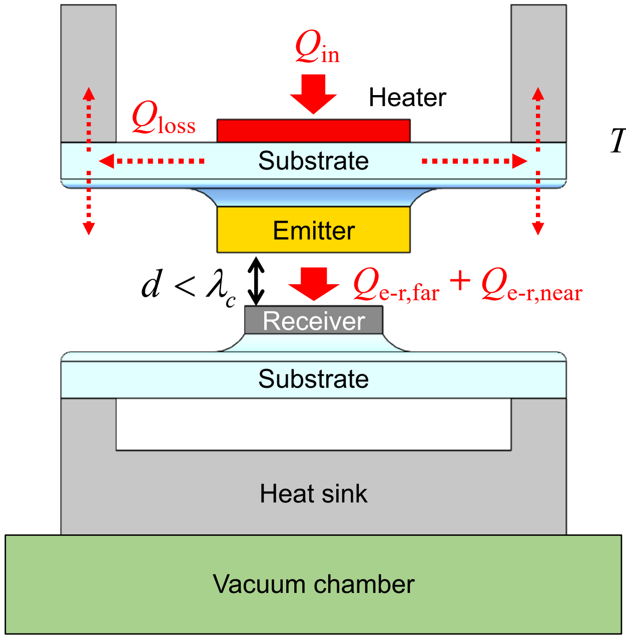


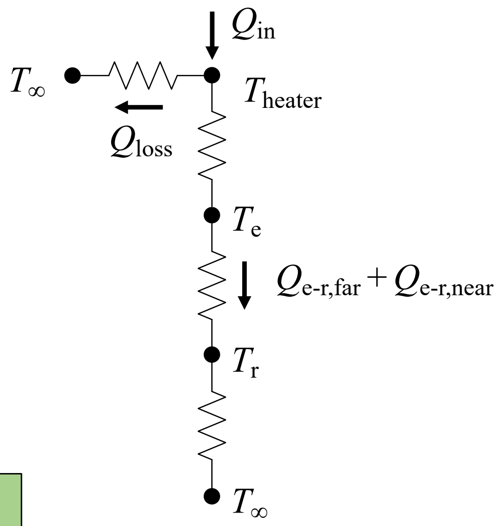


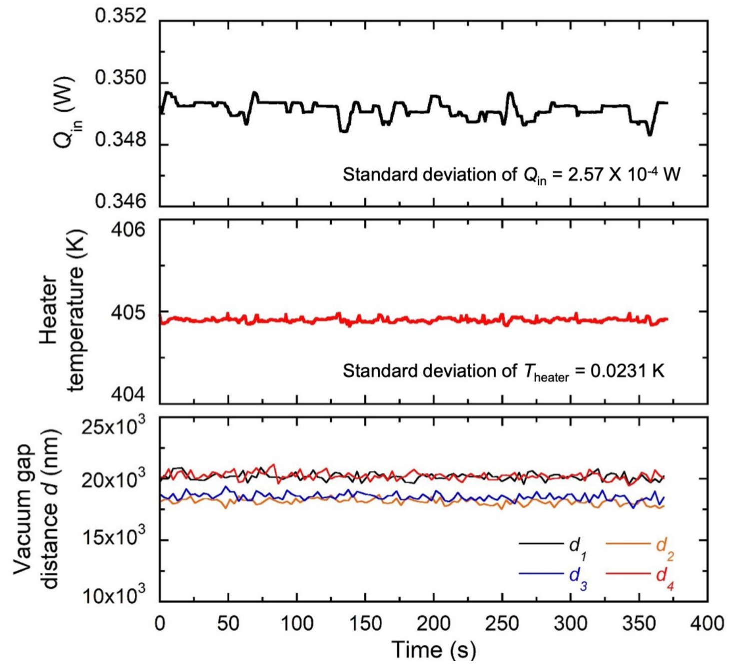


M. Lim, J. Song, S.S. Lee, J. Lee, and B.J. Lee, *Physical Review Applied* 14, 014070, 2020.

Coupling in Asymmetric Configuration – cont'd







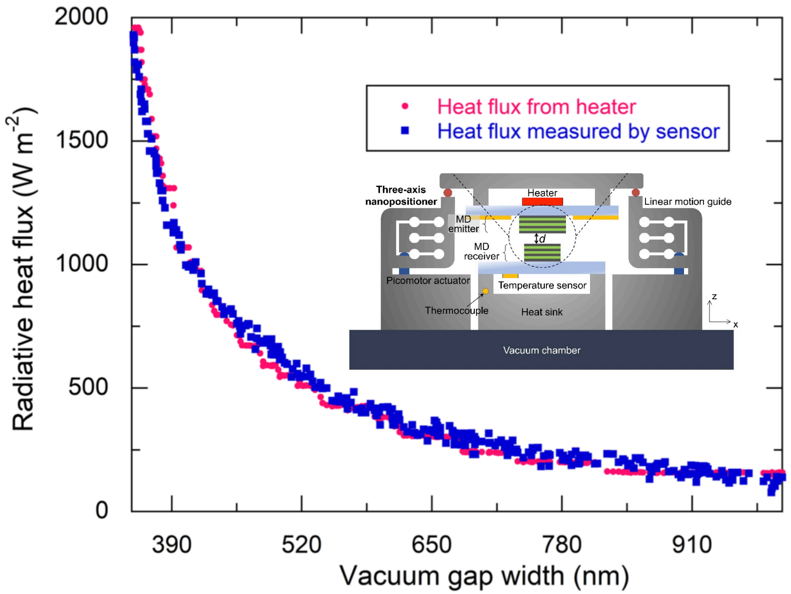
- Far-field

$$Q_{in} = Q_{e\text{-}r,far} + Q_{loss}$$

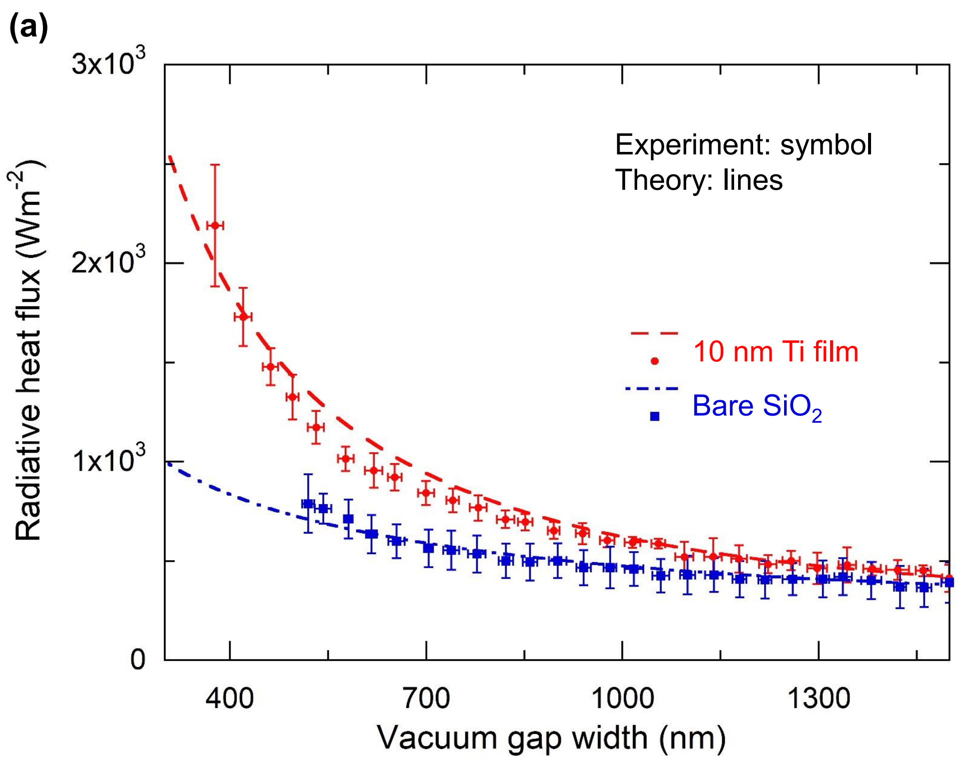
- Near-field

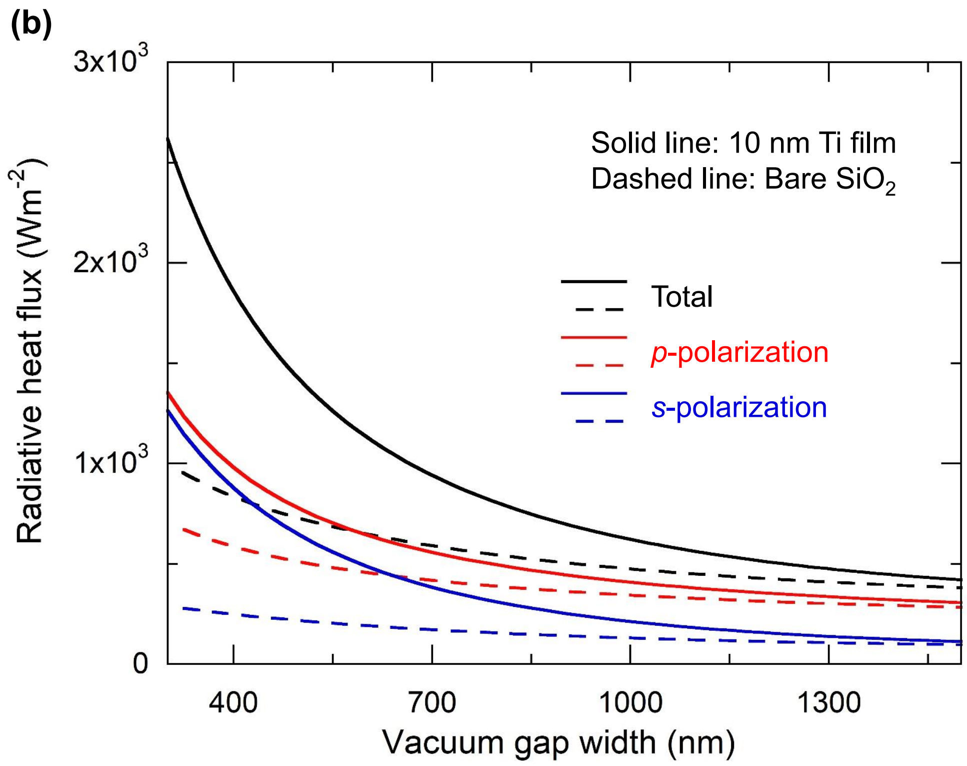
$$Q_{in}(d) = Q_{e\text{-}r,near}(d) + \underline{Q_{e\text{-}r,far} + Q_{loss}} \quad \text{constant}$$

$$Q_{e\text{-}r,near}(d) = Q_{in}(d) - (Q_{e\text{-}r,far} + Q_{loss})$$



Coupling in Asymmetric Configuration – cont'd

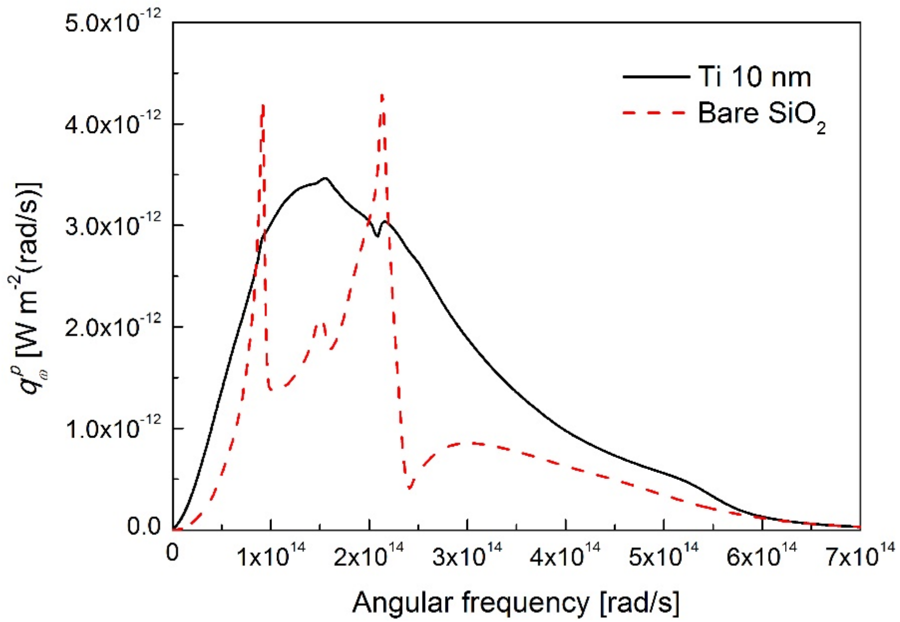


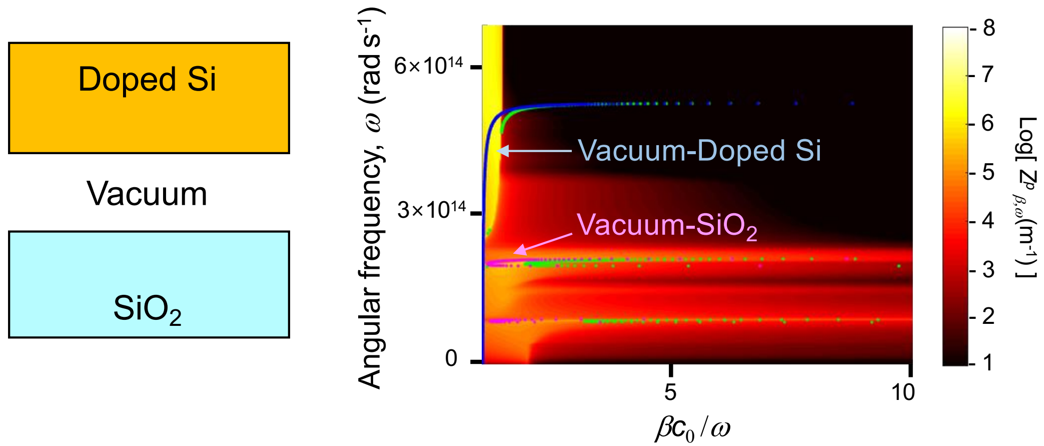


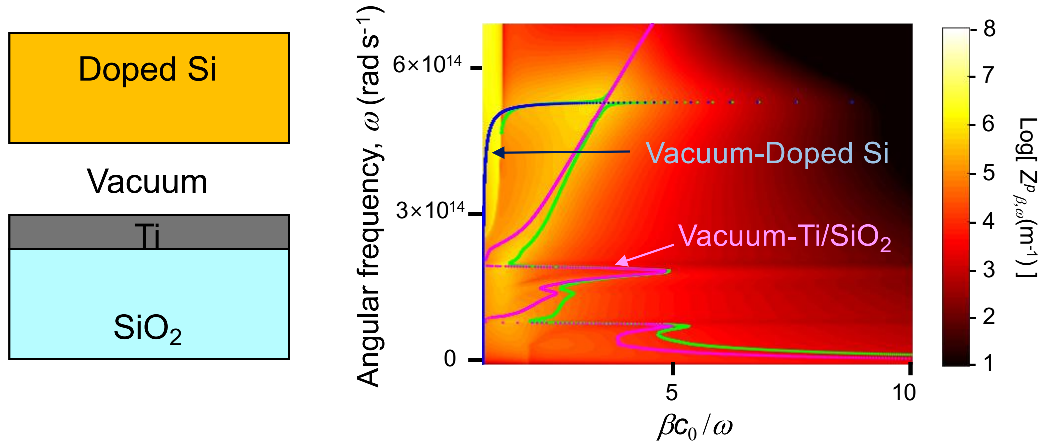
M. Lim, J. Song, S.S. Lee, J. Lee, and B.J. Lee, *Physical Review Applied* 14, 014070, 2020.

Coupling in Asymmetric Configuration – cont'd

$$q_\omega^p = \frac{\Theta(\omega,T_1)-\Theta(\omega,T_2)}{4\pi}\int_o^\infty Z_{\beta,\omega}^p d\beta$$

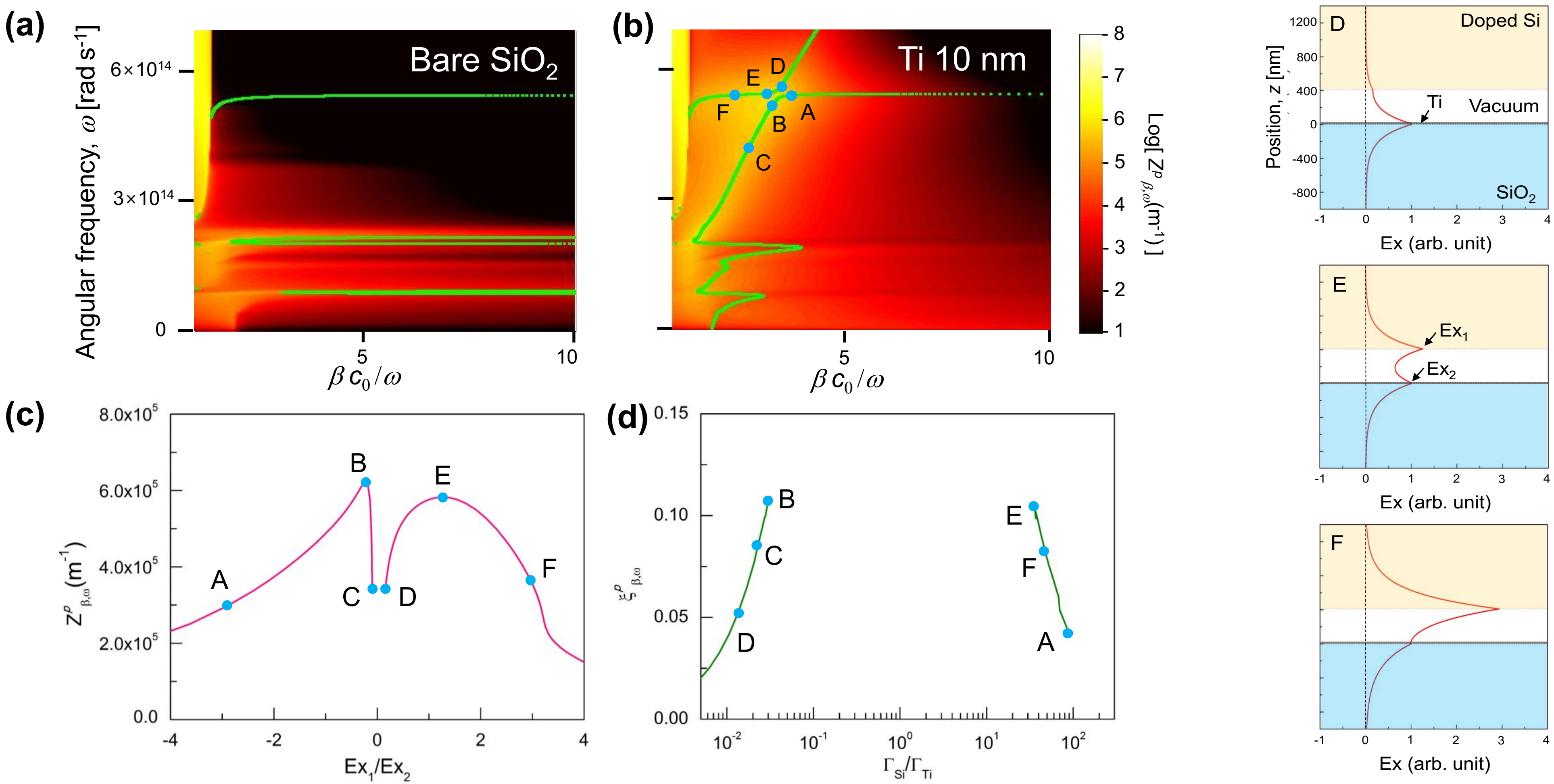






M. Lim, J. Song, S.S. Lee, J. Lee, and B.J. Lee, *Physical Review Applied* 14, 014070, 2020.

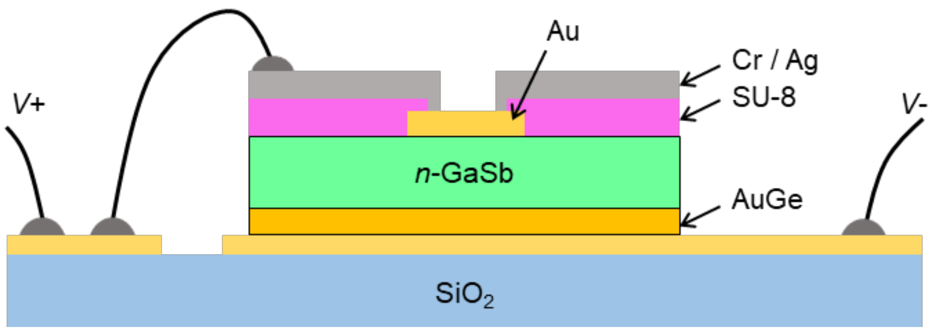
Coupling in Asymmetric Configuration – cont'd



M. Lim, J. Song, S.S. Lee, J. Lee, and B.J. Lee, *Physical Review Applied* 14, 014070, 2020.

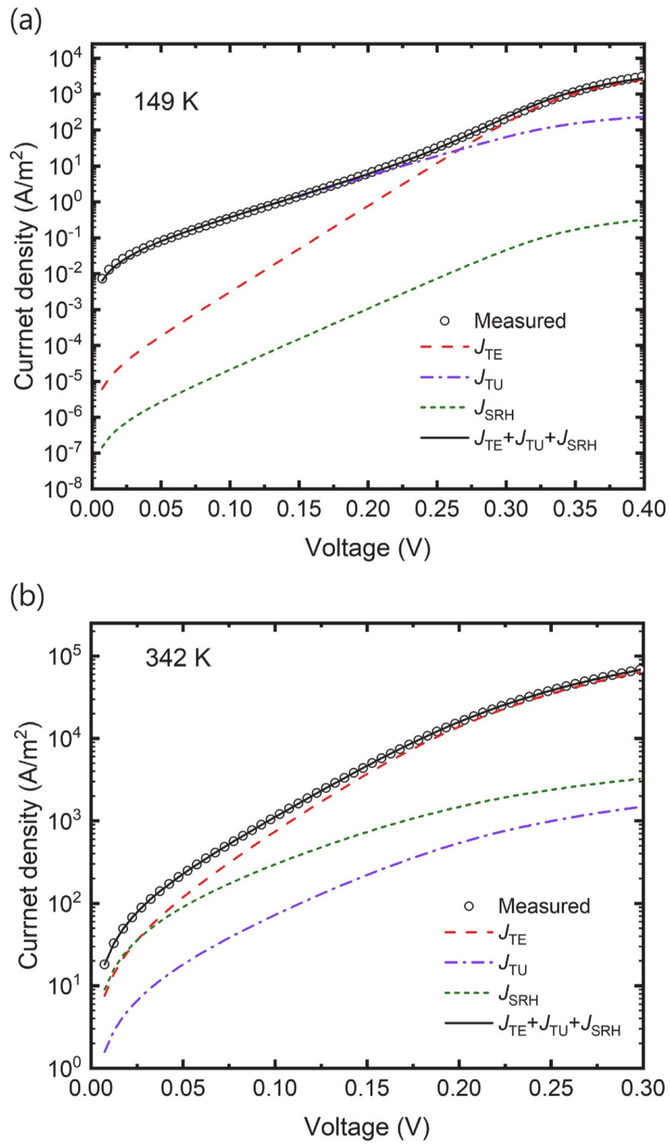
Schottky-Junction Cell

- Schematic of an Au/n-GaSb Schottky TPV cell attached on a chip carrier



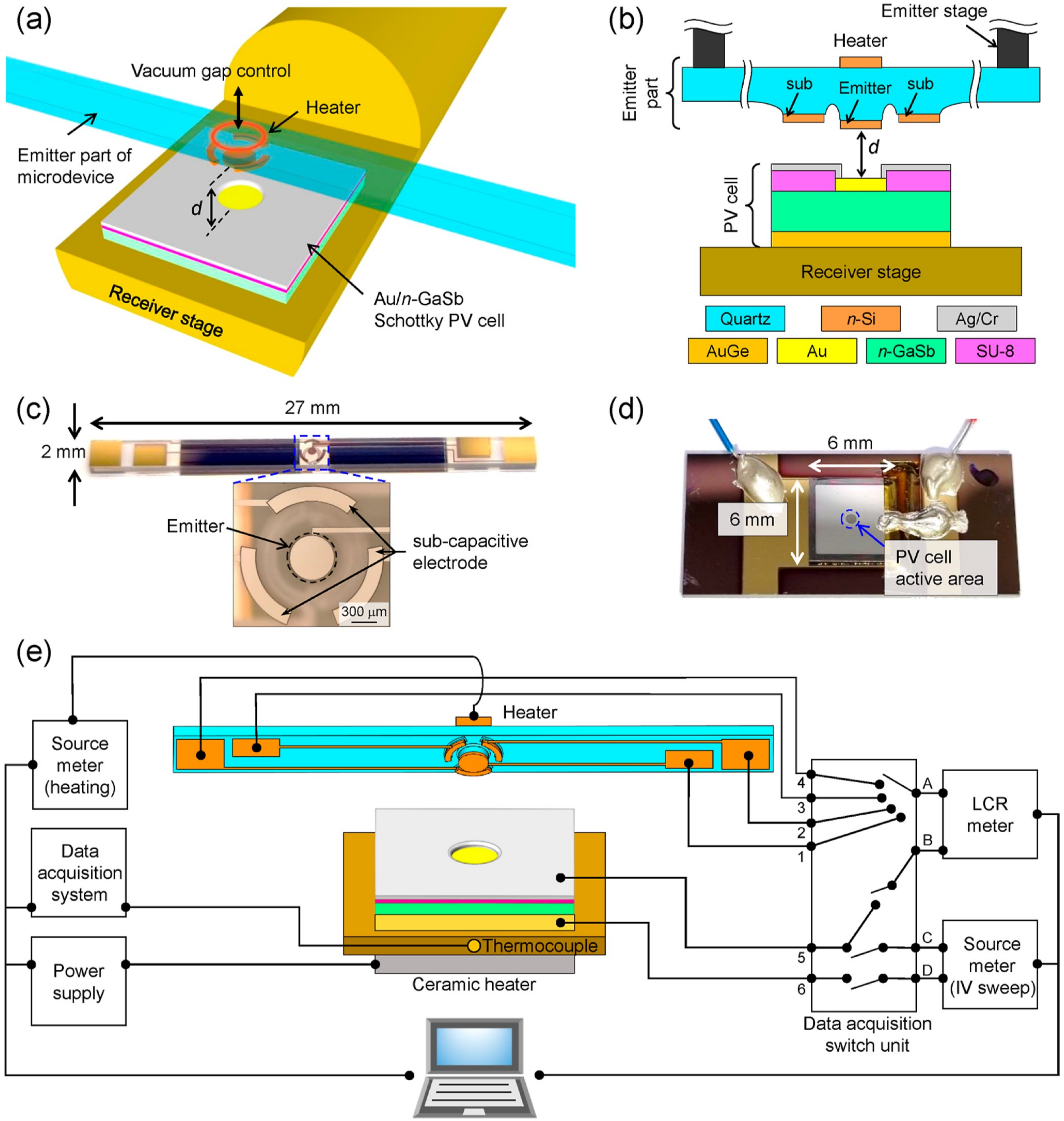
- Multiple current mechanism in Au/n-GaSb Schottky diode

$$
\begin{aligned}
J_{\mathrm{tot}} &= J_{\mathrm{TE}} + J_{\mathrm{sec}} \\
&= J_{\mathrm{TE}(0)}\{\exp[q(V - I R_S)/nkT] - 1\} \\
&\quad + J_{\mathrm{sec}(0)}\{\exp[q(V - I R_S)/E_{\mathrm{sec}}] - 1\} \\
&= J_{\mathrm{TE}(0)}\{\exp[q(V - I R_S)/nkT] - 1\} \\
&\quad + J_{\mathrm{TU}(0)}\{\exp[q(V - I R_S)/E_t] - 1\} \\
&\quad + J_{\mathrm{SRH}(0)}\{\exp[q(V - I R_S)/2kT] - 1\}
\end{aligned}
$$



J. Jang, J. Song, S.S. Lee, S. Jeong, B.J. Lee, and S. Kim, *Materials Science in Semiconductor Processing* 131, 105882, 2021.

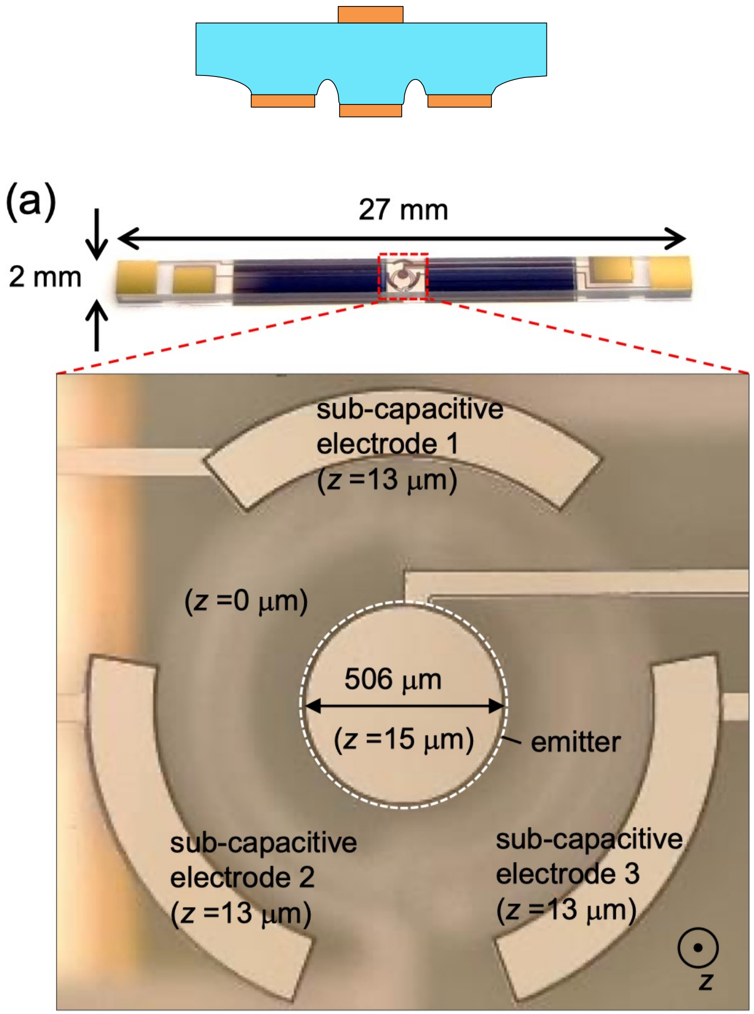
NF-TPV Conversion Experiment



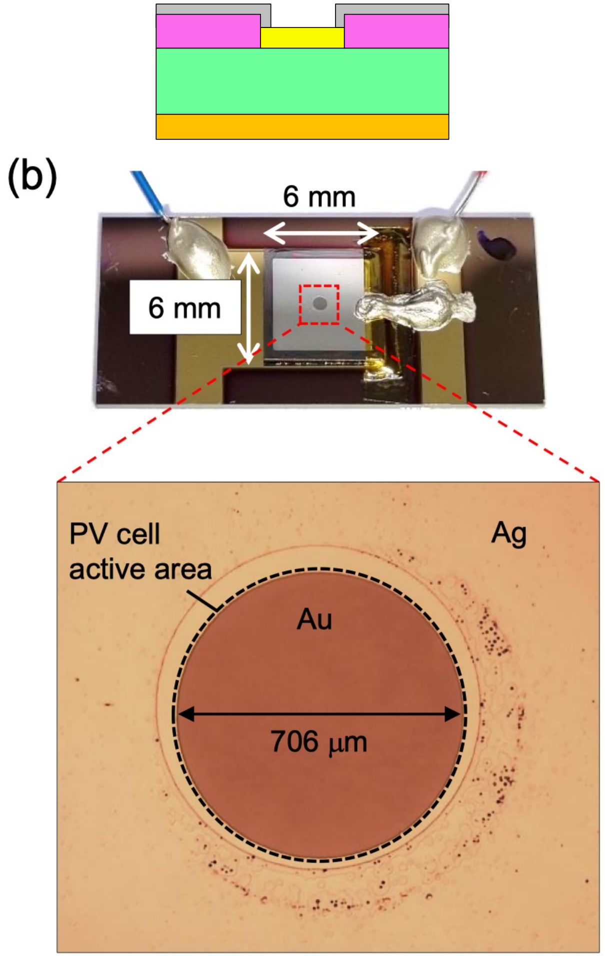
J. Song, J. Jang, M. Lim, M. Choi, J. Lee, and B.J. Lee, ACS Photonics 9, 1748 – 1756, 2022.

NF-TPV Conversion Experiment – cont'd

Emitter

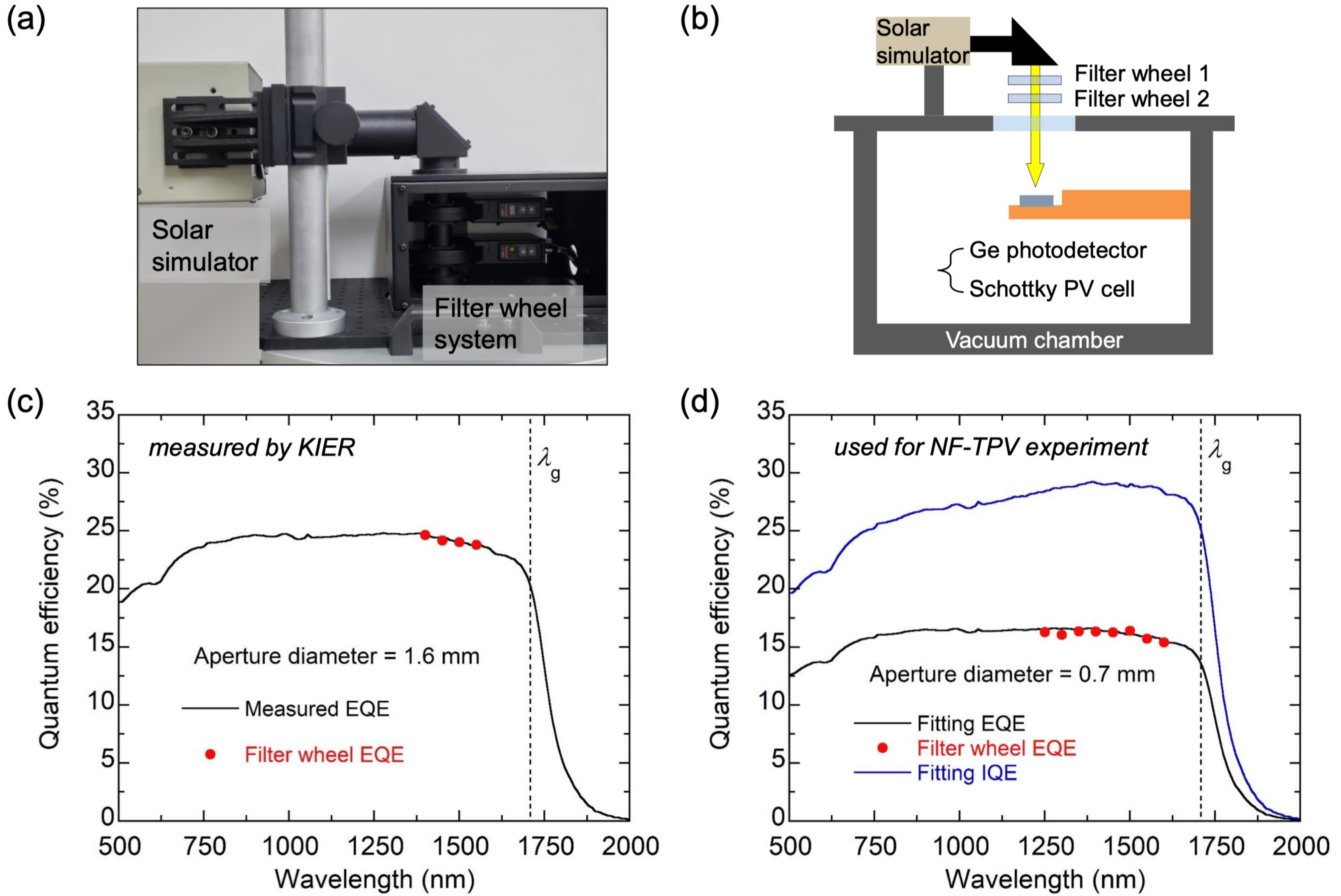


Au/n-GaSb Cell

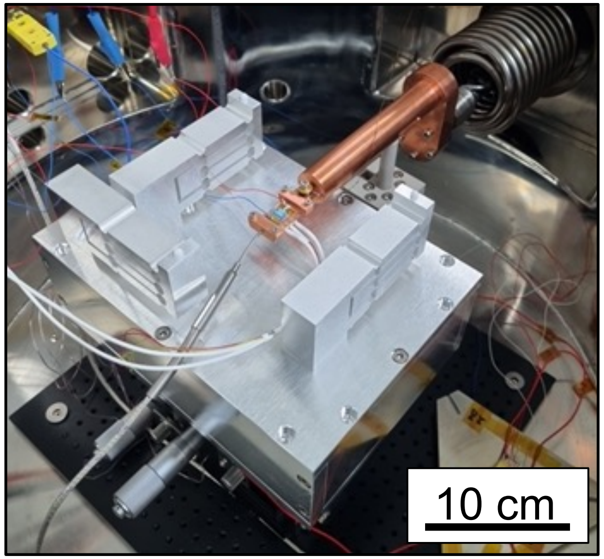


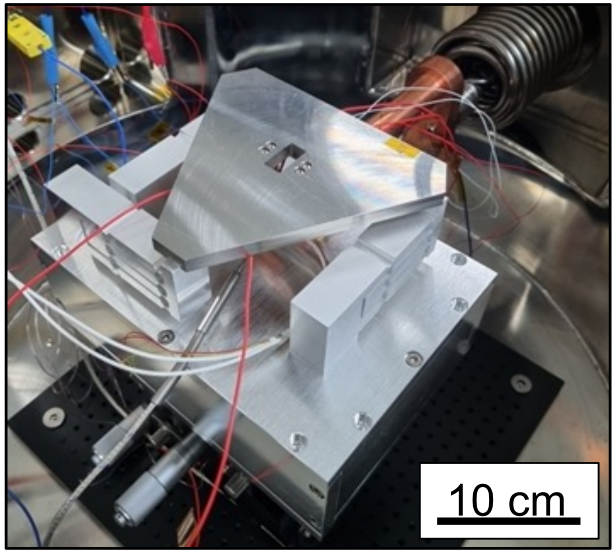
J. Song, J. Jang, M. Lim, M. Choi, J. Lee, and B.J. Lee, ACS Photonics 9, 1748 – 1756, 2022.

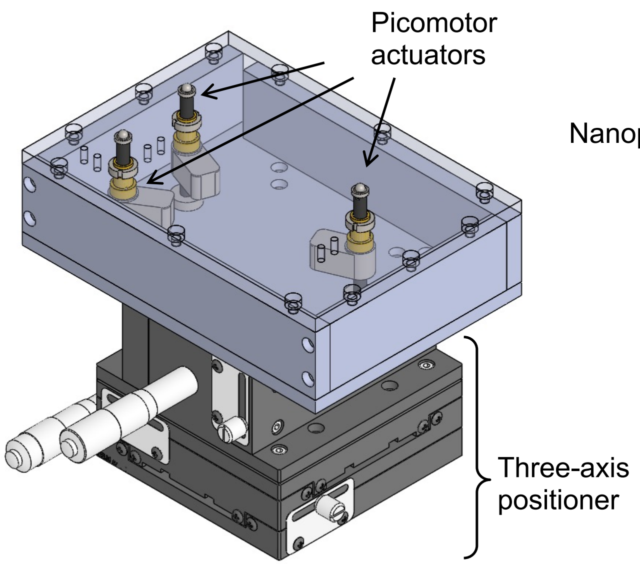
Schottky-Junction Cell – cont'd

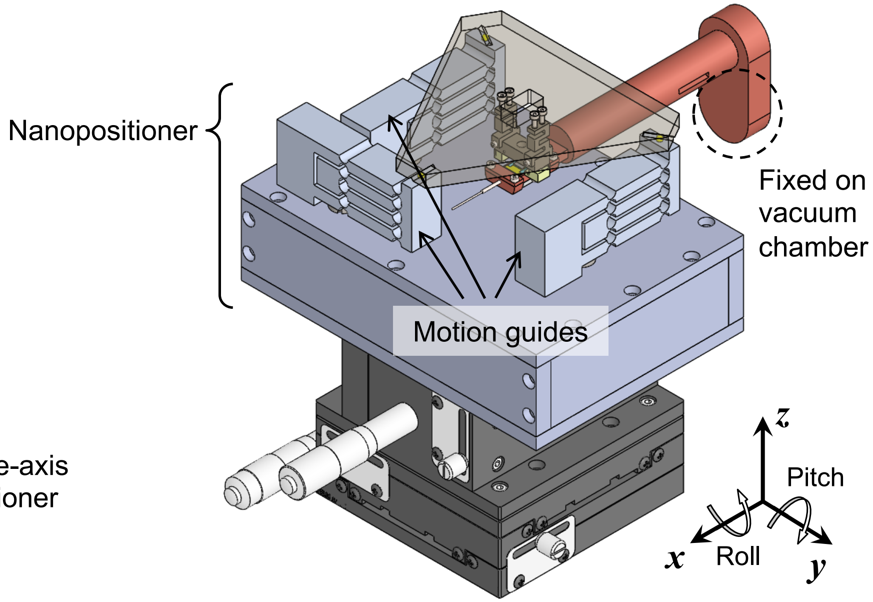


NF-TPV Conversion Experiment – cont'd









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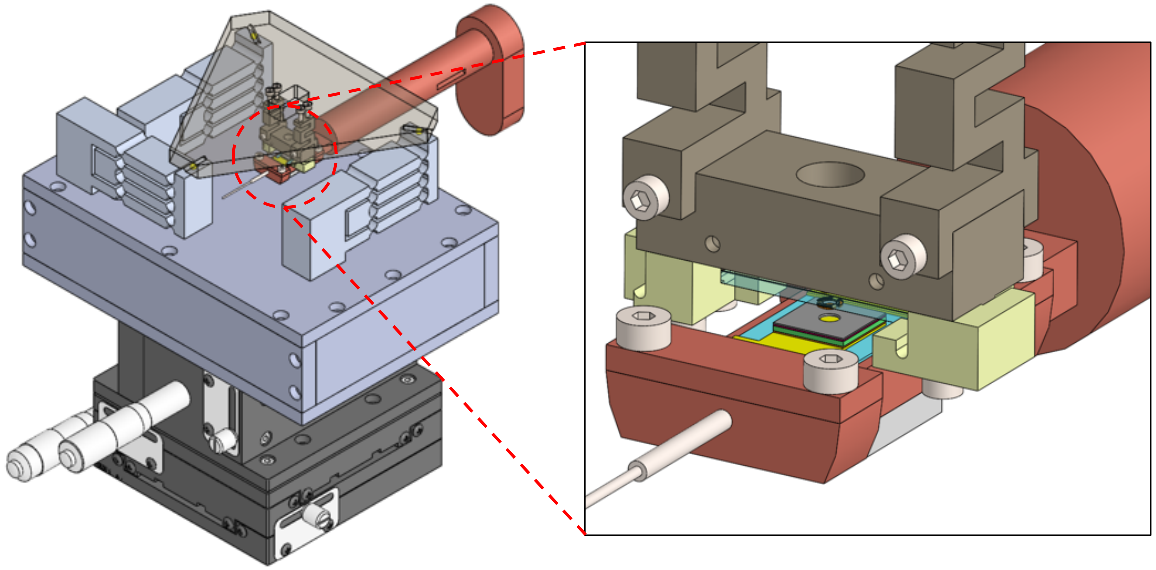
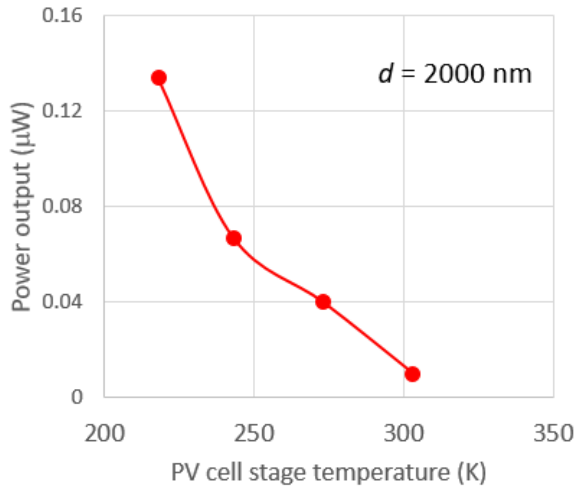
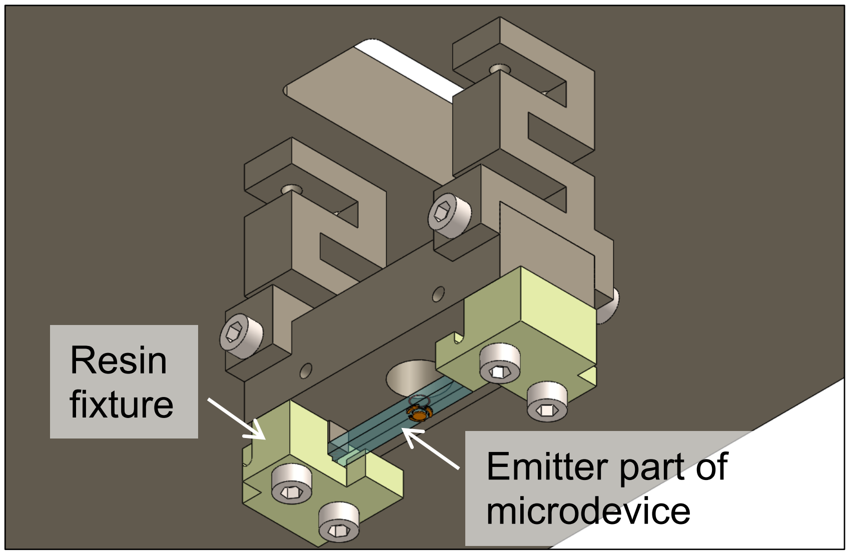
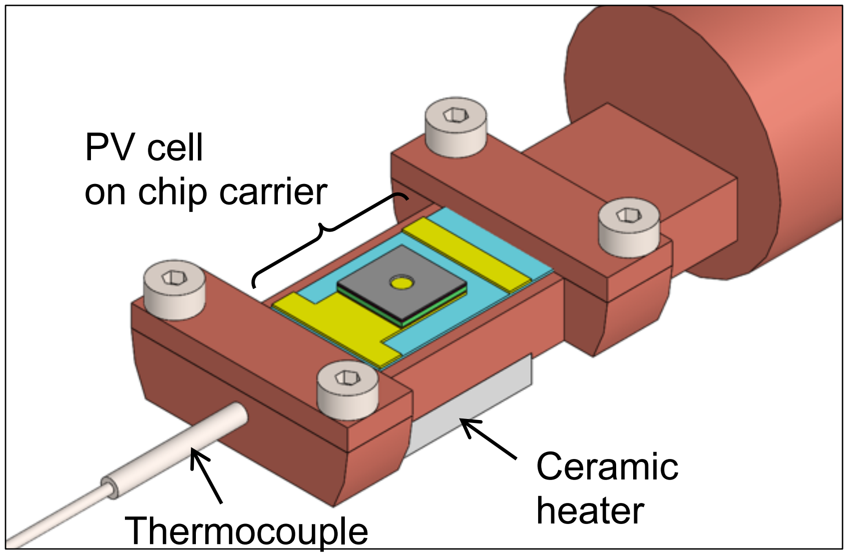
NF-TPV Conversion Experiment – cont’d

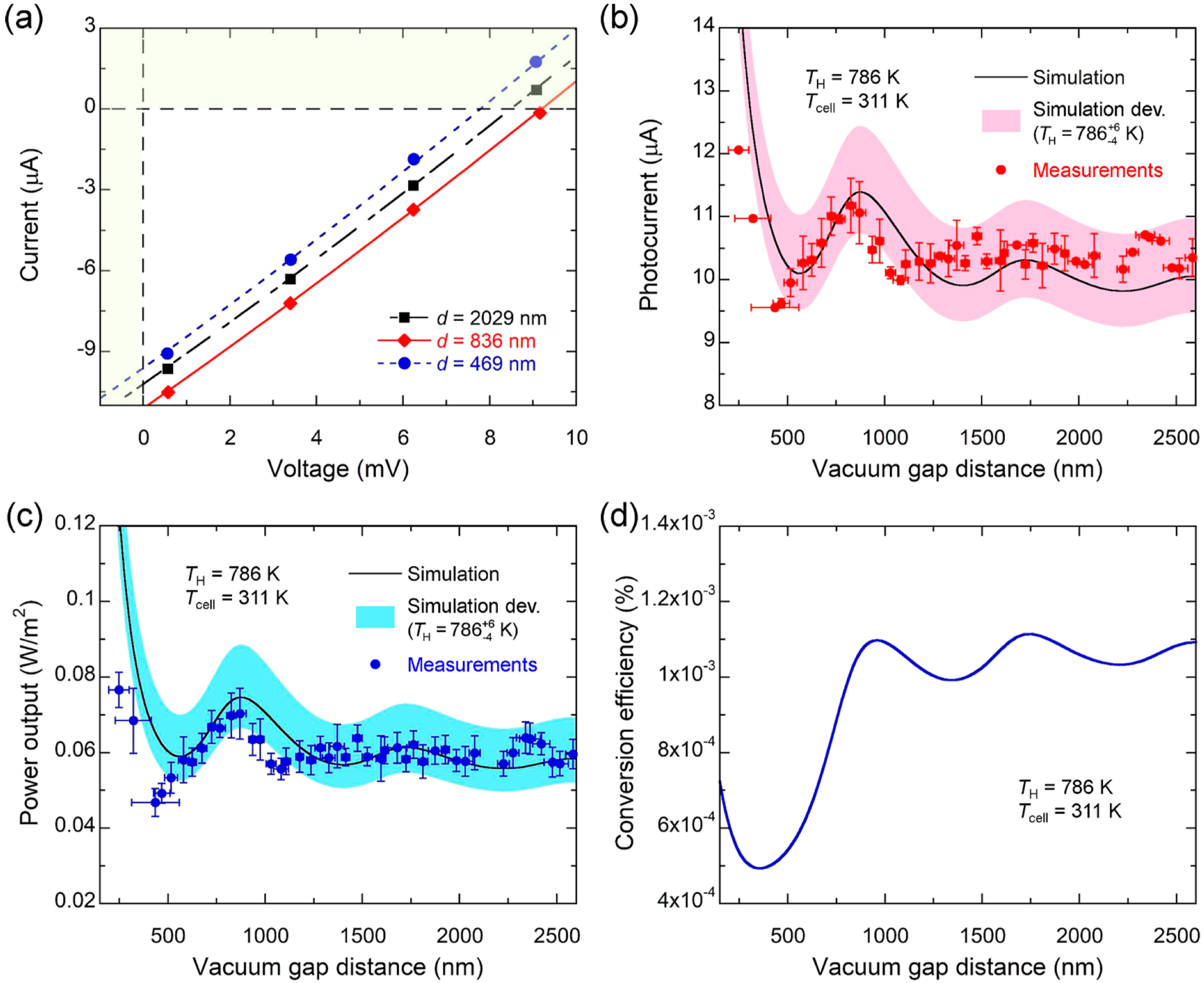








NF-TPV Conversion Experiment – cont'd



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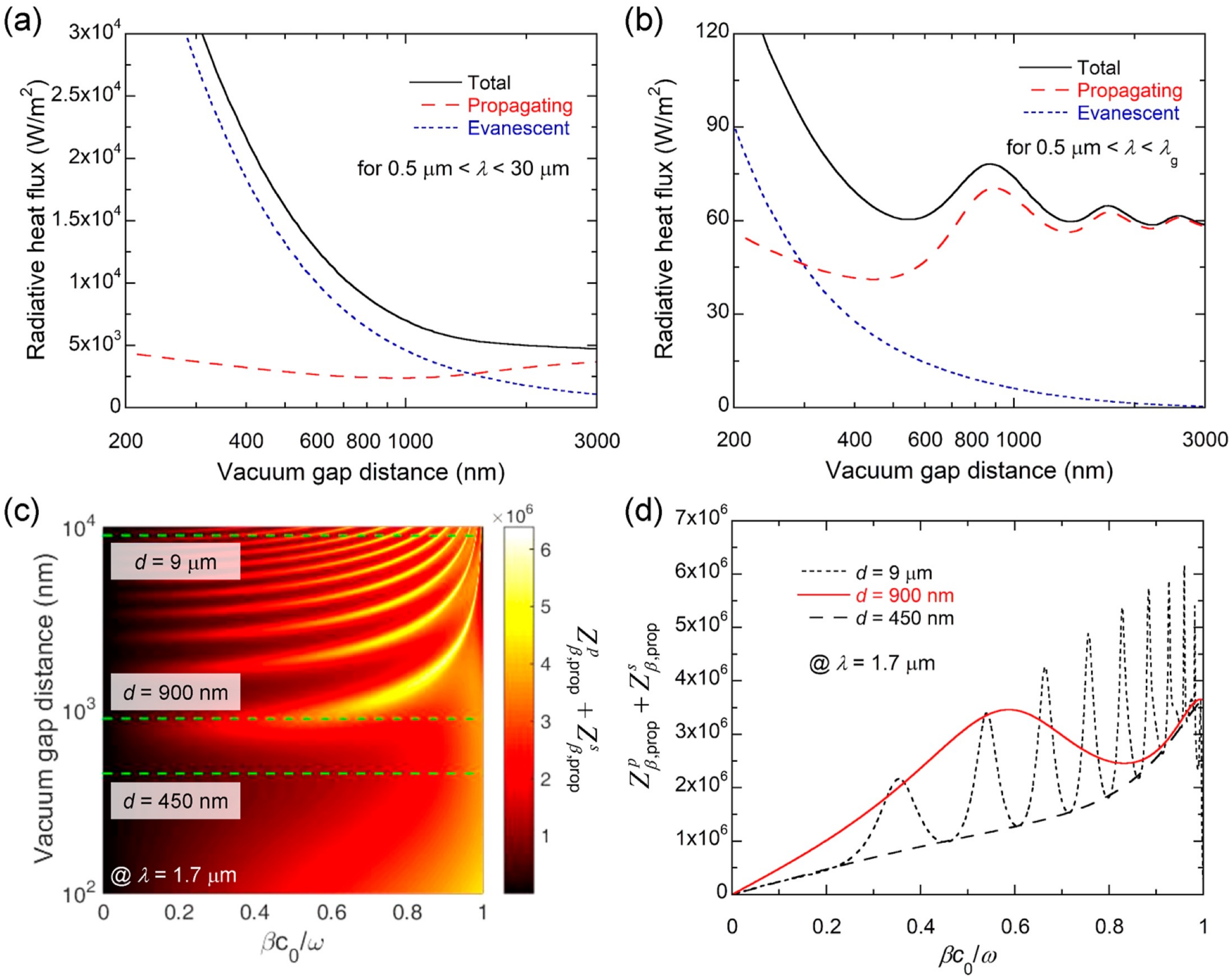
NF-TPV Conversion Experiment – cont'd



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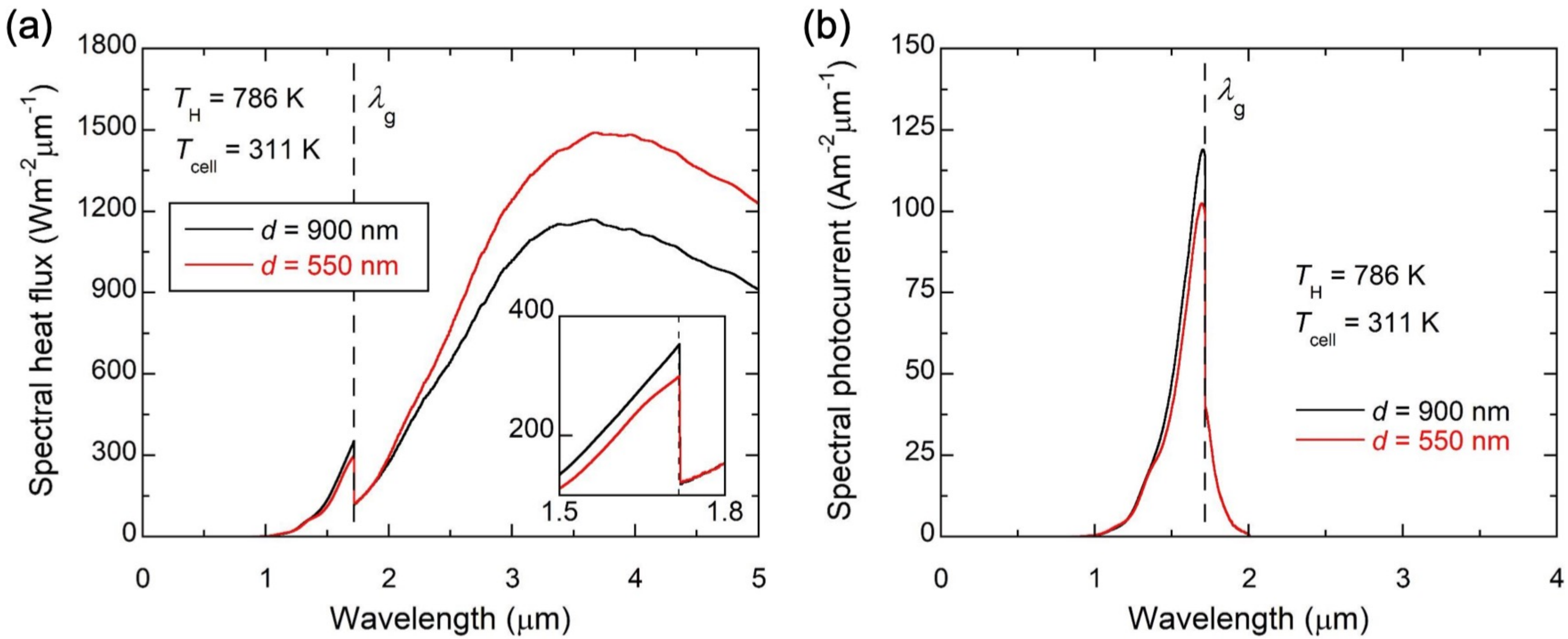
NF-TPV Conversion Experiment – cont'd



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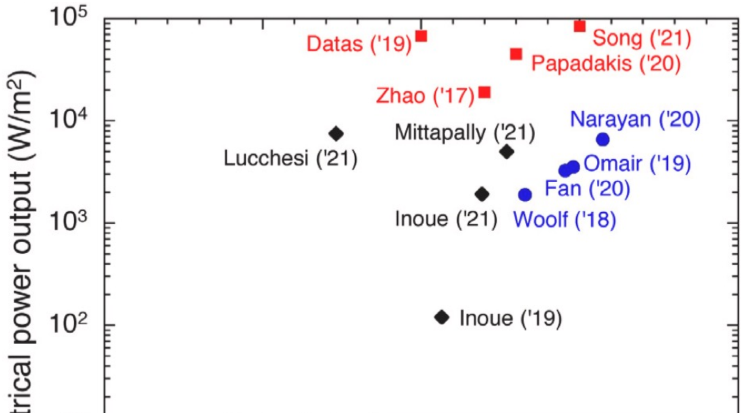
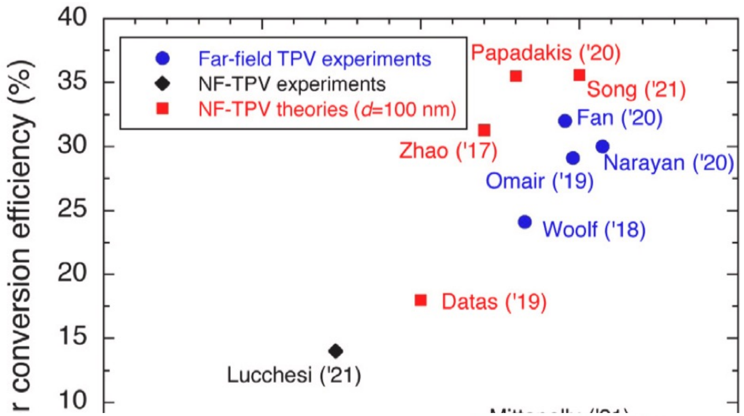
Prospects & Acknowledgements





2021 Cherry blossom