Thermotronics: thermal management and information treatment with thermal photons

Philippe Ben-Abdallah

Laboratoire Charles Fabry, Institut d'Optique, Paris, France

pba@institutoptique.fr

LABORATOIRE CHARLES FABRY

cnrs advancing the frontiers

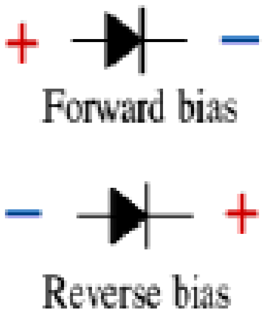
KITP-Lecture2-Emerging Regimes and Implications of Quantum and Thermal Fluctuational Electrodynamics

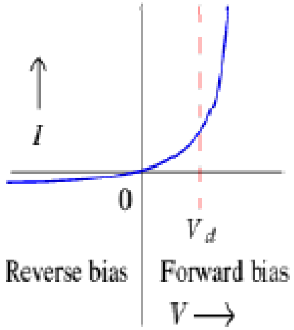
INSTITUT d'OPTIQUE GRADUATE SCHOOL

Basic blocks in electronics

Diode

Perfect rectification of current

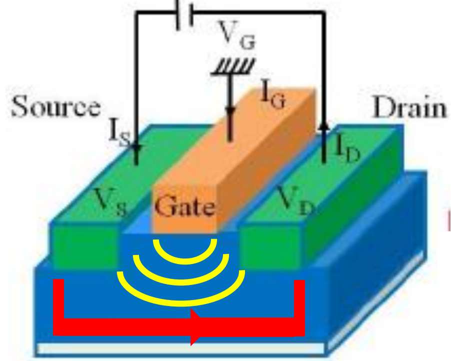


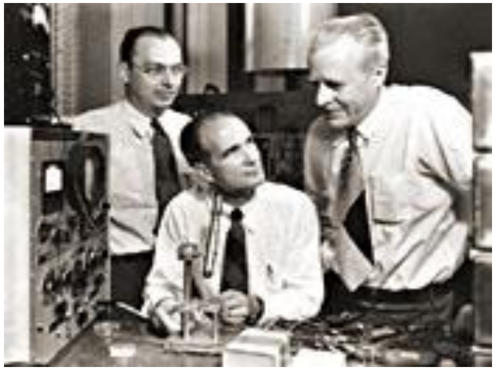


F. Braun
1874

Transistor

Electric switching, modulation and amplification



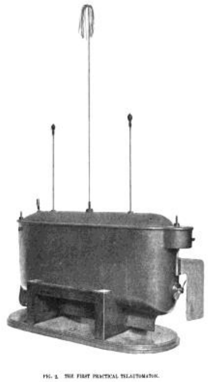


J. Bardeen, W. Brattain, W. Shockley
1947-1951

Random access memory (RAM)

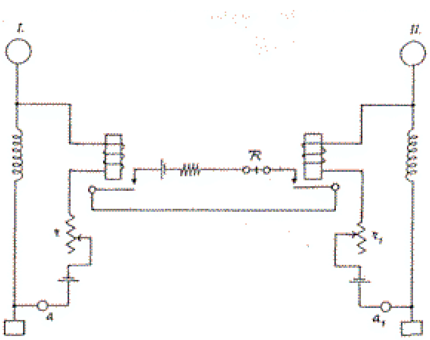
Volatile storing

Williams and Kilburn
1946



Telautomaton

logic gate

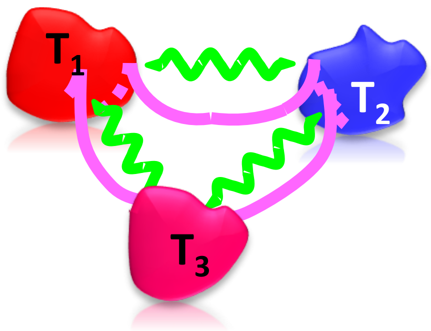


Tesla-1890

Question

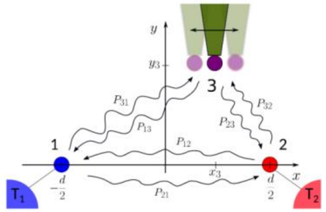
Are there thermal analogs to electric circuits to manage heat flows in solid networks at small scale with photons (near-field) as we do with electrons for electric current in solid state circuits?

Outline



- Brief historical overview about radiative heat transfer

- Building blocks for a thermotronics with thermal photons
  - Rectification and radiative thermal diode
  - Thermal transistor
  - Multistable thermal state in many-body and thermal memory
  - Logic gates



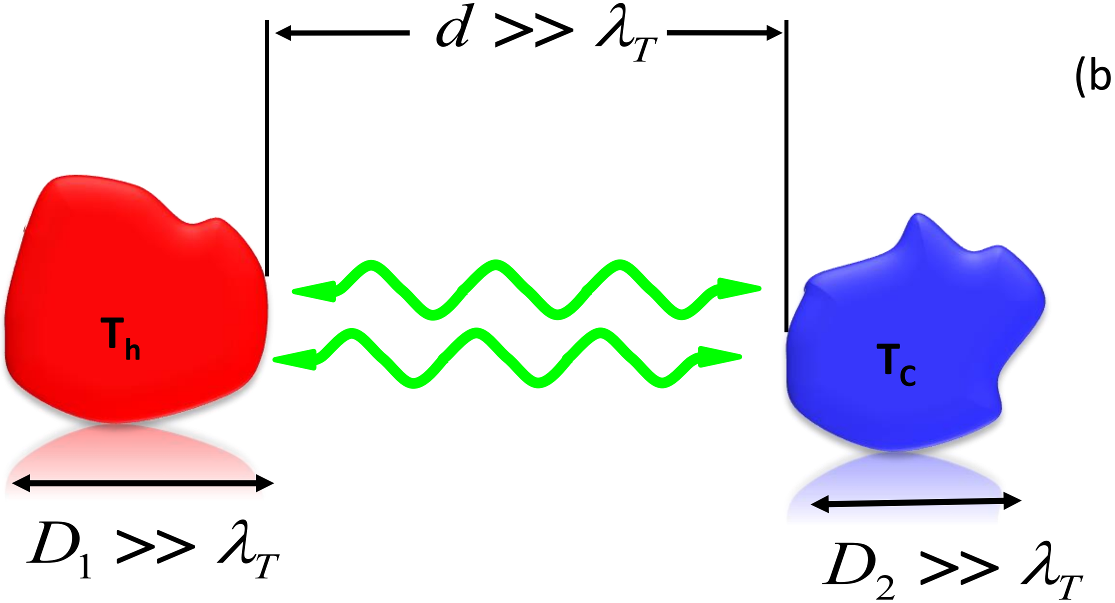
- Heat pumping in many-body systems

- Geometric pumping in non-reciprocal systems

Heat transfer in far field

Kirchoff 1862
(Radiometry)

Planck 1901
(blackbody theory)

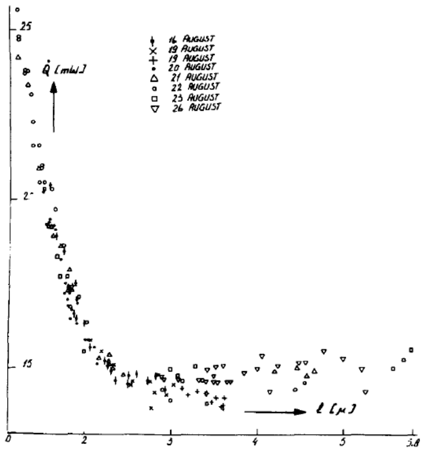


$$\phi < \underbrace{\sigma(T_h^4 - T_c^4)}_{\text{Heat transfer between two blackbody}}$$

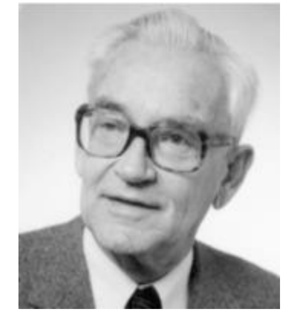
Stefan-Boltzmann limit

Heat transfer between two blackbody

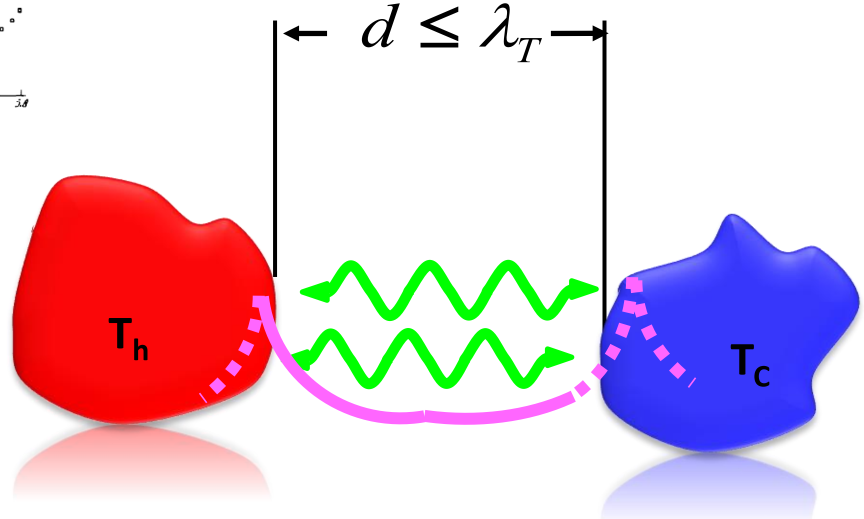
Heat transfer in near-field



Hargreaves
1969 experiment



Polder & Van Hove,
1971 theory



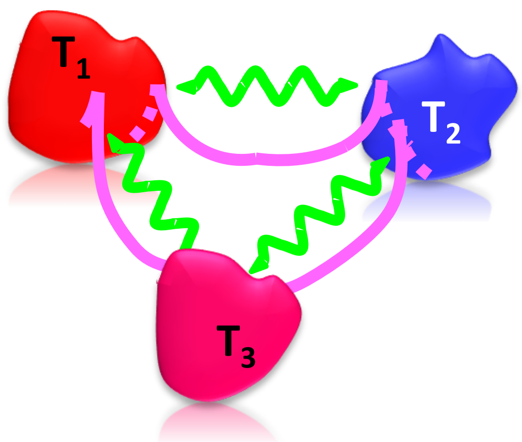
$$\phi \gg \sigma(T_h^4 - T_c^4)$$

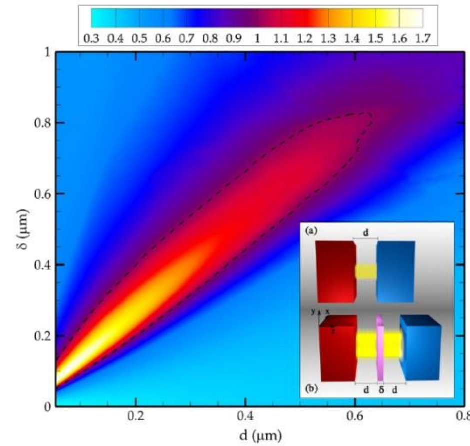
Tunneling of non-propagative photons

Since then, more than 20 experimental proofs:

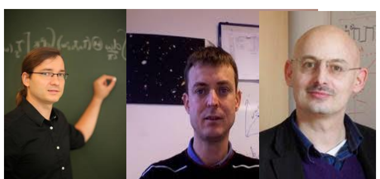
PRL,95, 224301, 2005; PRB, 78, 115303, 2008; APL 92, 133106, 2008; Nano Lett. 9, 2909 , 2009; Nature Photon. 3, 514, 2009; PRL 107, 014301, 2011; Rev. Sci. Instrum. 82, 055106 , 2011; PRL 109, 224302, 2012; PRL, 108, 234301, 2012; PRL 109, 264301, 2012; Nature Nano. 10, 253, 2015; Nature 528, 387, 2015; Nature Nano. 11, 515, 2016; APL, 109, 203112, 2016; Nat. Commun. 8, 14475, 2017, PRL , 120, 175901 (2018)…

Many-body near-field heat transfer





PRL, 109, 244302 (2012)



... dipoles 2011

 ... 

3 body 2014

  ... 

N body 2017

<u>Many body effects</u>:

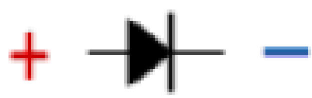
-non additivity of flux
-anomalous heat transport regimes
-photon tunneling amplification
-multistable states
...
-open the door to new functionalities

<u>Review</u>:
Biehs et al. Rev. Mod. Phys., 93, 025009 (2021)
Latella et al., Opt. Express, 29 (16) , 24816 (2021)

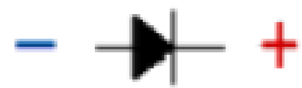
A-Radiative thermal diode

Radiative thermal diode

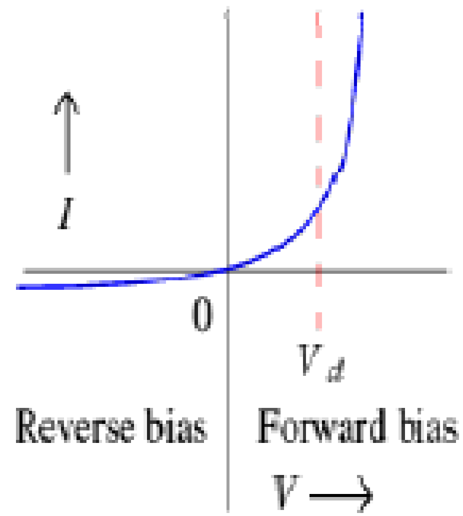
Electric



Forward bias

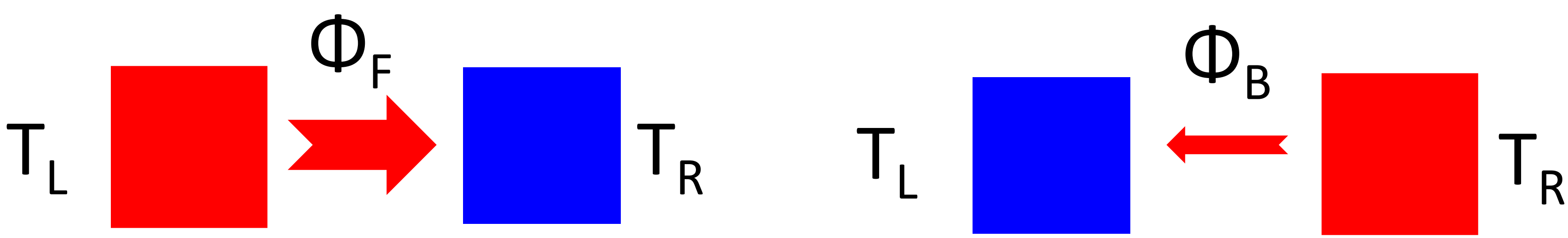


Reverse bias



Thermal

$\Delta T = T_L - T_R \leftrightarrow \Delta V$ $\Phi \leftrightarrow I$



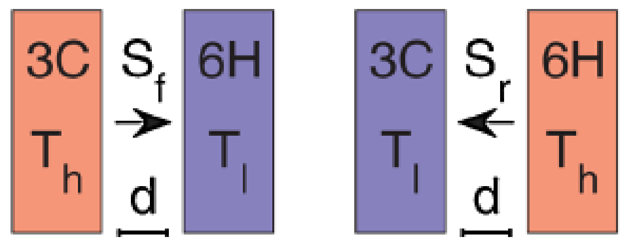
$$\Phi_{F,B} = \int_0^{\infty} \frac{d\omega}{2\pi}[\Theta(\omega, T_{L,R}) - \Theta(\omega, T_{R,L})]\int \frac{d\vec{K}}{(2\pi)^2}\tau_{F,B}(\omega, \vec{K})$$

Optical properties independent on the temperature → $\Phi_F = \Phi_B$

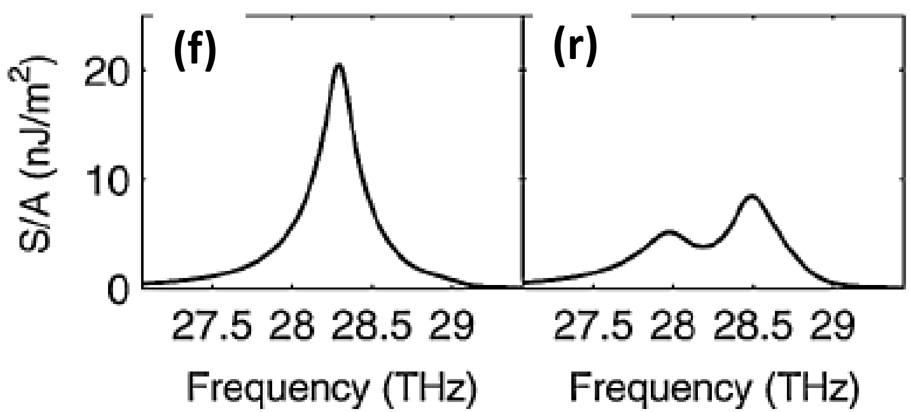
PRL **104**, 154301 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

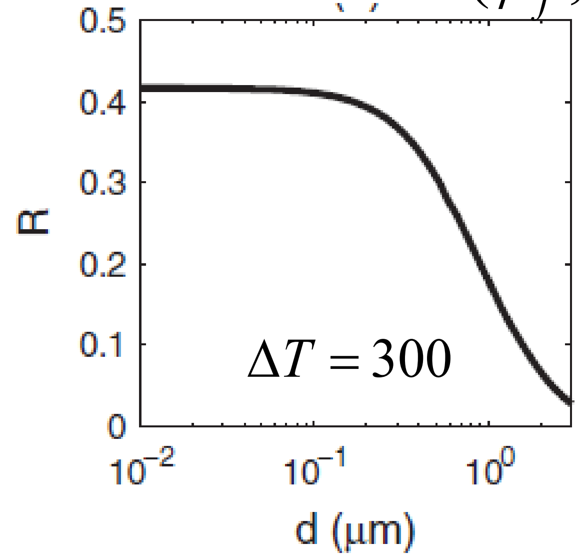
Thermal Rectification through Vacuum

Clayton R. Otey,[1,*] Wah Tung Lau (留華東),[2] and Shanhui Fan (范汕洄)[2,†]



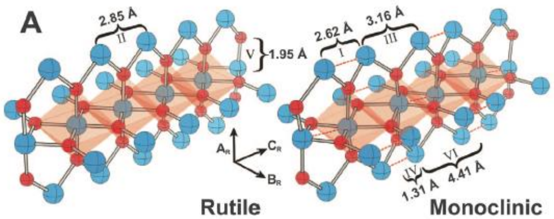
$$R = \frac{|\varphi_f - \varphi_r|}{\max(\varphi_f;\varphi_r)}$$



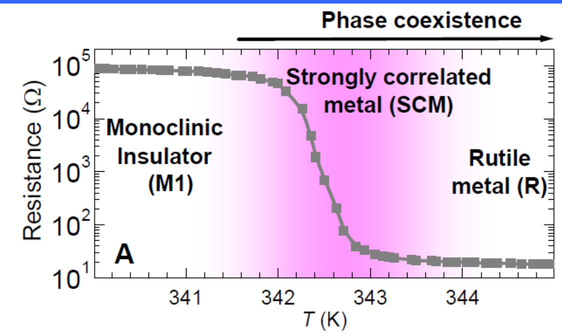


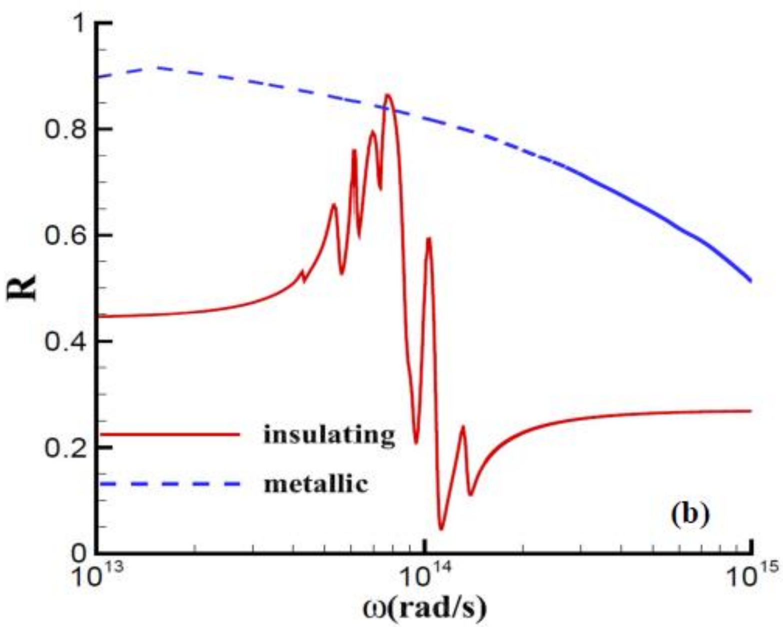
But rectification is not strong enough to make a thermal diode

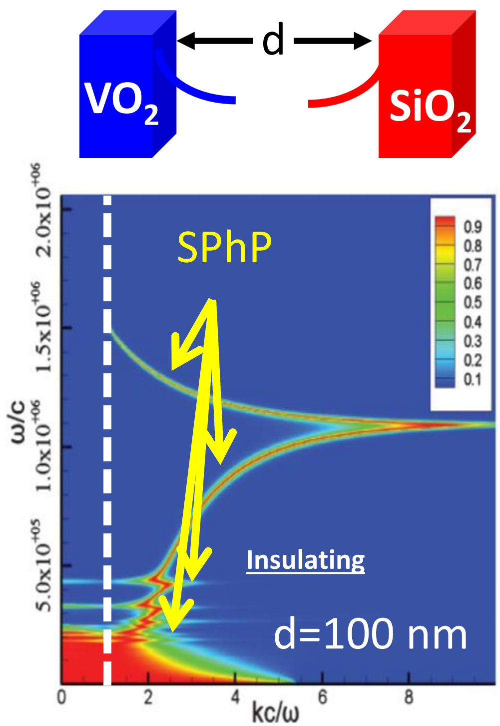
Dielectric catastrophe with VO2

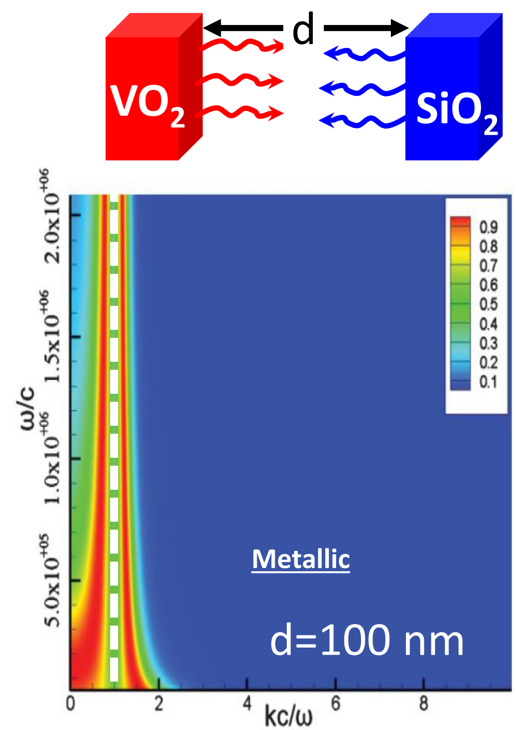


Mott transition
at T_c =340K





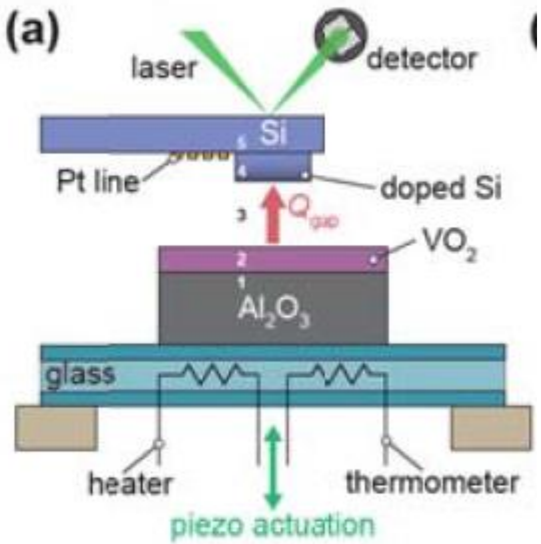




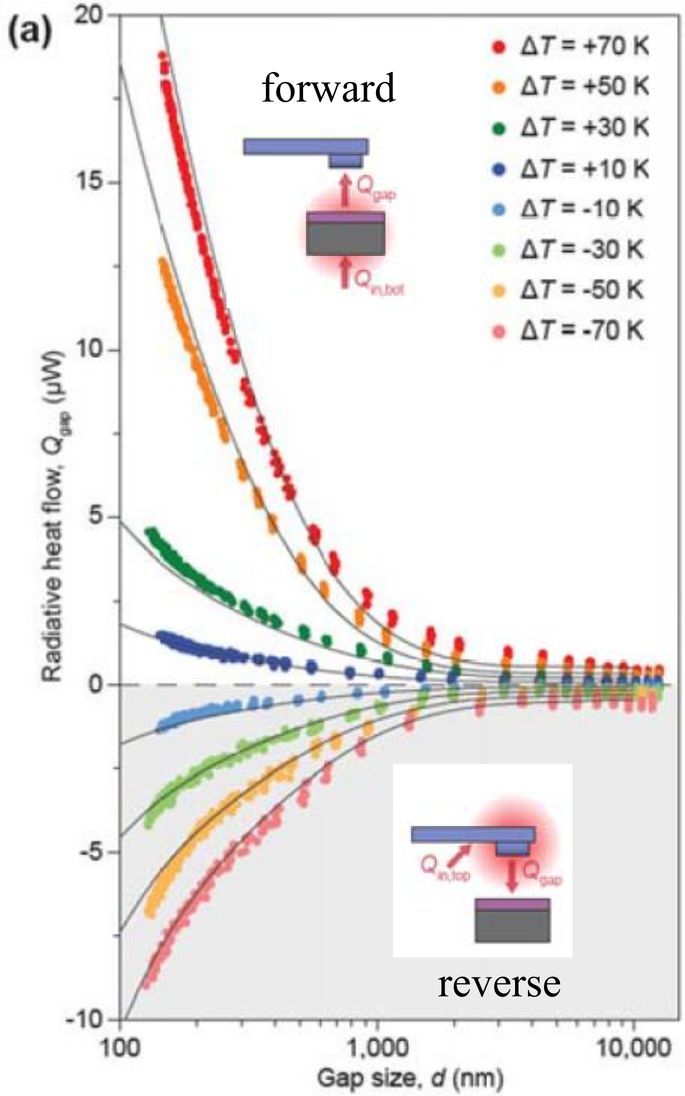
Far field

Near field

Radiative heat transfer vs separation distance

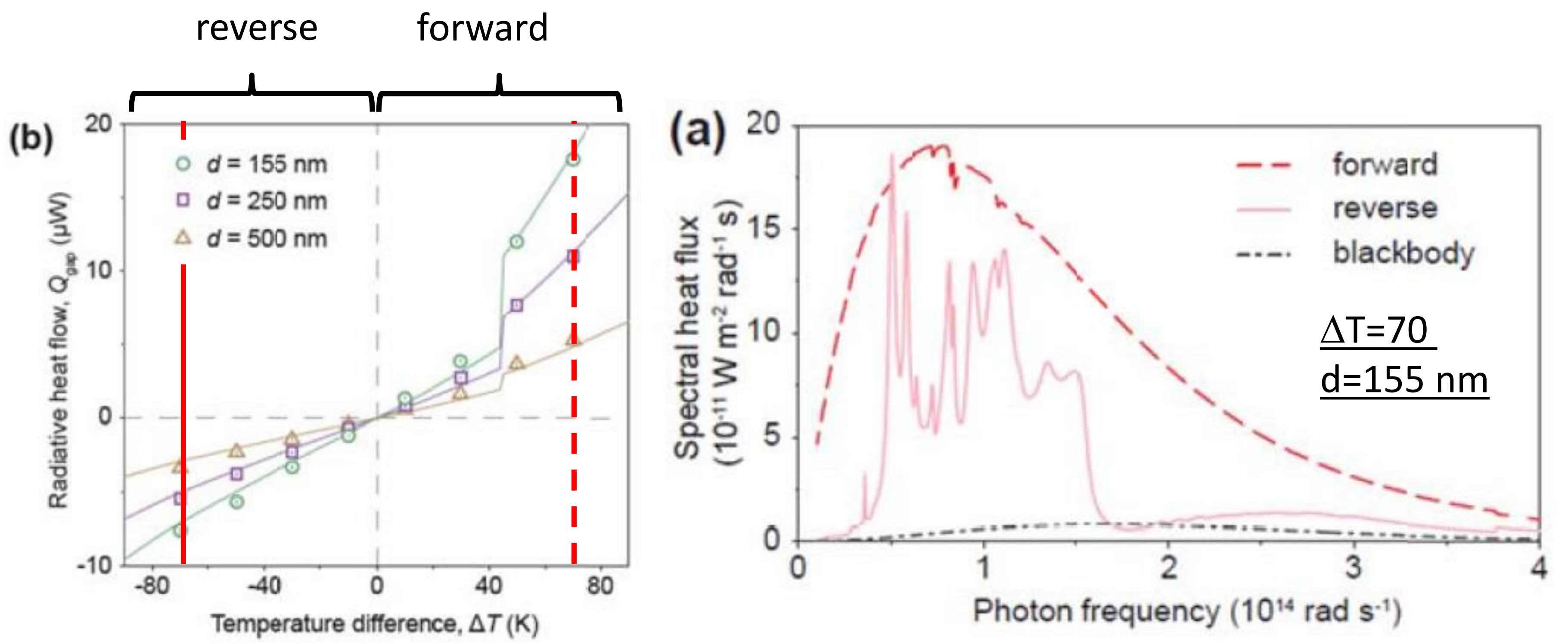


$\Delta T = T_{VO2} - T_{doped\text{-}Si}$



P. Reddy et al. , ACS Nano, 12 (6), 5774–5779, *2018*

Diode characteristics



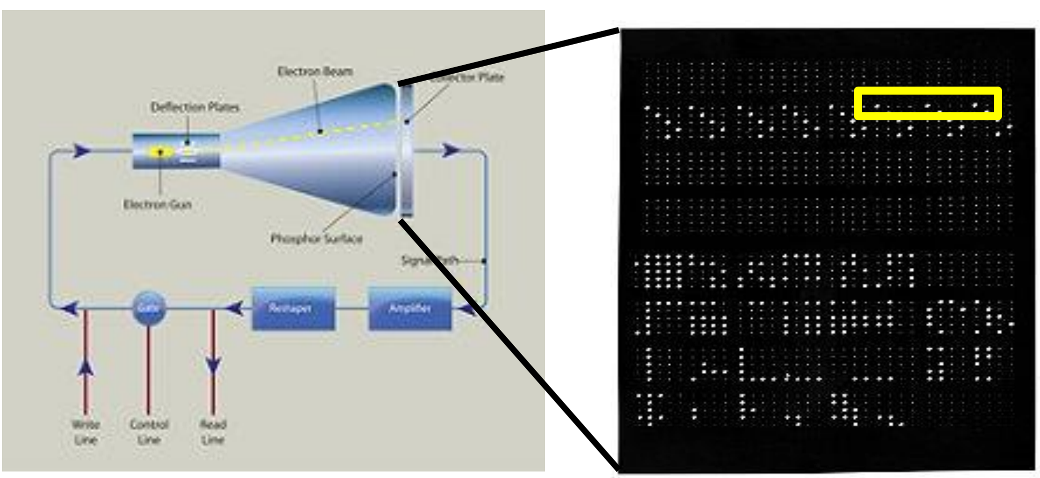
Thermal rectification

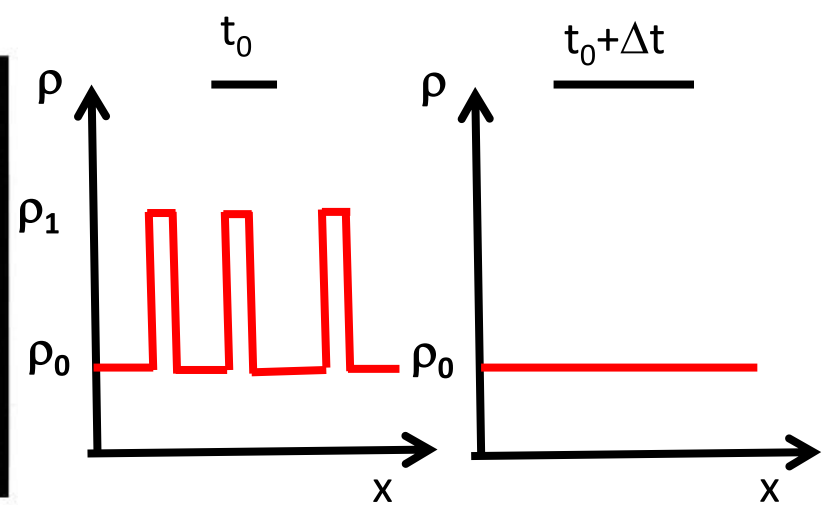
~60% at 155 nm

B-Bistability and thermal memory

The first volatile memory

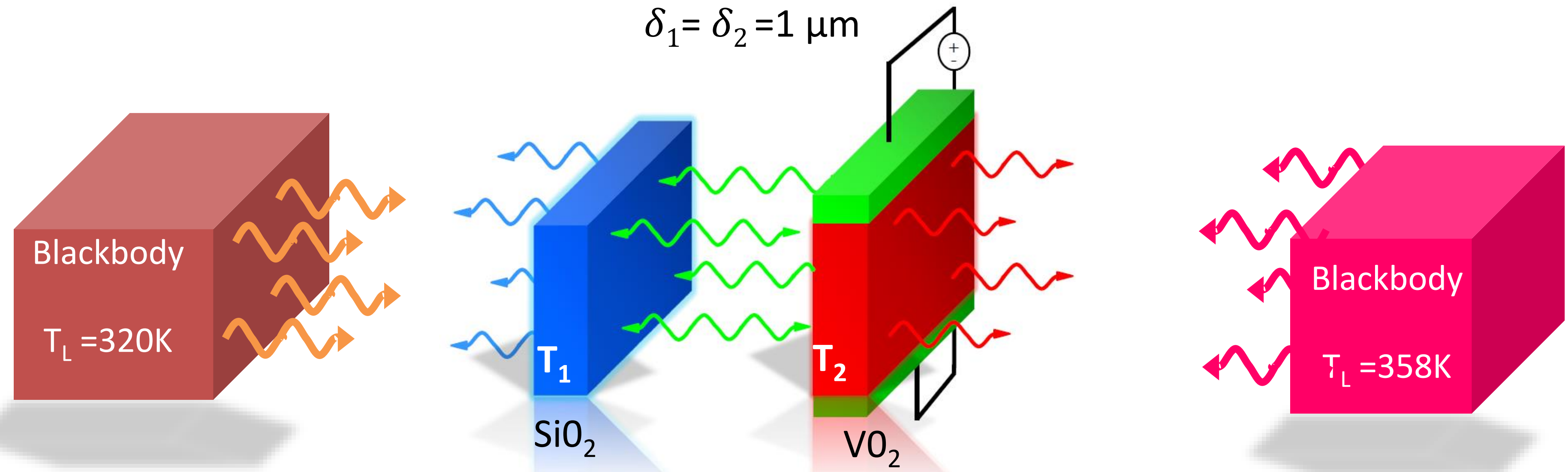
Williams and Kilburn
1946



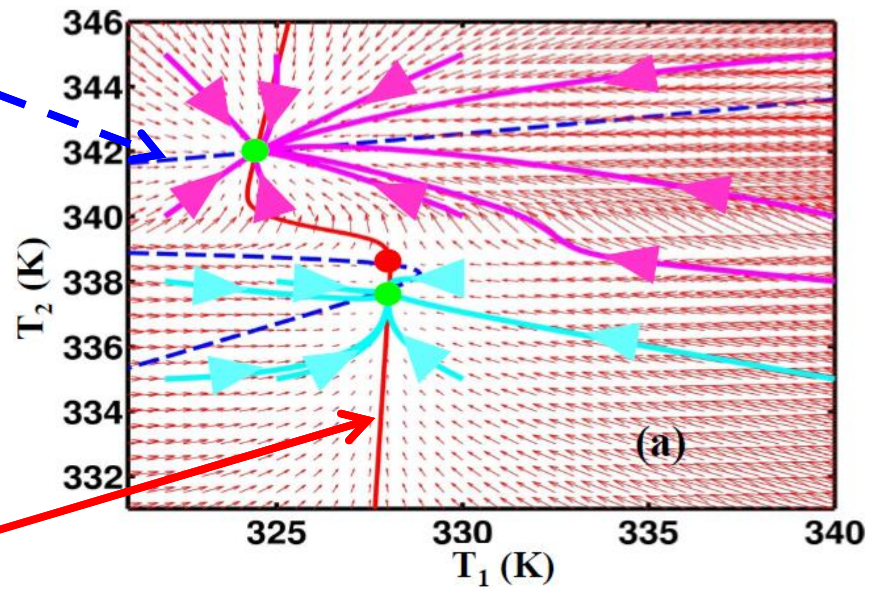


$(\rho_0, \rho_1) \leftrightarrow (0,1)$ ➡ a volatile bit of information

Bistability and thermal memory



$\Phi_1(T_1, T_2)=0$

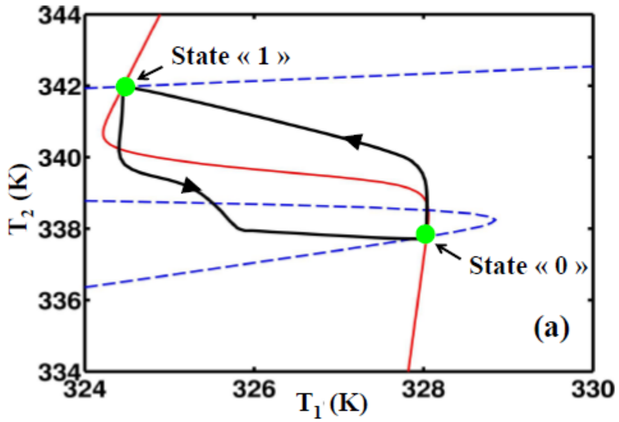


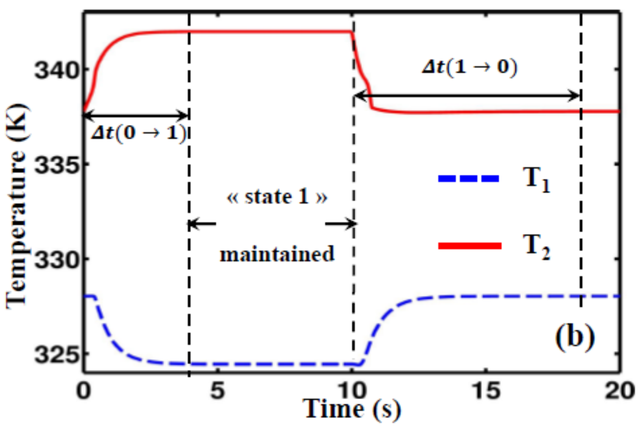
$\Phi_2(T_1, T_2)=0$

2 stables states
=
a bit (0,1) of information

*PRL, **113**, 074301 (2014)*

Writing of thermal states





Writing of state « 1 »

$$\begin{cases} \rho_1 C_1 \partial_t T_1 = \Phi_1/\delta_1 \\ \rho_2 C_2 \partial_t T_2 = \Phi_2/\delta_2 + Q_2 \\ (T_1, T_2)_0 \quad \text{State « 0 »} \end{cases}$$

Writing of state « 0 »

$$\begin{cases} \rho_1 C_1 \partial_t T_1 = \Phi_1/\delta_1 \\ \rho_2 C_2 \partial_t T_2 = \Phi_2/\delta_2 - \tilde{Q}_2 \\ (T_1, T_2)_1 \quad \text{State « 1 »} \end{cases}$$

In near-field regime the writing is achieved in few ms (Dyakov et al., J. Phys. D: Appl. Phys. 48, 305104, 2015)

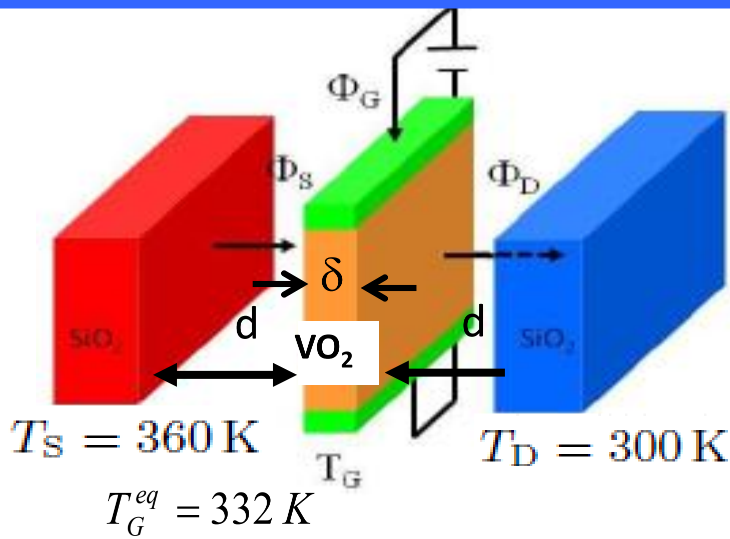
The thermal states are permanent while both thermal baths radiate

C-Radiative transistor

A near-field thermal transistor

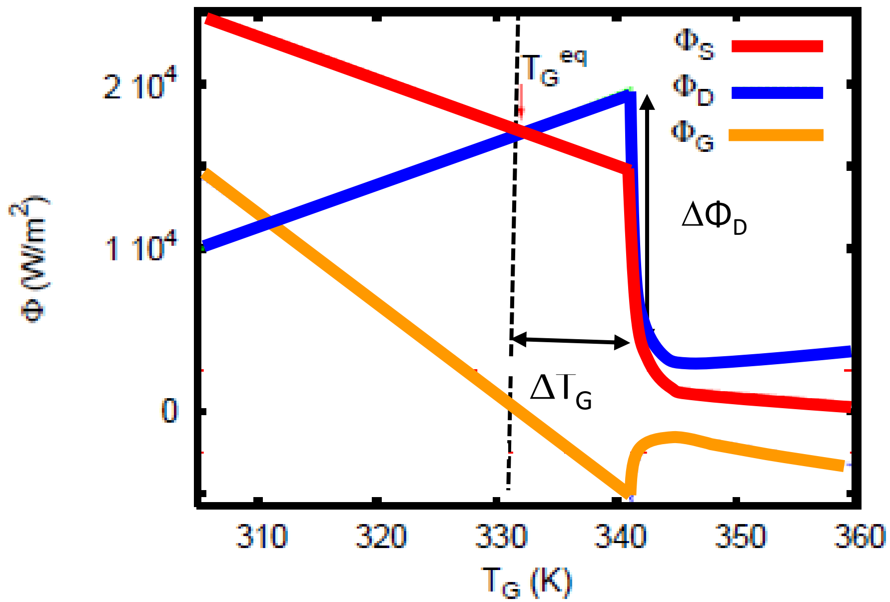
Operating modes :

1-Thermal switch
2-Flux modulation
3-Flux amplification

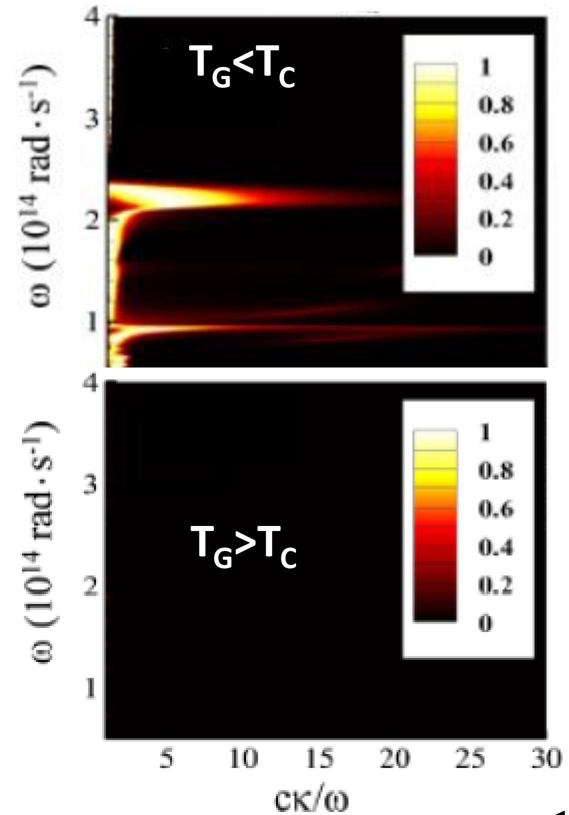


d=100 nm<<λ_W

δ=50 nm

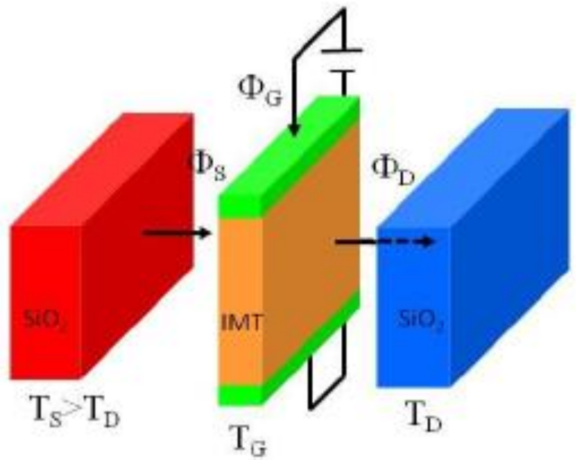


Coupling efficiency:



PRL, **112**, 044301 (2014)

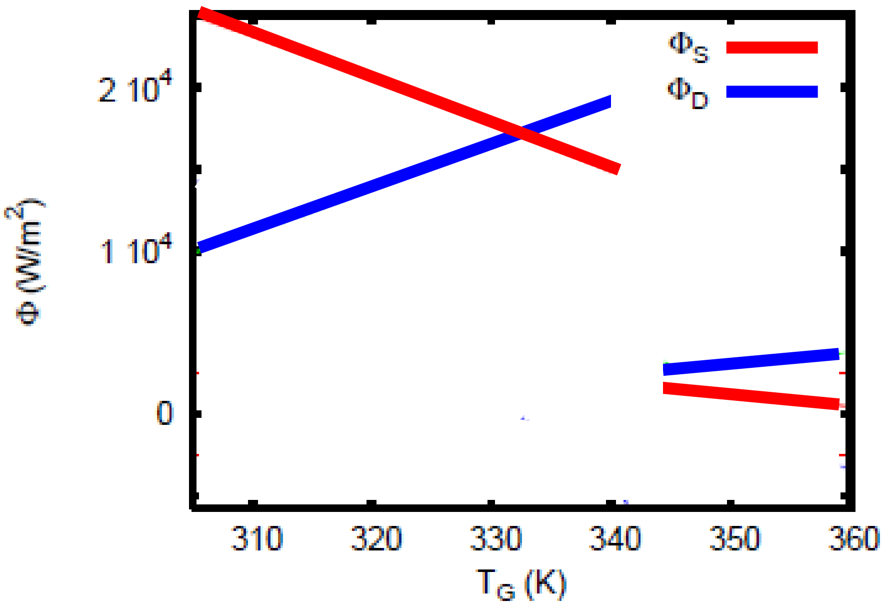
How to get a transistor effect?



Flux amplification:

$$a \equiv \left| \frac{\partial \Phi_D}{\partial \Phi_G} \right| = \left| \frac{\partial \Phi_D}{\partial (\Phi_S - \Phi_D)} \right| \qquad \Phi_G = \Phi_S - \Phi_D$$

Differential thermal resistance :



$$R_S = -\left(\frac{\partial \Phi_S}{\partial T_G}\right)^{-1}, \quad R_D = \left(\frac{\partial \Phi_D}{\partial T_G}\right)^{-1} \Rightarrow a = \left| \frac{R_S}{R_S + R_D} \right|$$

$R_S > 0$ and $R_D > 0$ ➡ a<1

Far from the transition, the thermal transistor does not work!

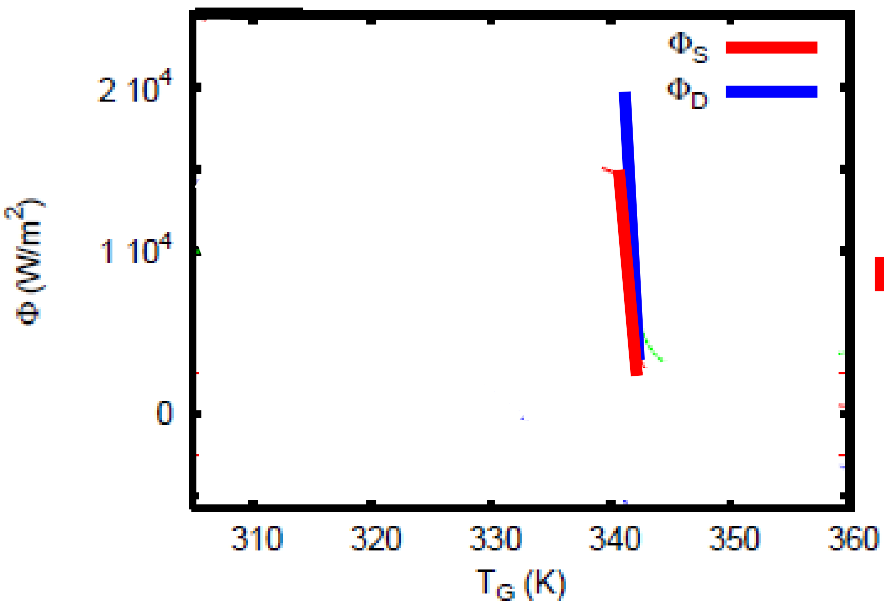
A near-field thermal transistor

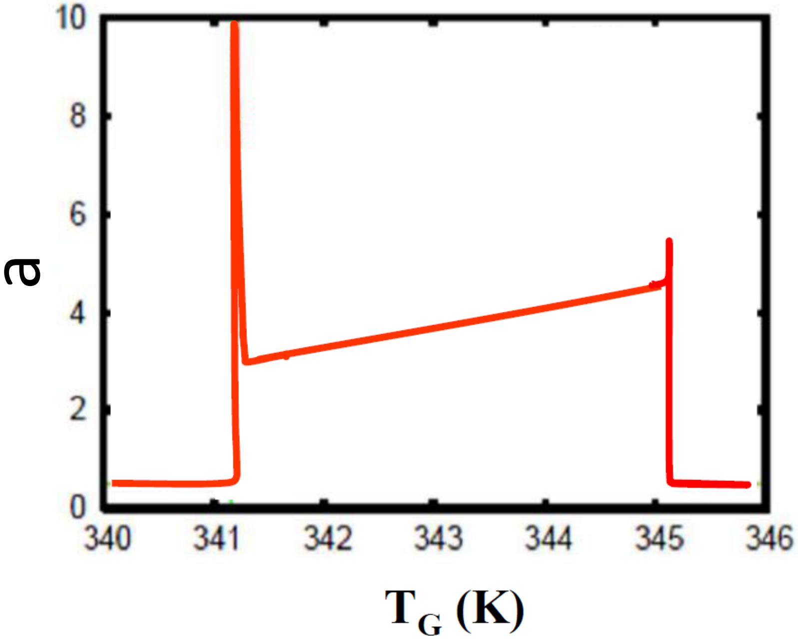
Operating modes :

$R_S > 0$ and $R_D < 0$ Negative differential Resistance

1-Thermal switch
2-Flux modulation
3-Flux amplification

$$a = \left| \frac{R_S}{R_S + R_D} \right| > 1$$

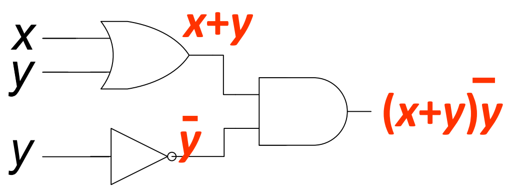




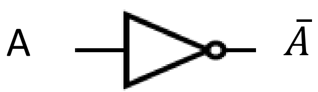
Amplification requires a negative differential resitance

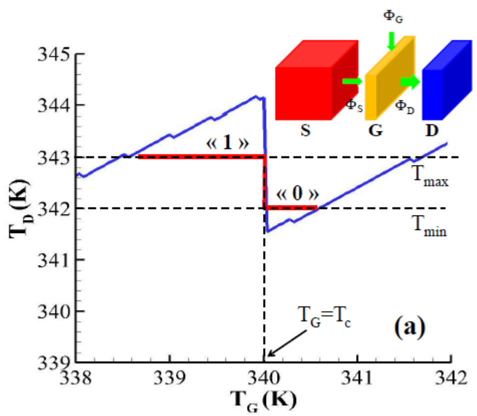
D-Boolean treatment of information

Making logical operations...



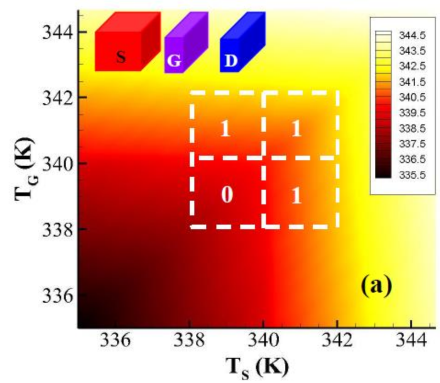
NOT





In	Out
0	1
1	0

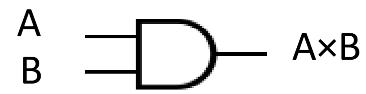
OR

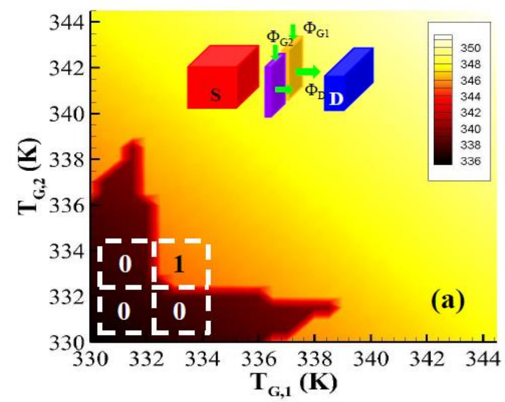


In	In	Out
0	0	0
0	1	1
1	0	1
1	1	1

PRB **94**, 241401(R) (2016)

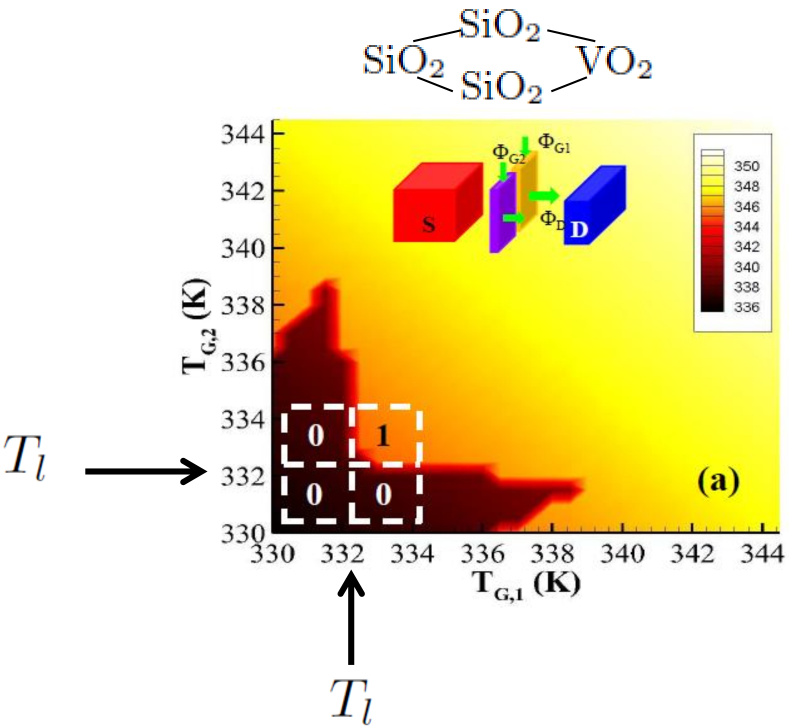
AND

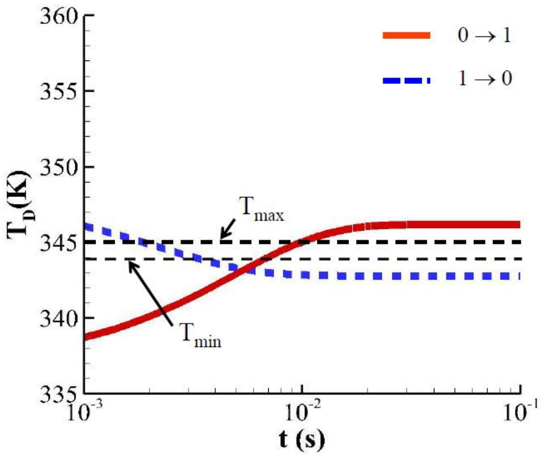




In	In	Out
0	0	0
0	1	0
1	0	0
1	1	1

AND gate and its operating mode



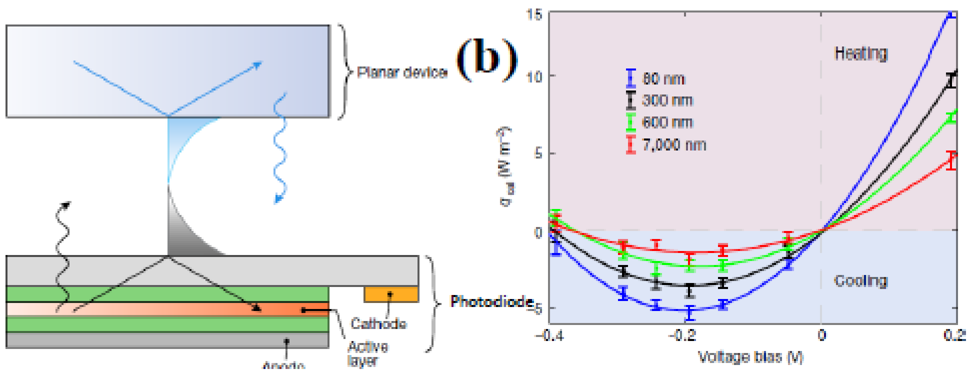


Lattice relaxation ~ ms

Inputs		Output
T_{G1}	T_{G2}	T_D
$T_{G1}<T_l \leftrightarrow 0$	$T_{G2}<T_l \leftrightarrow 0$	$T_D<T_{min} \leftrightarrow 0$
$T_{G1}<T_l \leftrightarrow 0$	$T_{G2}>T_l \leftrightarrow 1$	$T_D<T_{min} \leftrightarrow 0$
$T_{G1}>T_l \leftrightarrow 1$	$T_{G2}<T_l \leftrightarrow 0$	$T_D<T_{min} \leftrightarrow 0$
$T_{G1}>T_l \leftrightarrow 1$	$T_{G2}>T_l \leftrightarrow 1$	$T_D>T_{max} \leftrightarrow 1$

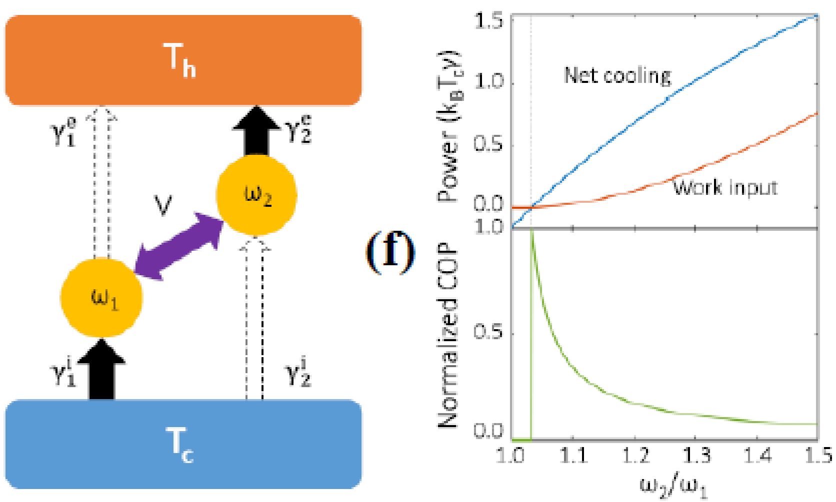
Many-body heat pumping
In driven systems

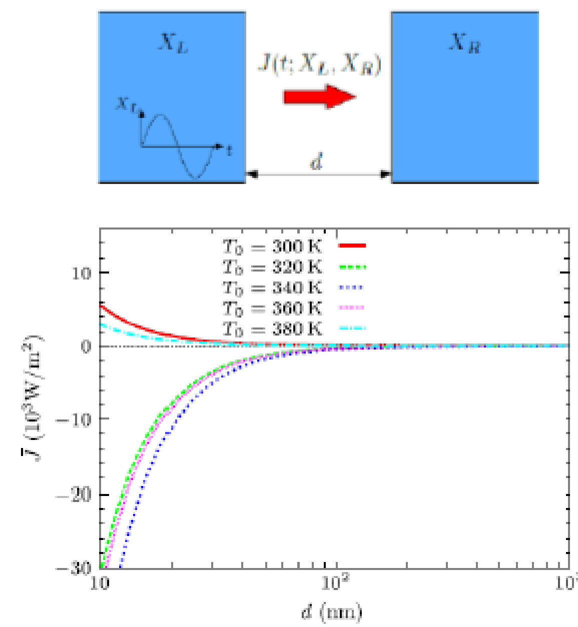
Two-body radiative cooling



Chen et al. Phys. Rev. B 91, 134301 (2015)

Zhu et al. Nature 566, 239-244 (2019)



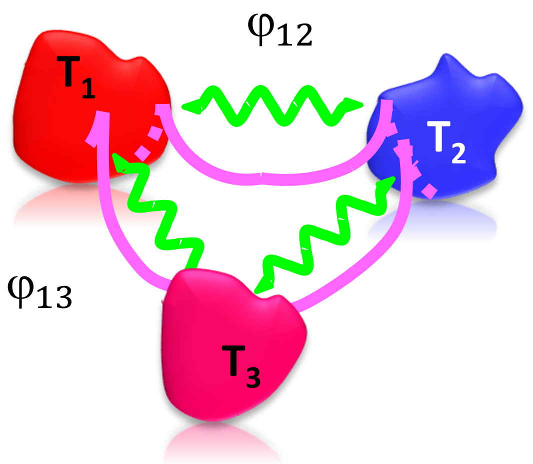


Buddhiraju et al. PRL. 124, 077402 (2020)

Latella et al. PRL, 121, 023903 (2018)

See Latella et al. Opt. Express (2021) for a review

Many-body radiative shuttling



Net flux on body 1:

$$\varphi_1 = \sum_j \varphi_{1j}(p_1, p_2)$$

with the adiabatic (slow) modulation

$$\begin{cases} p_1 = \bar{p}_1 + \delta_1 \,\mathrm{Sin}(\omega t) \\ p_2 = \bar{p}_2 + \delta_2 \,\mathrm{Sin}(\omega t + \theta) \end{cases} \qquad p_i = T_i, \mu_i \,\ldots.$$

$$\varphi_{1j}(p_1,p_2) = \varphi_{1j}(\bar{p}_1, \bar{p}_1) + (\delta_1 \,\mathrm{Sin}(\omega t), \delta_2 \,\mathrm{Sin}(\omega t + \theta)) \begin{pmatrix} \frac{\partial \varphi_{1j}}{\partial p_1} \\ \frac{\partial \varphi_{1j}}{\partial p_2} \end{pmatrix}$$

$$+ \frac{1}{2} (\delta_1 \,\mathrm{Sin}(\omega t), \delta_2 \,\mathrm{Sin}(\omega t + \theta)) \begin{pmatrix} \frac{\partial^2 \varphi_{1j}}{\partial p_1^2} & \frac{\partial^2 \varphi_{1j}}{\partial p_1 \partial p_2} \\ \frac{\partial^2 \varphi_{1j}}{\partial p_2 \partial p_1} & \frac{\partial^2 \varphi_{1j}}{\partial p_2^2} \end{pmatrix} \begin{pmatrix} \delta_1 \,\mathrm{Sin}(\omega t) \\ \delta_2 \,\mathrm{Sin}(\omega t + \theta) \end{pmatrix}$$

Average flux :

$$\langle \varphi_1 \rangle = \frac{1}{T} \int_0^T \varphi_1(t)\,dt = \varphi_1(\bar{p}_1, \bar{p}_2) + \frac{1}{4} (\delta_1, \delta_2) \begin{pmatrix} \frac{\partial^2 \varphi_1}{\partial p_1^2} & \frac{\partial^2 \varphi_1}{\partial p_1 \partial p_2} Cos \\ \frac{\partial^2 \varphi_1}{\partial p_2 \partial p_1} Cos\,\theta & \frac{\partial^2 \varphi_1}{\partial p_2^2} \end{pmatrix} \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix}$$

Many-body radiative shuttling

$$\langle\varphi_1\rangle=\varphi_1(\bar{p}_1,\bar{p}_1)+\frac{1}{4}(\delta_1,\delta_2)\underbrace{\begin{pmatrix}\frac{\partial^2\varphi_1}{\partial {p_1}^2} & \frac{\partial^2\varphi_1}{\partial p_1\partial p_2}Cos\\ \frac{\partial^2\varphi_1}{\partial p_2\partial p_1}Cos\,\theta & \frac{\partial^2\varphi_1}{\partial {p_2}^2}\end{pmatrix}}_{A}\begin{pmatrix}\delta_1\\ \delta_2\end{pmatrix}$$

→ The spectrum (real) of A defines the pumping effect

Without dephasing (Cos θ=1) :

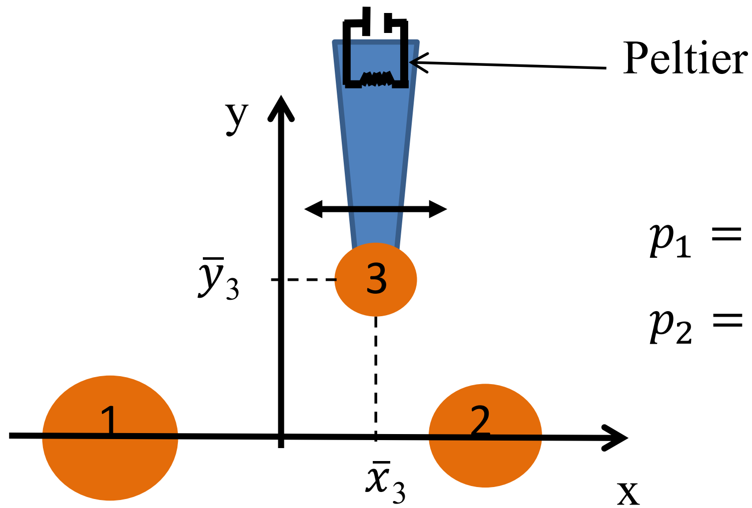
if φ1 is convex → No pumping

if φ1 is concave → Pumping (classical shuttling)

With dephasing (Cos θ≠1) : See PRL, 121, 023903 (2018)

A is negative definite → Pumping

Example



$p_1 = T_3 = T_{eq} + \Delta T\ \mathrm{Sin}(\omega t)$

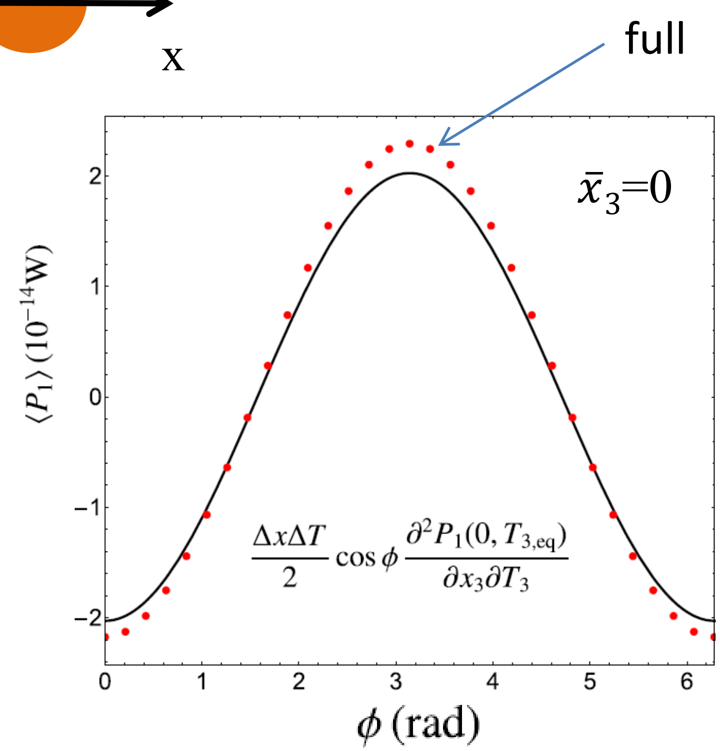
$p_2 = x_3 = \bar{x}_3 + \Delta\, x\ \mathrm{Sin}(\omega t + \phi)$

$T_{eq} = T_1 = T_2$ ⇨ $P_1(T_{eq}, \bar{x}_3) = 0$

Average power:

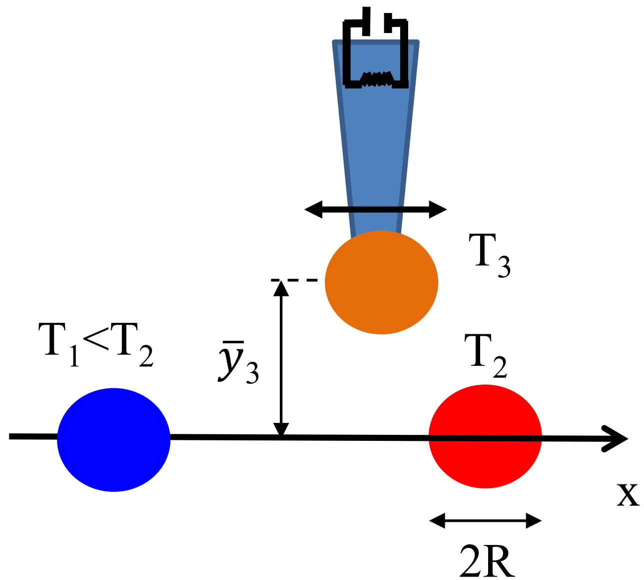
$$\langle P_1 \rangle \simeq \frac{\Delta T}{2}\left(\Delta x \frac{\partial^2 P_1}{\partial x_3 \partial T_3}\cos\phi + \frac{\Delta T}{2}\frac{\partial^2 P_1}{\partial T_3^2}\right)$$

Positive
if no NDTR



PRB **101**, 165435 (2020)

Control of the direction of flux



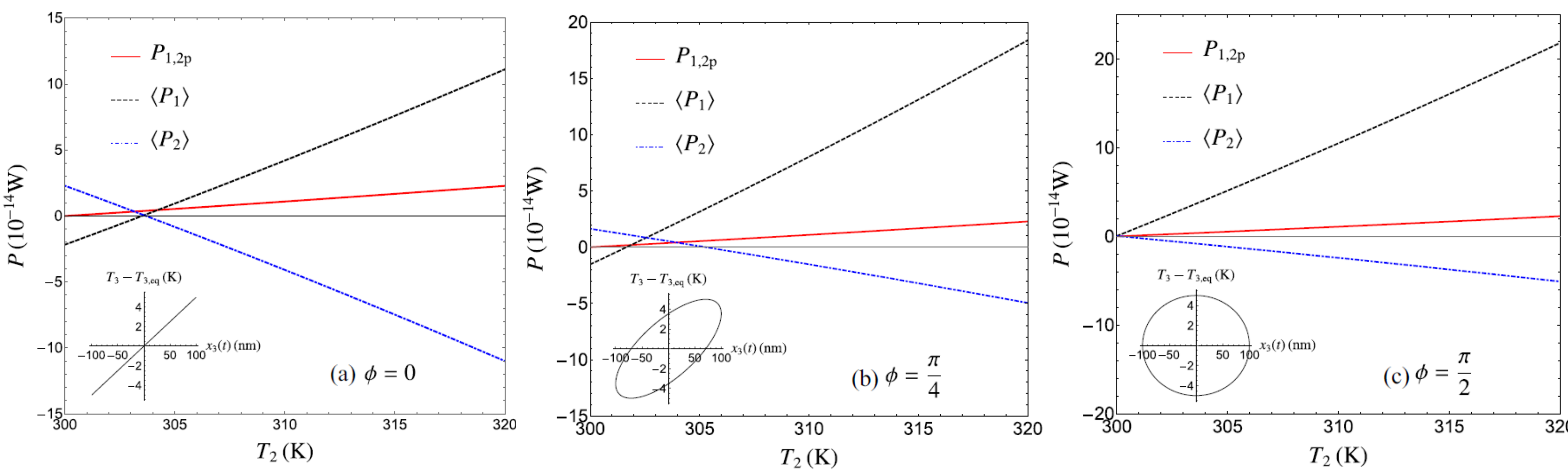
T_1=300 K

ΔT =5 K

Δx =100 nm

$\bar{y}_3$=600 nm

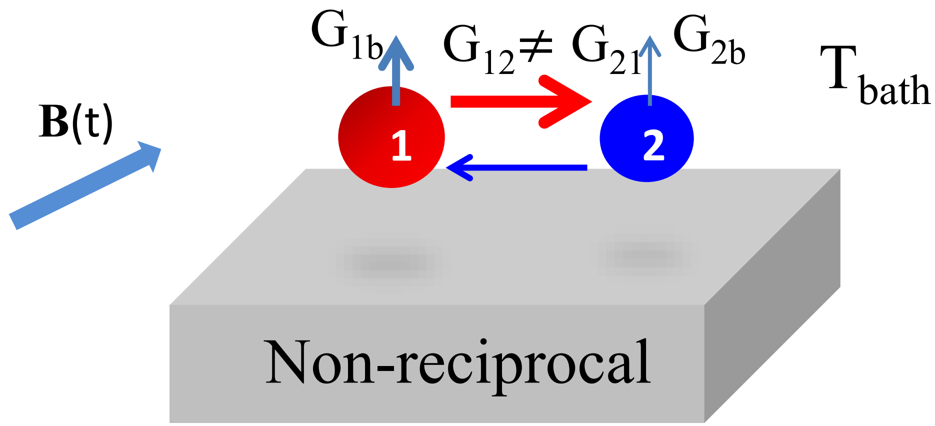
2R=100 nm



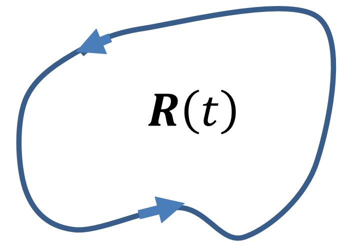
PRB **101**, 165435 (2020)

Geometric heat pumping in non-reciprocal systems

Heat pumping in non-Hermitian systems



Cycling of an external field



$\boldsymbol{R} = (R_1, \dots, RN)$

Energy (master) equation:

$$\partial_t \bar{T} = \hat{G}(\mathrm{R(t)})\, \bar{T} + \bar{S}$$

$$\hat{G} = \begin{pmatrix} -(G_{12} + G_{1b}) & G_{12} \\ G_{21} & -(G_{21} + G_{2b}) \end{pmatrix} \qquad \bar{S} = \begin{pmatrix} G_{1b} T_{bath} \\ G_{2b} T_{bath} \end{pmatrix} \qquad \bar{T} = \begin{pmatrix} T_1 \\ T_2 \end{pmatrix}$$

Thermal state:

$\bar{T} = T_{bath} \begin{pmatrix} 1 \\ 1 \end{pmatrix} + \sum c_i(t) e^{\gamma_{di}(t)} \varphi_i(t)$ into the master equation

⇓ (+ adiabatic approximation)

$$\bar{T} = T_{bath} \begin{pmatrix} 1 \\ 1 \end{pmatrix} + \sum \alpha_i e^{\gamma_{di}(t)} e^{\gamma_{gi}(t)} \varphi_i(t)$$

φ_i, χ_i eigenvectors of $\hat{G}$ and ${}^t\hat{G}$

$\gamma_{di}(t) = \int_0^t \lambda_i(\tau) d\tau$ — dynamical phase

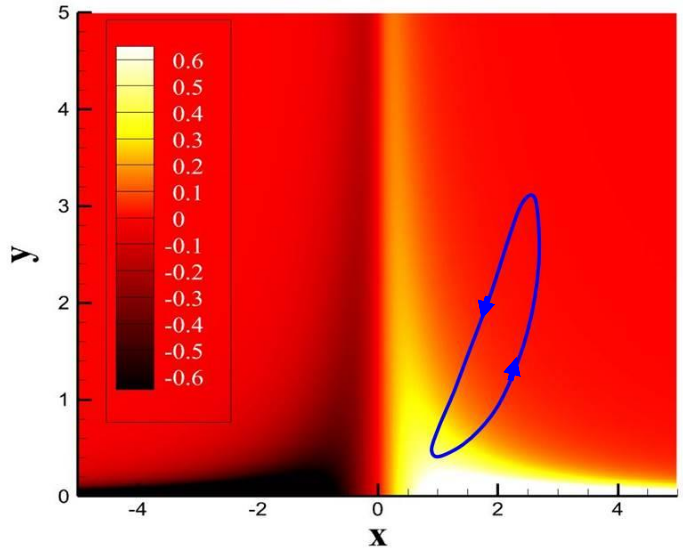
$\gamma_{gi}(t) = -\int_0^t (\chi_i, \dot{\varphi}_i) d\tau$ — geometric phase

Geometric pumping in non-Hermitian systems

Accumulated geometric phase over one cycle: $\gamma_{gi}=-\int_0^T (\chi_i, \dot{\varphi}_i) d\tau$

Setting $x_i = \frac{G_{12}}{G_{21}+G_{2b}+\lambda_i}$ and $y_i = \frac{G_{12}}{G_{21}}$ we get

$$\gamma_{gi}=-\int_0^T \frac{x_i \dot{x}_i y_i}{1+x_i^2 y_i} d\tau$$



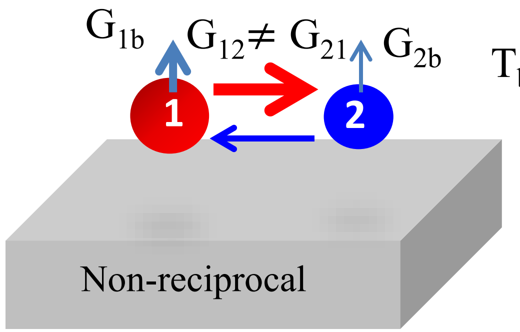
$$G_{1b} = g + \delta g\ Cos(2\pi t/\tau)$$

$$G_{2b} = h + \delta h\ Sin(2\pi t/\tau)$$

$$G_{12} = G + \delta G\ Cos(2\pi t/T)$$

$$G_{21} = G + \delta G\ Sin(2\pi t/T)$$

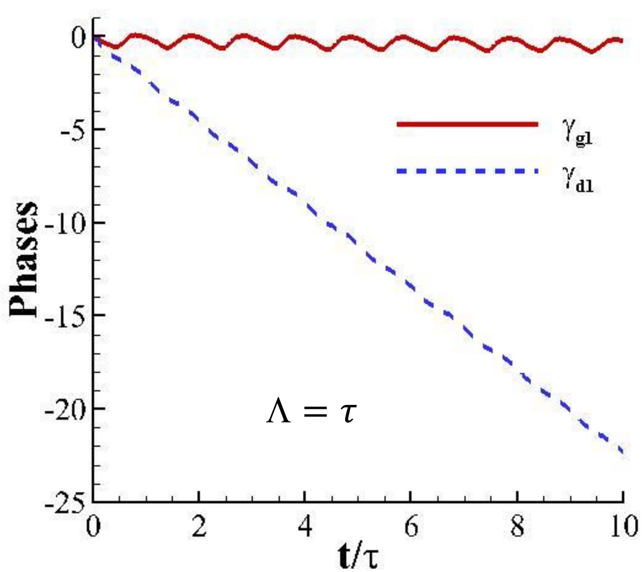
Geometric pumping : an example

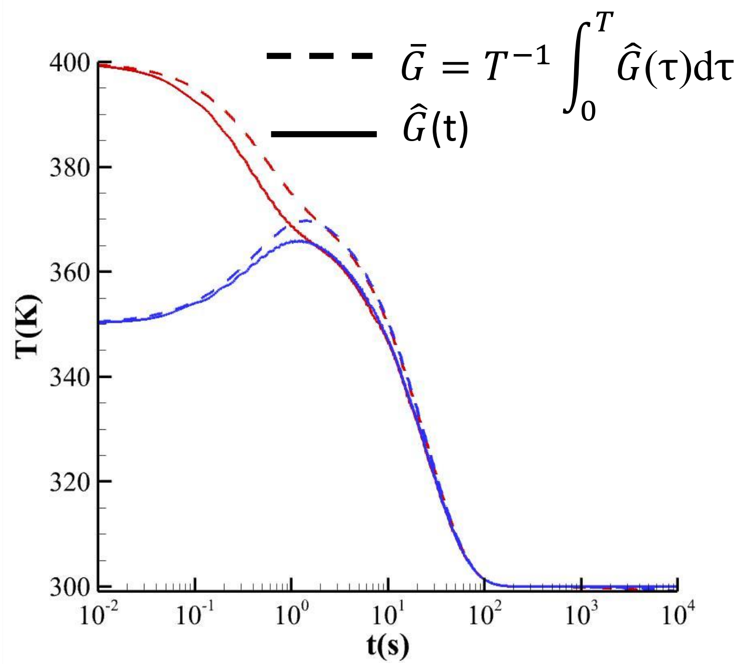


T_{bath}=300 K

$T_1(t=0)=400K$

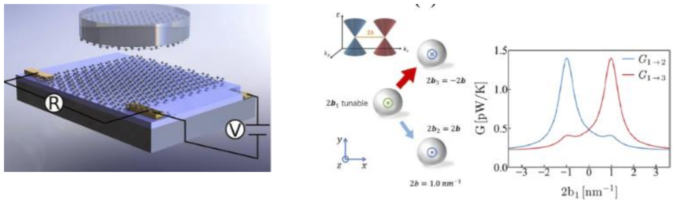
$T_2(t=0)=350K$





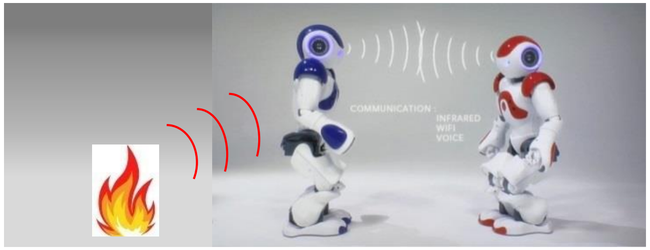
Thermotronic to what for ?

-Thermal management at nanoscale



New functionalities
(splitting, rectification, storage, pumping…)

-Wireless sensors working with heat coming from various systems (people, machines, electric devices…) and used them to trigger specific actions



No battery

-Low-power communication technology for the Internet of Things allowing machine-to-machine communication with heat as well as thermal computing

Computing with heat….but slowly

But…up to now slow operating speed (ms scale)

→ Two dimensional systems (low heat capacity)
Systems far from equilibrium (electrons and phonons at different temperatures)

Acknowledgments

Collaborators

S.A. Biehs (Oldenburg, Germany)

J. C. Cuevas (Madrid, Spain)

C. Henkel (Potsdam, Germany)

K. Joulain (Poitiers, Fr)

A. Rodriguez (Princeton, USA)

R. Messina (LCF, Palaiseau)

Post-doc/PhD students

V. Kubytskyi (LCF, Palaiseau)

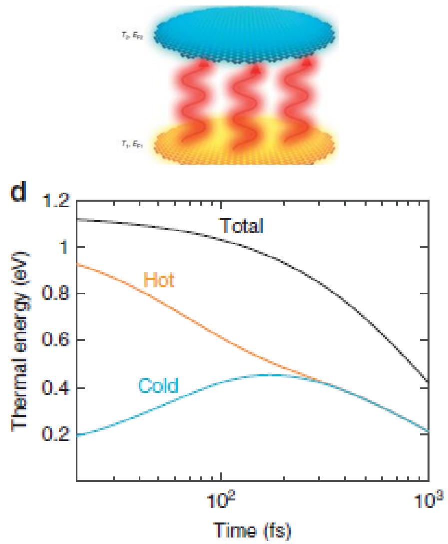
A. Ott (Oldenburg, Germany)

P. S. Venkataram (Princeton, USA)

I. Latella (LCF, Palaiseau)

Thank you!

R. Yu et al., Nature Comm **8**, 2 (2017)



Electronic relaxation ~ ps