Thermotronics: toward the developement of circuits to manage radiative heat flux

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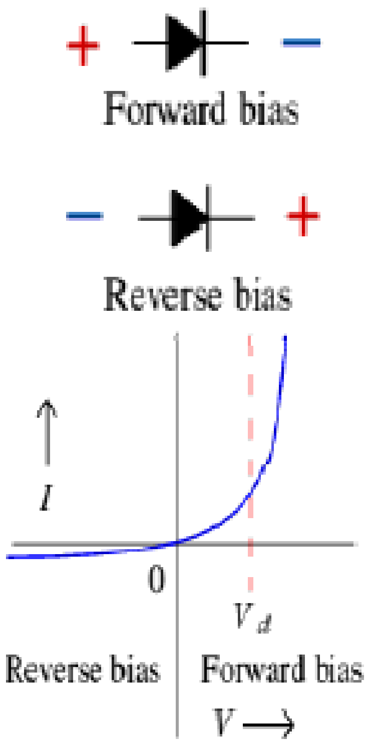
Bad Honnef , 13 April 2016

Historical breakthroughs in electronics

F. Braun
1874

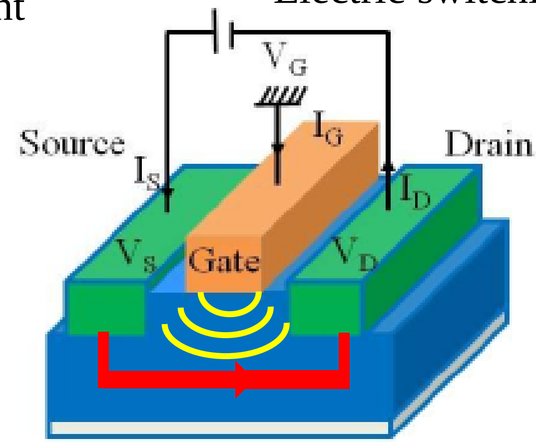
Diode

Perfect rectification of current



Transistor (FET)

Electric switching, modulation and amplification



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

Random access memory (RAM)

Volatile memory

Williams and Kilburn
1946

Question

Are there thermal analogs to electric circuits to manage heat flows with photons as we do with electrons for electric current?

Outline

- **Radiative diode with phase change materials**
- **Thermal transistor in systems with negative differential thermal resistance**
- **Thermal memory with multistable thermal states in many body systems**
- **Heat flux splitting with graphene tuning and photon thermal Hall effect**

Radiative diode

What is the thermal rectification?

Forward: Backward:

Landauer formulation of heat exchanges :

$$\Phi_{F,B} = \int_0^\infty \frac{d\omega}{2\pi} \underbrace{[\Theta(\omega, T_{L,R}) - \Theta(\omega, T_{R,L})]}_{\text{Energy } \hbar\omega \text{ of mode}} \underbrace{\int \frac{d\vec{K}}{(2\pi)^2} \tau_{F,B}(\omega, \vec{K})}_{\text{Probability (efficiency) of transfer}}$$

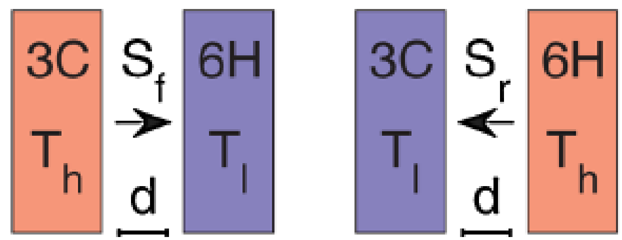
Rectifying the flux requires a dependence of optical properties with the temperature

PRB, 84, 161413, 2011

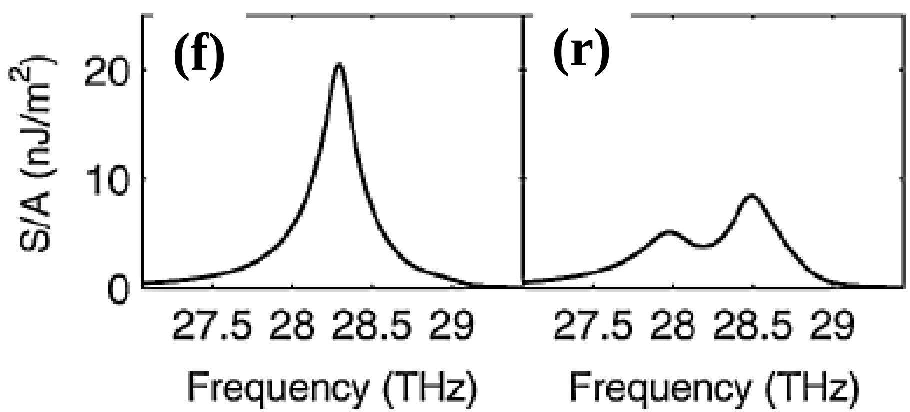
PRL **104,** 154301 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

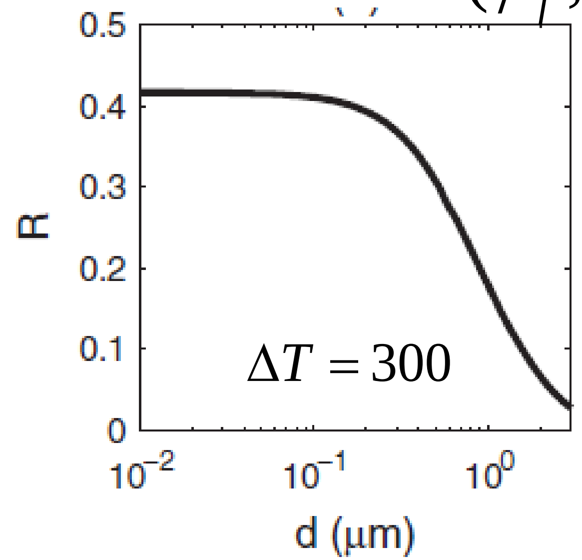
Thermal Rectification through Vacuum

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



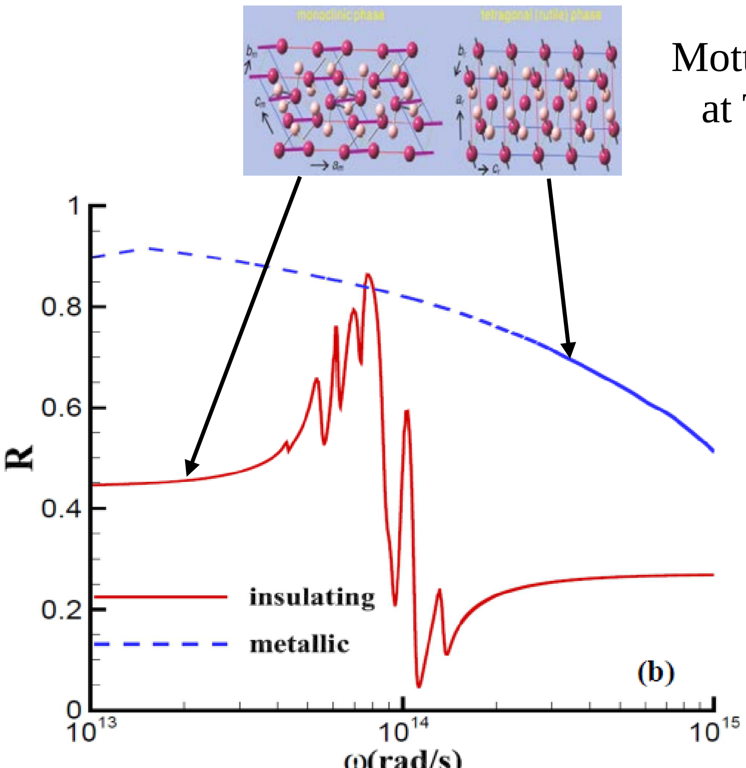
$$R = \frac{|\varphi_f - \varphi_r|}{\max(\varphi_f ; \varphi_r)}$$



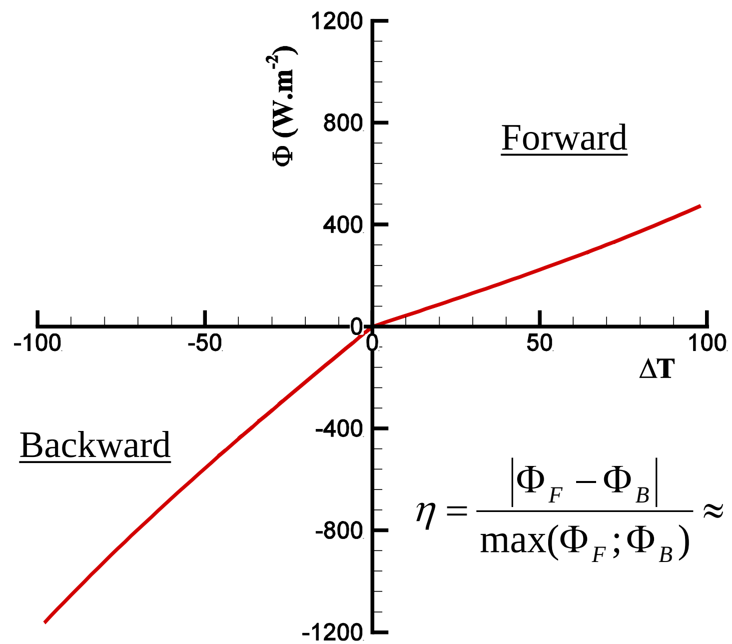


But rectification is not strong enough to make a thermal diode

A phase-change radiative thermal diode



Mott transition at T_c =340K

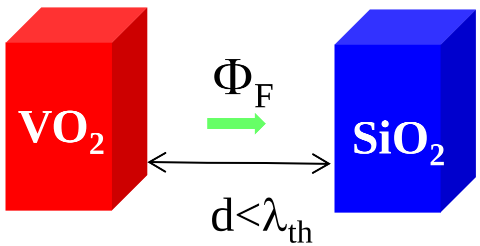


$$\eta = \frac{|\Phi_F - \Phi_B|}{\max(\Phi_F;\Phi_B)} \approx 60\%$$

APL, 103, 191907 (2013)

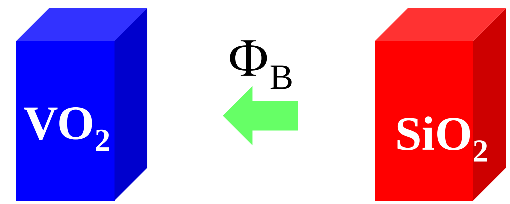
A phase-change radiative thermal diode

Forward ($\Delta T>0$)



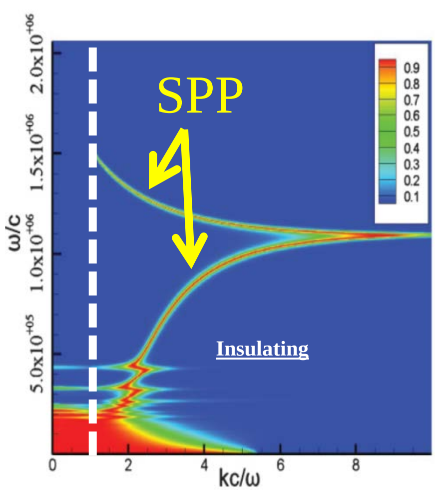
$T_1=T_c+\Delta T$ $T_2=T_c-\Delta T$

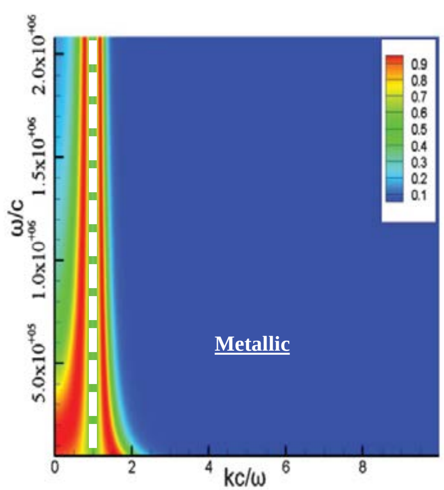
Backward ($\Delta T<0$)

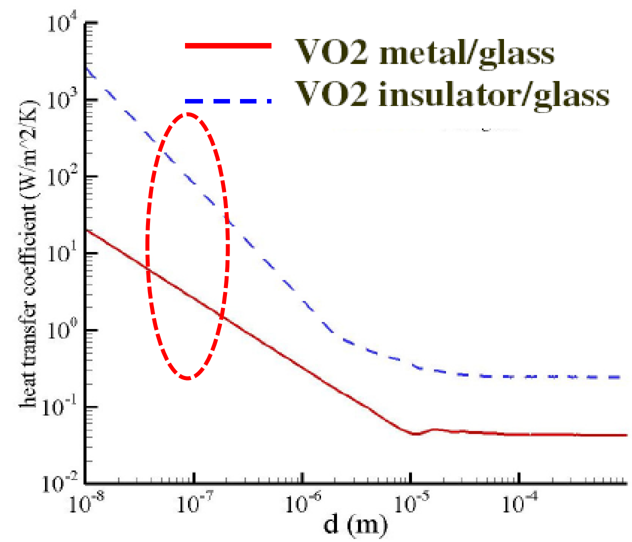


$T_1=T_c-\Delta T$ $T_2=T_c+\Delta T$

Coupling efficiency





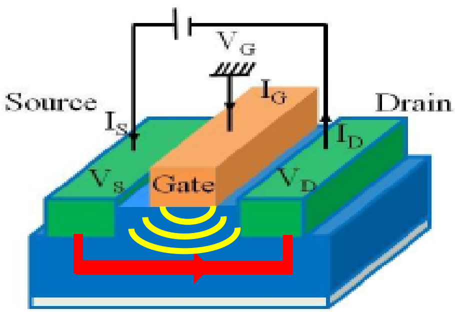


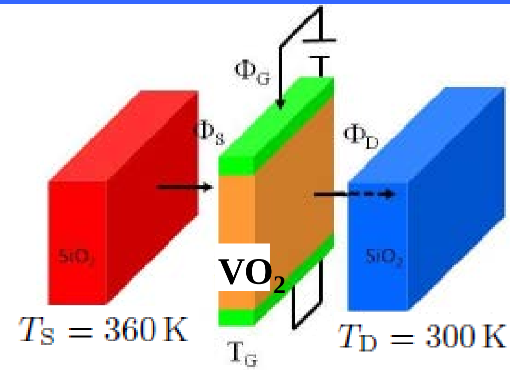
$d<100\ nm$ ➡ $$\eta=\frac{|\Phi_F-\Phi_B|}{\max(\Phi_F;\Phi_B)}>99\%$$

PRB, 83, 201404(R) (2011)

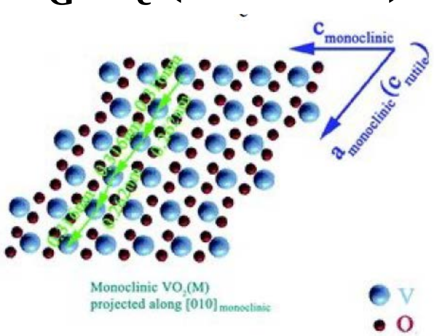
Radiative transistor

A near-field thermal transistor



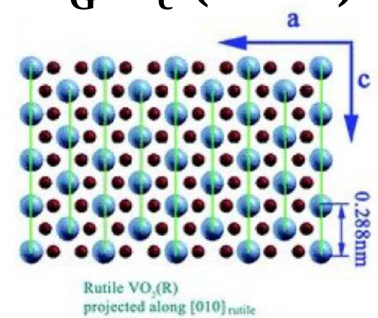


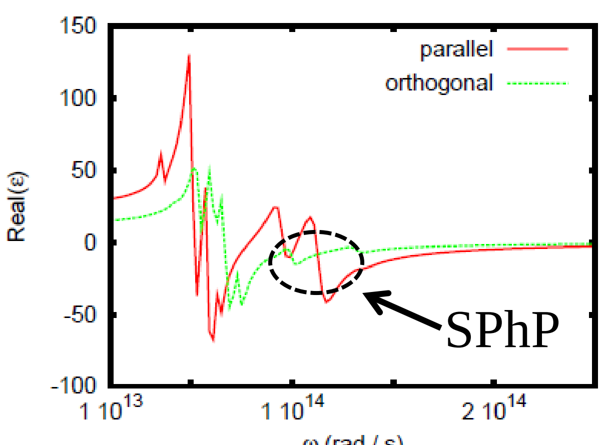
$T_G<T_c$ (insulator)

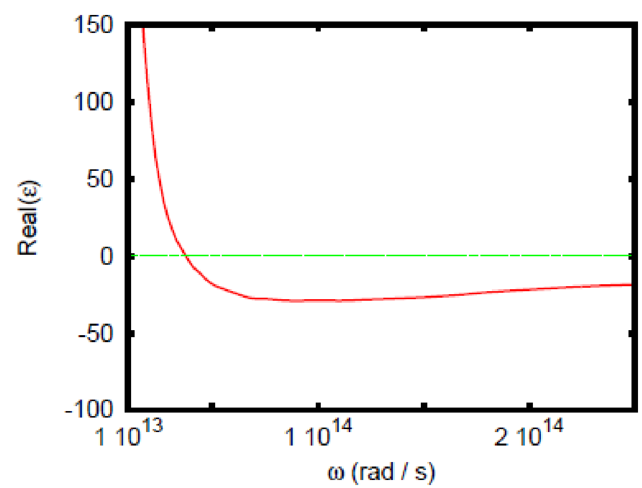


Phase transition
at T_c =341 K

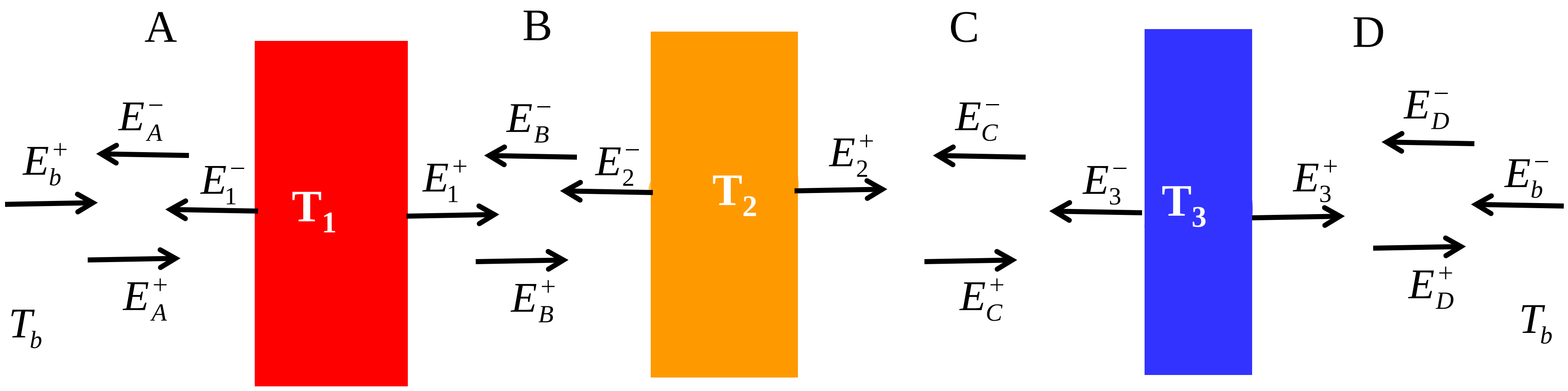
$T_G>T_c$ (metal)







Two and many body radiative heat transfer :



Normal component of Poynting vector:

$$\langle S \rangle . e_z = \langle E \times H \rangle . e_z = \sum_p \int \frac{d^2k}{(2\pi)^2} \sum_{\phi,\phi'} \int_0^\infty \frac{d\omega}{2\pi} F_p^{\phi\phi'}(k,\omega) \langle E_p^{\phi}(k,\omega), E_p^{\phi'}(k,\omega) \rangle$$

From the scattering theory:

$$E_B^+ = E_1^+ + \mathfrak{I}_1^+ E_b^+ + \mathfrak{R}_1^- E_B^-$$
$$E_B^- = E_2^- + \mathfrak{I}_2^- E_C^- + \mathfrak{R}_2^+ E_B^+$$

etc…

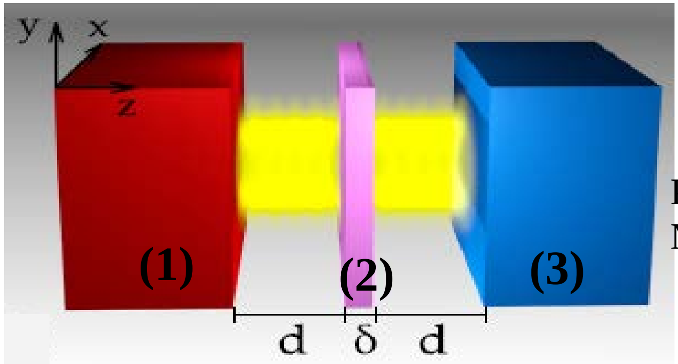
$$\langle E_p^{\phi}(k,\omega), E_p^{\phi'}(k,\omega) \rangle = \sum_{i=1,2,3,b} \alpha_i C_{p,i}^{\phi\phi'}$$

Fluctuation theory:

$$C_{p,i}^{\phi\phi'} \propto n(\omega, T_i)$$

Messina et al. PRA **89**, 052104 (2014)

Heat transfer in a three slab system



PRL, **109**, 244302 (2012) ;
Messina et al. PRA **89**, 052104 (2014)

$$\varphi_3(\omega,d,\delta)=\varphi_3^{(23)}(\omega,d,\delta)+\varphi_3^{(12)}(\omega,d,\delta)$$

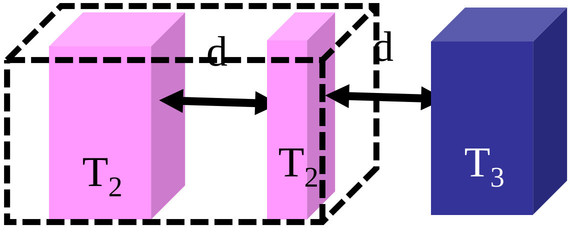
where

$$\varphi_3^{(23)}=\hbar\omega\sum_p\int\frac{d^2k}{(2\pi)^2}[n(\omega,T_2)-n(\omega,T_3)]\tau_p^{(23)}(\omega,k,d,\delta)$$

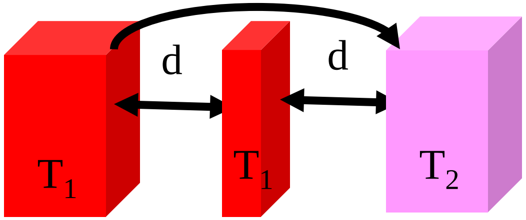
$$\varphi_3^{(12)}=\hbar\omega\sum_p\int\frac{d^2k}{(2\pi)^2}[n(\omega,T_1)-n(\omega,T_2)]\tau_p^{(12)}(\omega,k,d,\delta)$$

$$\tau_p^{(23)}=\frac{4\,\mathrm{Im}(\rho_{12,p}(\delta))\,\mathrm{Im}(\rho_{3,p})e^{-2\,\mathrm{Im}(k_z)d}}{\left|1-\rho_{12,p}(\delta)\rho_{3,p}e^{-2\,\mathrm{Im}(k_z)d}\right|^2}$$

$$\tau_p^{(12)}=\frac{4\left|t_{2,p}(\delta)\right|^2\,\mathrm{Im}(\rho_{1,p})\,\mathrm{Im}(\rho_{3,p})e^{-4\,\mathrm{Im}(k_z)d}}{\left|1-\rho_{12,p}(\delta)\rho_{3,p}e^{-2\,\mathrm{Im}(k_z)d}\right|^2\left|1-\rho_{1,p}\rho_{2,p}(\delta)e^{-2\,\mathrm{Im}(k_z)d}\right|^2}$$



2 body exchange between
the couple (1,2) at temperature T_2 and (3)

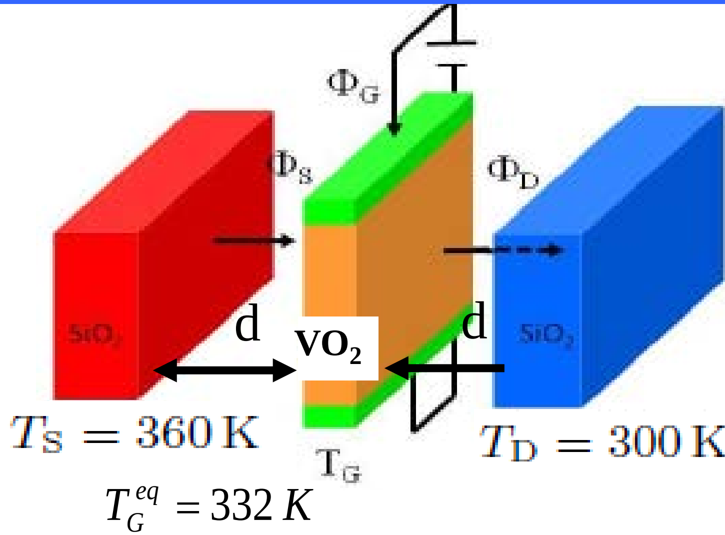


purely 3 body effect

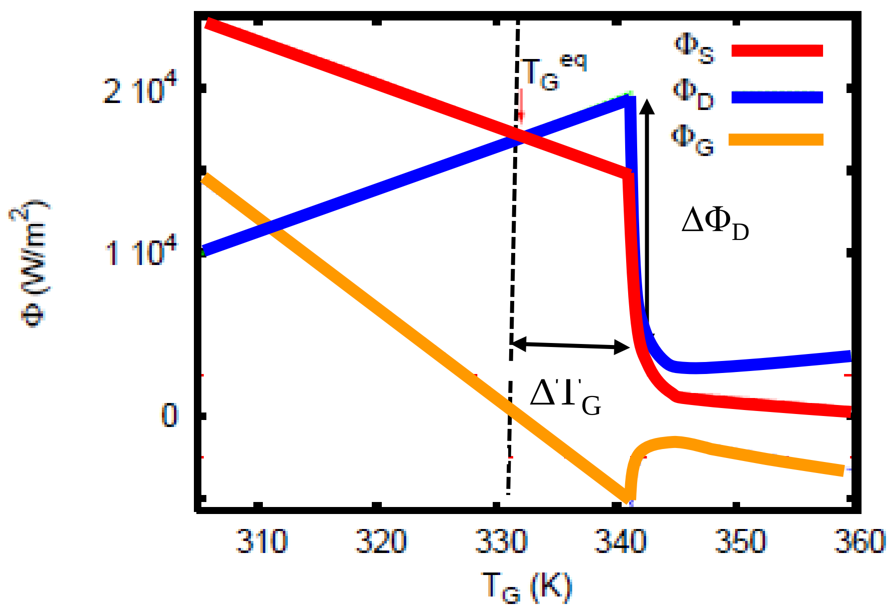
A near-field thermal transistor

Operating modes :

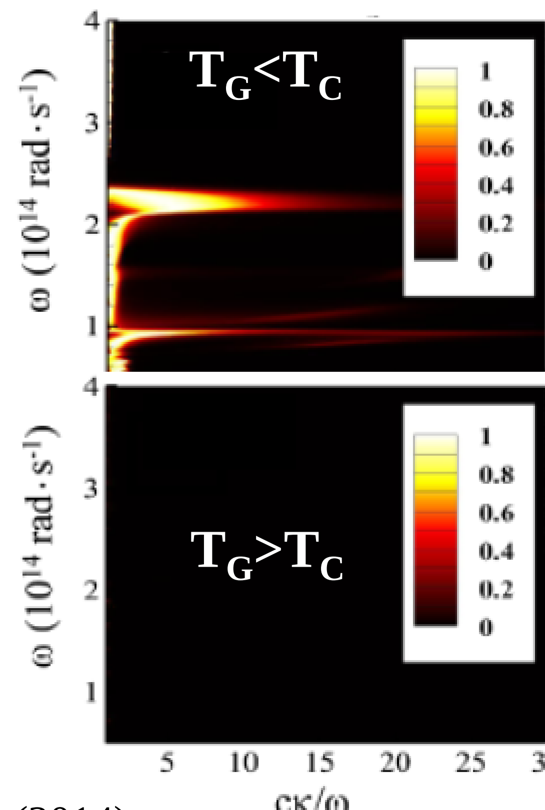
1-Thermal switch
2-Flux modulation
3-Flux amplification



$d << \lambda_W$

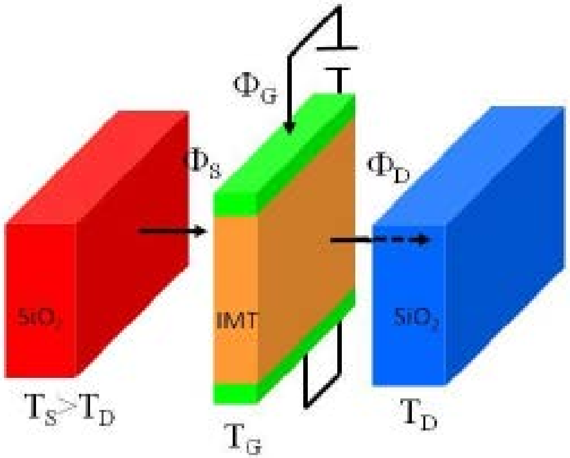


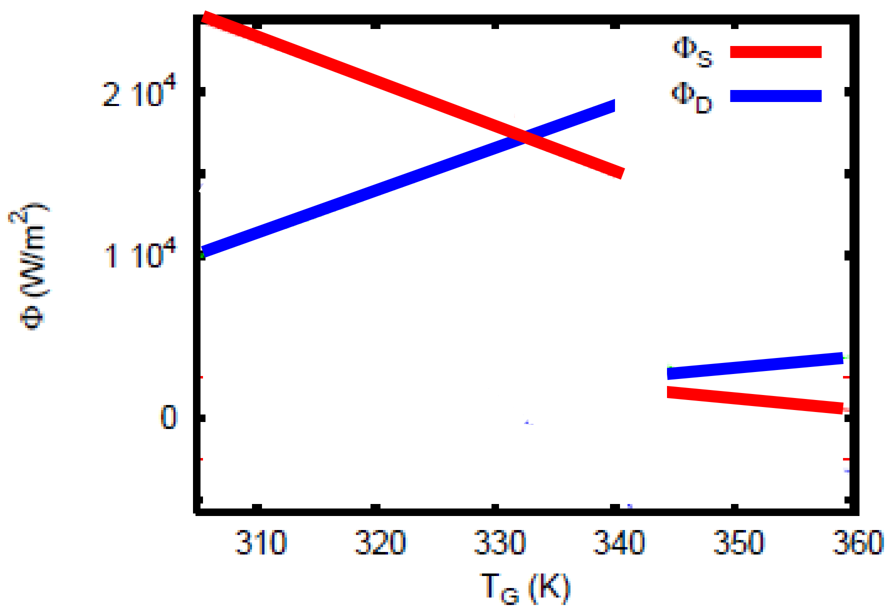
Coupling efficiency:



PRL, **109**, 244302 (2012) ;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 :

$$R_S = -\left(\frac{\partial \Phi_S}{\partial T_G}\right)^{-1}$$

$$R_D = \left(\frac{\partial \Phi_D}{\partial T_G}\right)^{-1}$$

$$\Rightarrow \quad a = \left|\frac{R_S}{R_S + R_D}\right|$$

$R_S > 0$ and $R_D > 0$ ➡ a<1

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

A near-field thermal transistor

<u>Operating modes</u> :

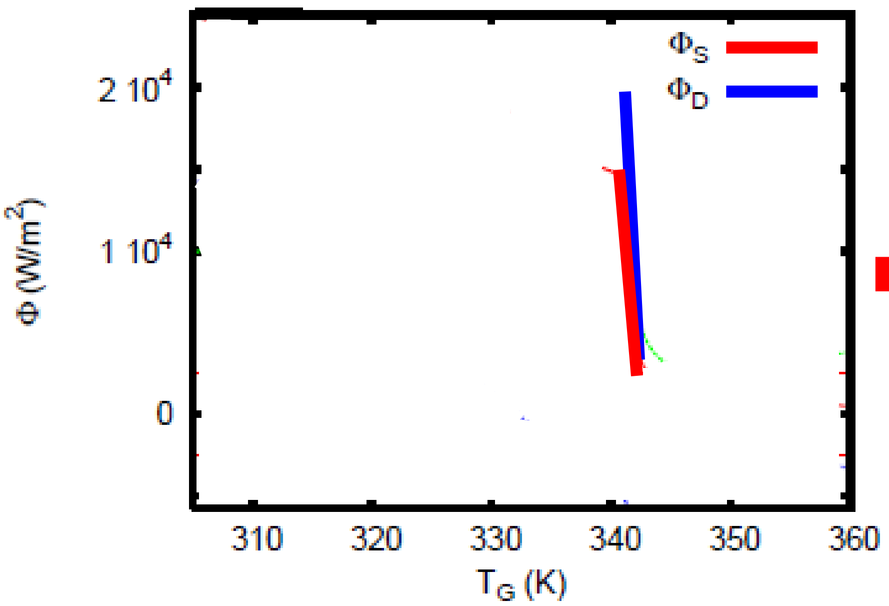
$R_S > 0$ and $R_D < 0$ Negative differential Resistance

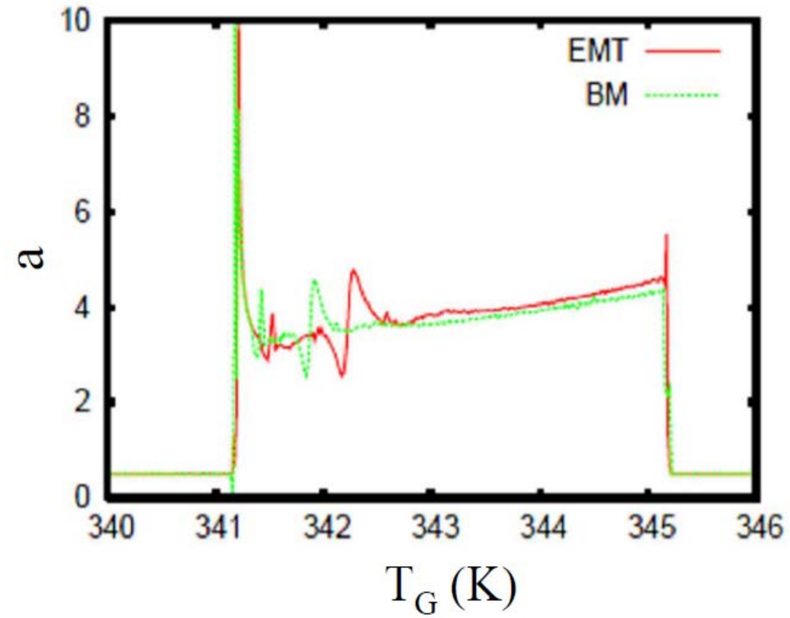
$$a = \left| \frac{R_S}{R_S + R_D} \right| > 1$$

1-Thermal switch

2-Flux modulation

3-Flux amplification



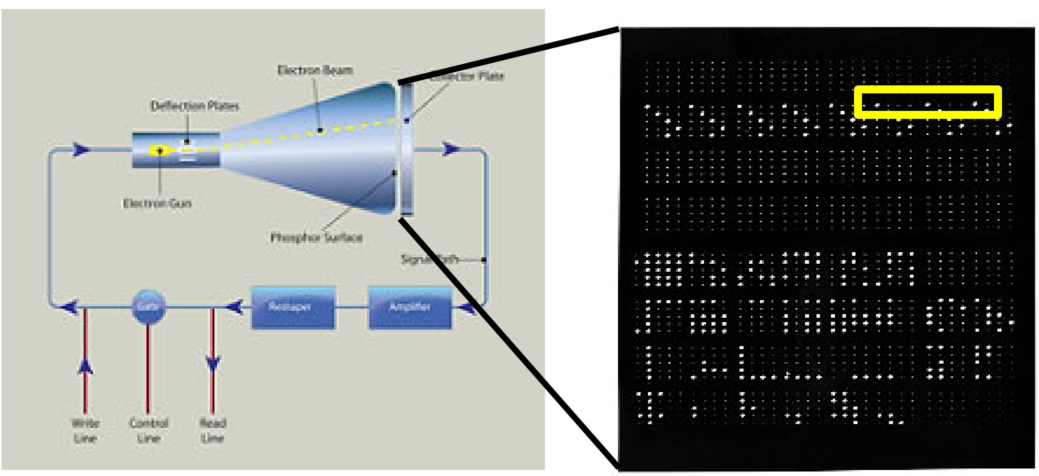


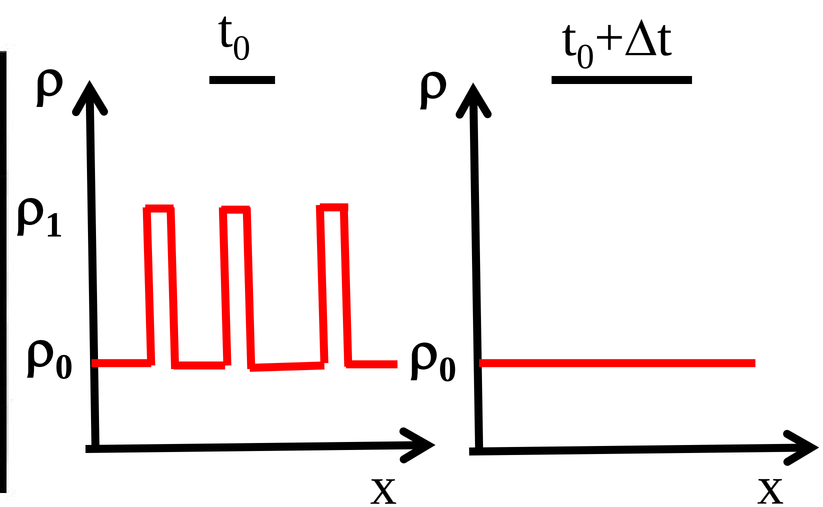
Amplification requires a negative differential resitance

Radiative memory

The first volatile memory

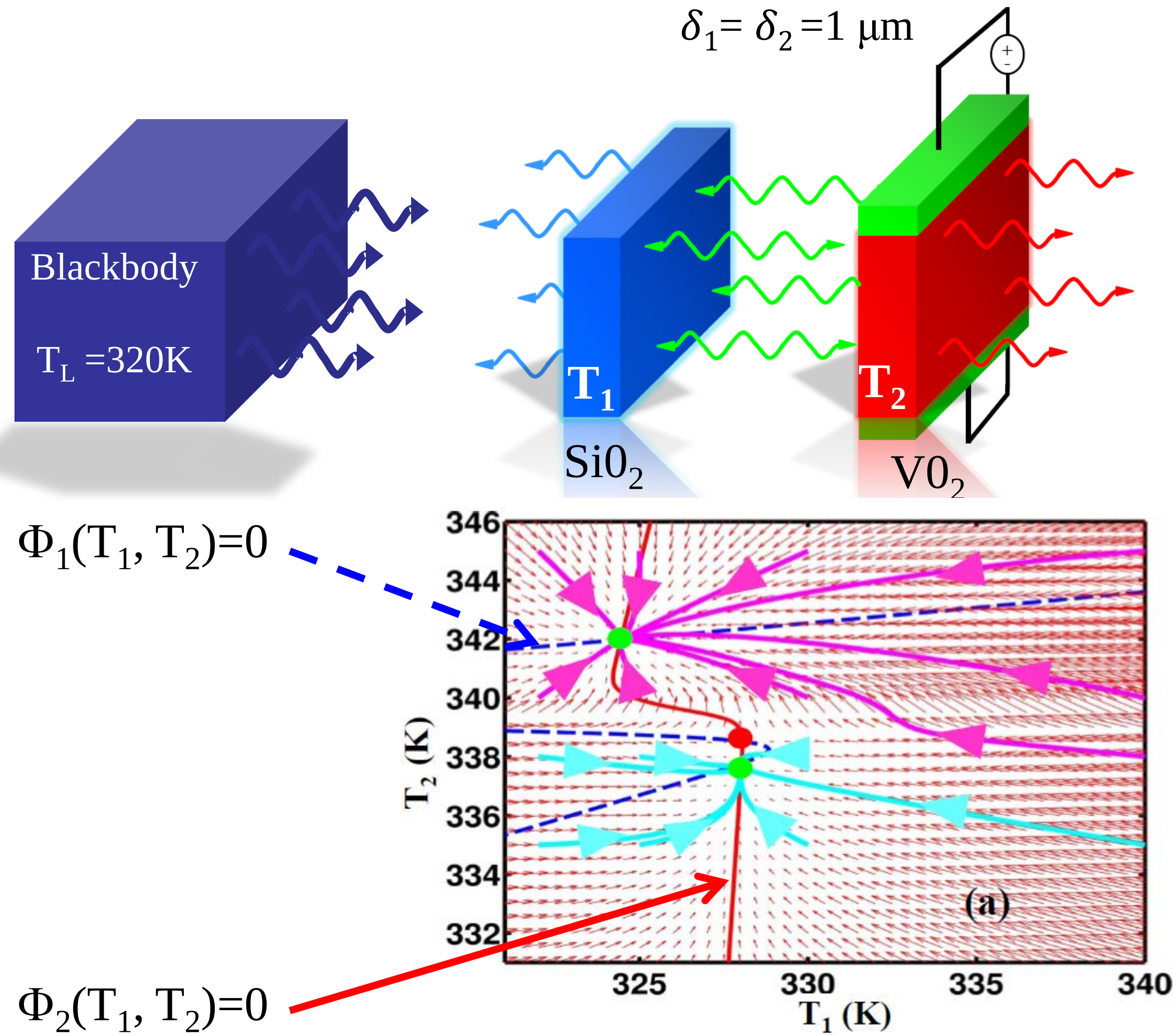
Williams and Kilburn
1946





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

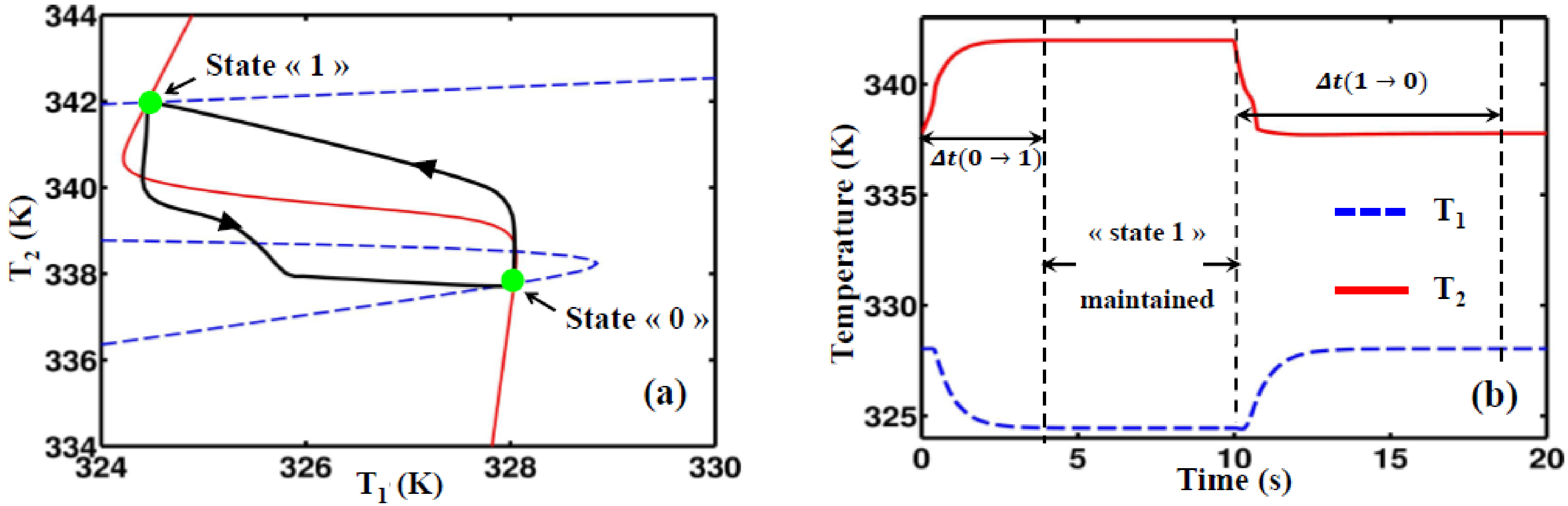
Bistability and thermal memory



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

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

Volatile thermal memory



Writing of state « 1 »

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

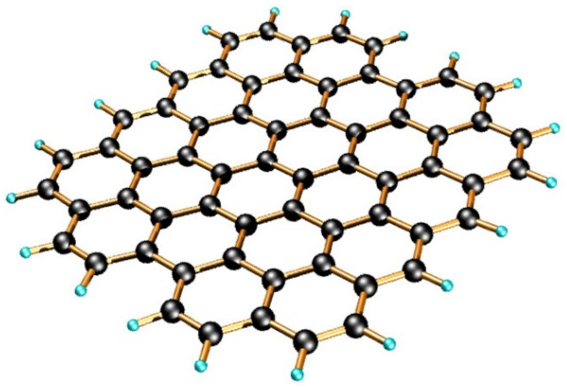
Writing of state « 0 »

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

The thermal states are permanent while both baths radiate

Active splitting of heat flux

Near-field heat splitter

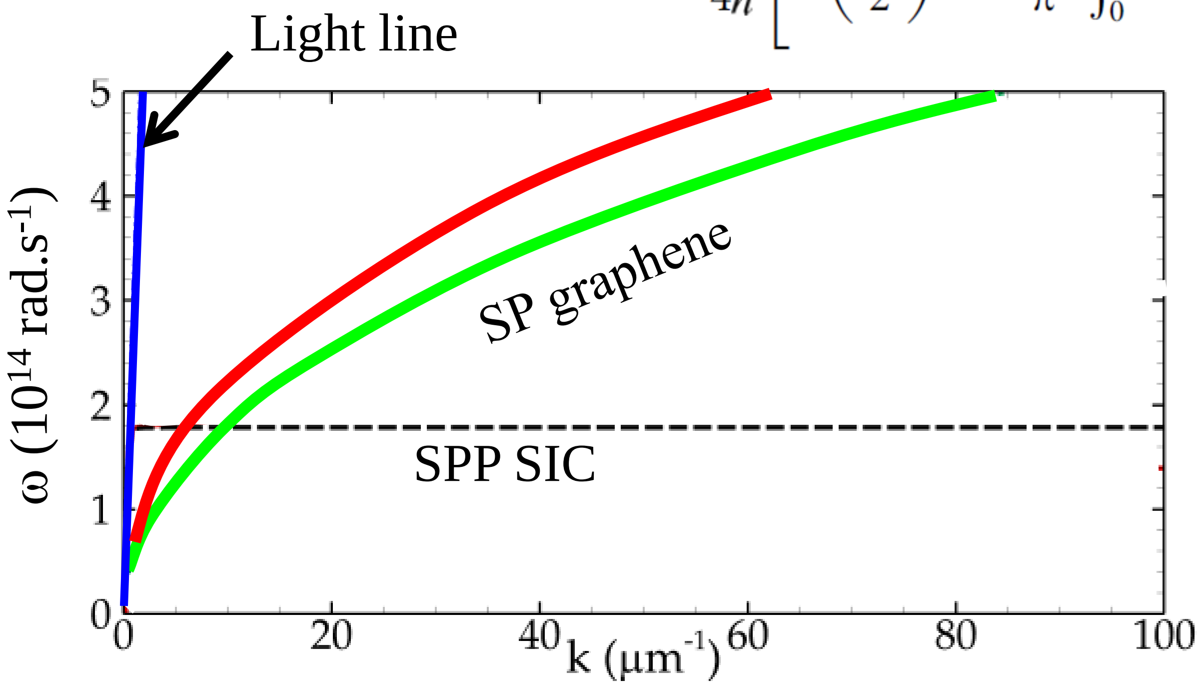


Electronic conductivity :

$$\sigma = \sigma_D + \sigma_I$$

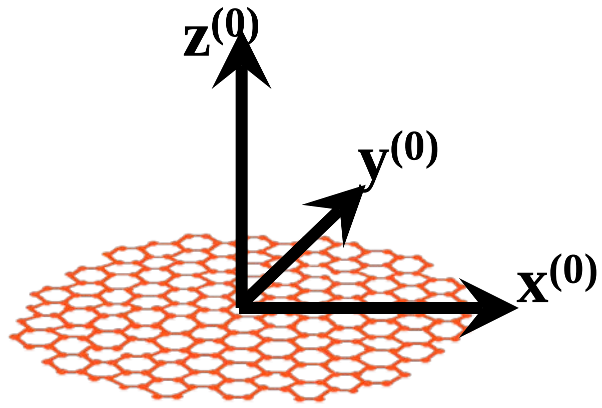
$$\sigma_D(\omega) = \frac{i}{\omega + \frac{i}{\tau}} \frac{2e^2 k_B T}{\pi\hbar^2} \log\left(2\cosh\frac{\mu}{2k_B T}\right)$$

$$\sigma_I(\omega) = \frac{e^2}{4\hbar}\left[G\left(\frac{\hbar\omega}{2}\right) + i\frac{4\hbar\omega}{\pi}\int_0^{+\infty}\frac{G(\xi) - G\left(\frac{\hbar\omega}{2}\right)}{(\hbar\omega)^2 - 4\xi^2}d\xi\right]$$



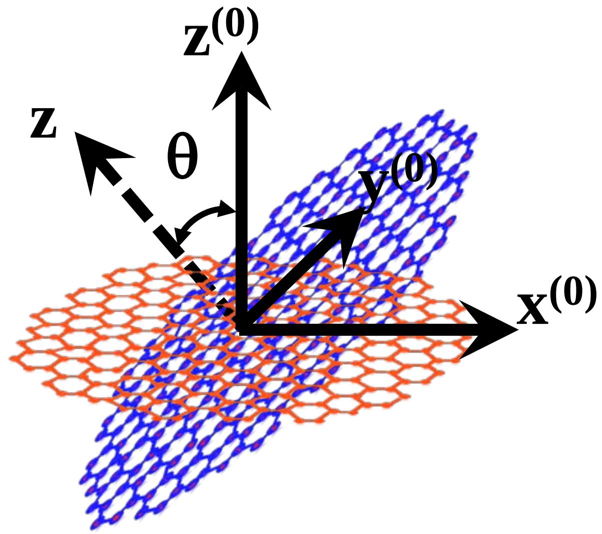
Geim et al. PRB, 78, 085432 (2008); Falkovsky J. Phys. Conf. Ser. **129**, 012004 (2008)

Near-field heat splitter



Thongrattanasiri et al. PRL. 108, 047401 (2012).

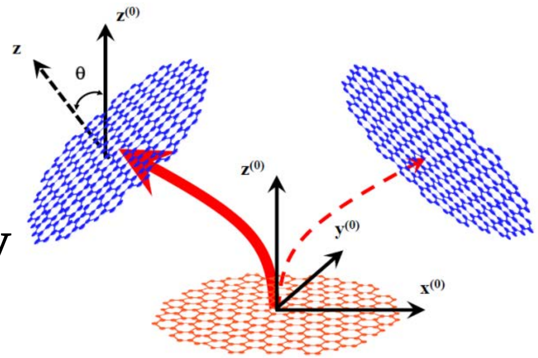
$$\bar{\bar{\alpha}}^{0} = \begin{pmatrix} \alpha_i & 0 & 0 \\ 0 & \alpha_i & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{with} \quad \alpha_i(\omega) = 3\frac{c^3\kappa_{r,i}}{2\omega_{p,i}^2}\frac{1}{\omega_{p,i}^2 - \omega^2 - i\kappa_i\omega^3/\omega_{p,i}^2}$$



$$\bar{\bar{\alpha}}^{\,0} = \begin{pmatrix} \alpha_i & 0 & 0 \\ 0 & \alpha_i & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \text{with} \quad \alpha_i(\omega) = 3\frac{c^3\kappa_{r,i}}{2\omega_{p,i}^2}\frac{1}{\omega_{p,i}^2 - \omega^2 - i\kappa_i\omega^3/\omega_{p,i}^2}$$

$$\bar{\bar{\alpha}} = R\bar{\bar{\alpha}}^{\,0}R^{-1}$$ with the rotation matrix R

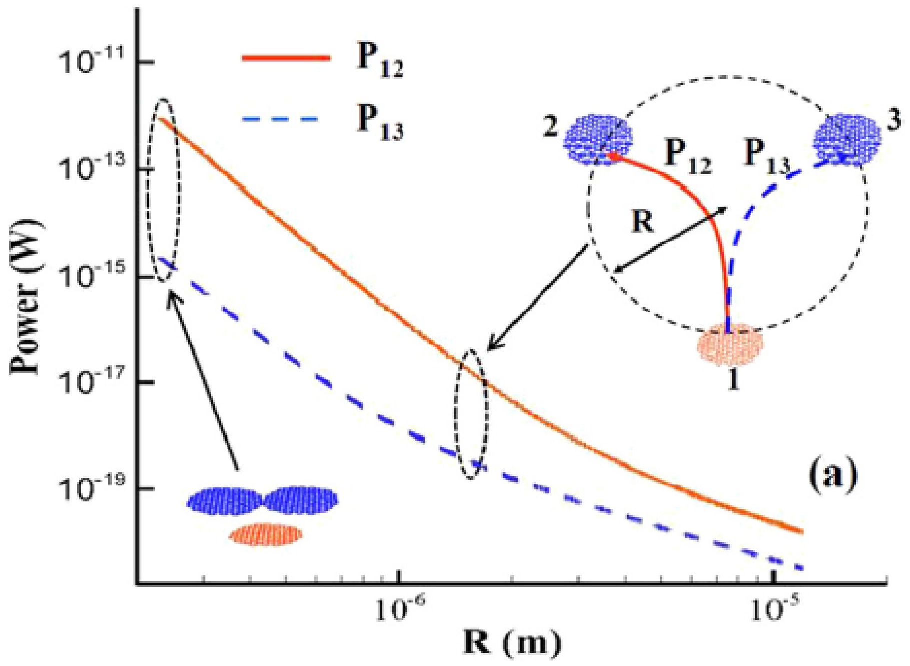
Near-field heat splitter



T_2=273K
E_{F2}=0.1eV

T_3=273K
E_{F3}=0.8eV

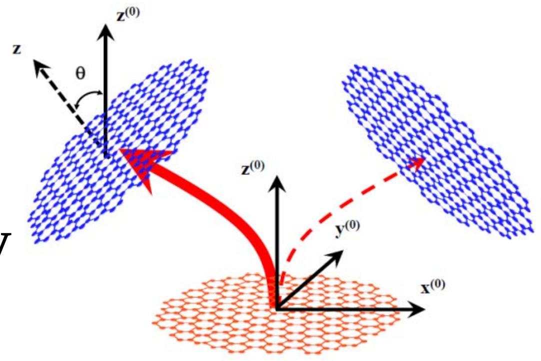
T_1=350K E_{F1}=0.1eV



APL, ***107***, *053109 (2015)*

99:1 splitter at micrometer scale

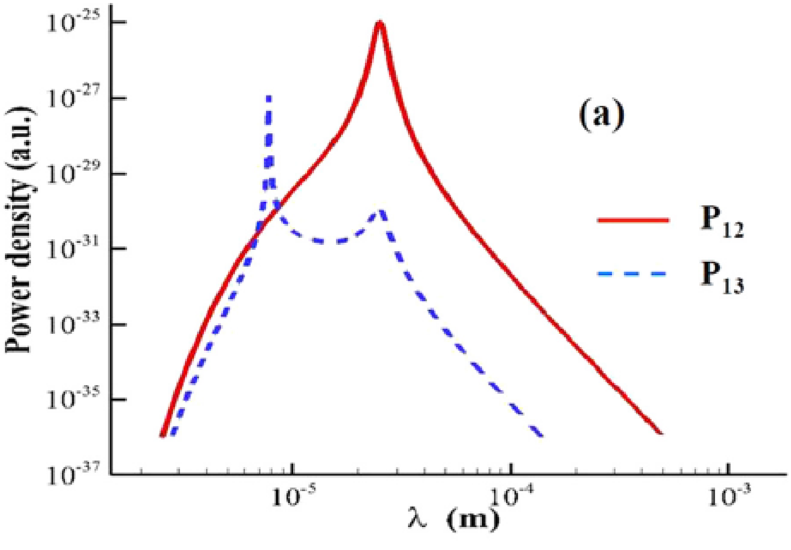
Near-field heat splitter

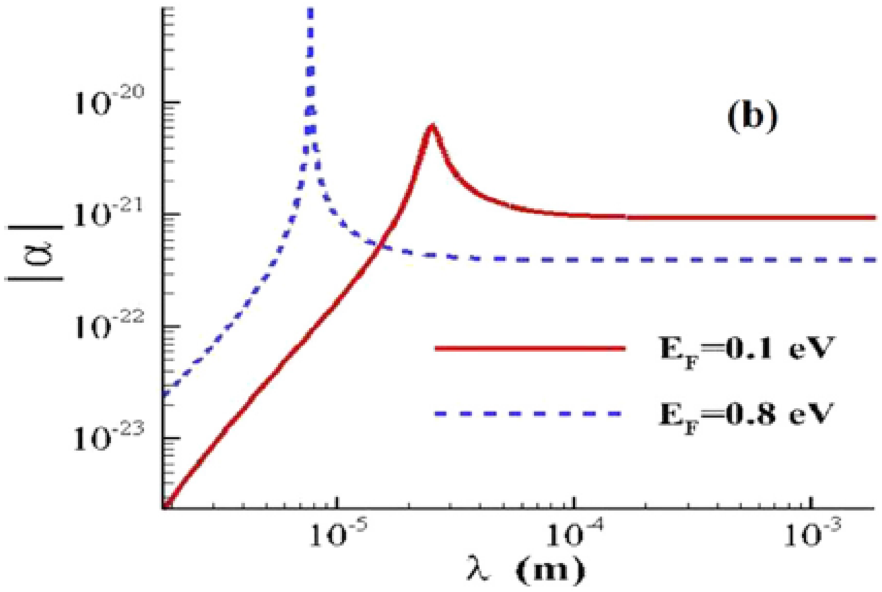


T_2=273K
E_{F2}=0.1eV

T_3=273K
E_{F3}=0.8eV

T_1=350K E_{F1}=0.1eV





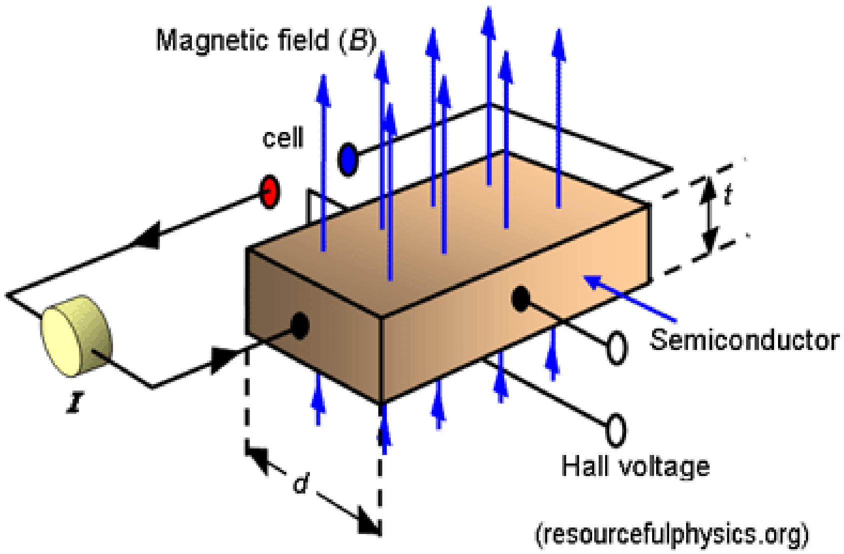
APL, ***107***, *053109 (2015)*

Hall effect-Thermal Hall effect

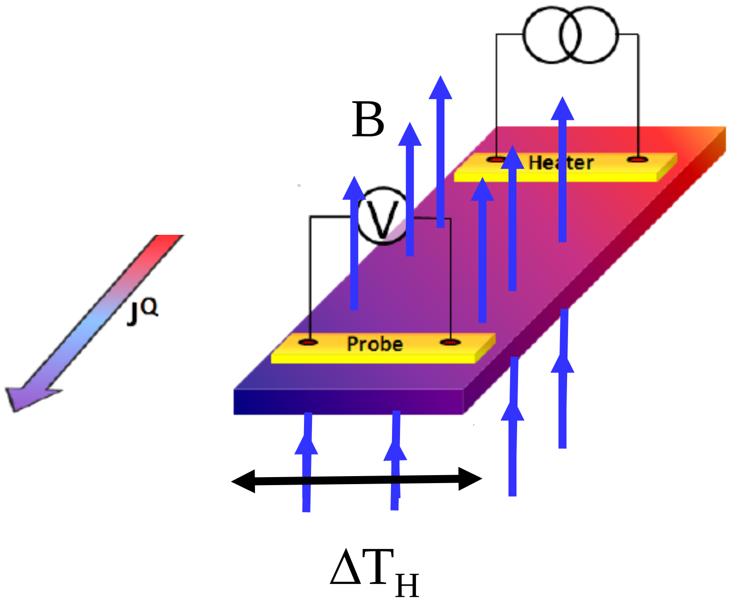
Edwin Hall,1879

Lorentz Force:

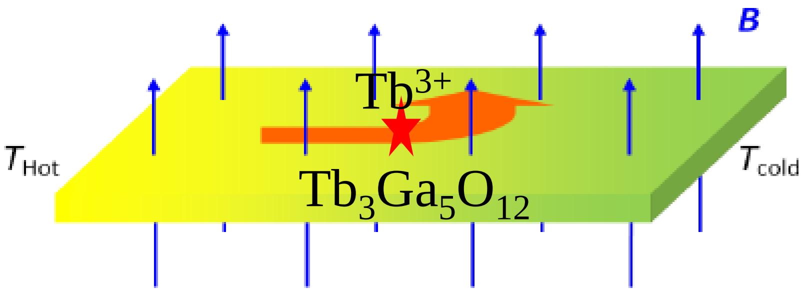
$F = q[E + (v \times B)]$



Righi,Leduc,1888

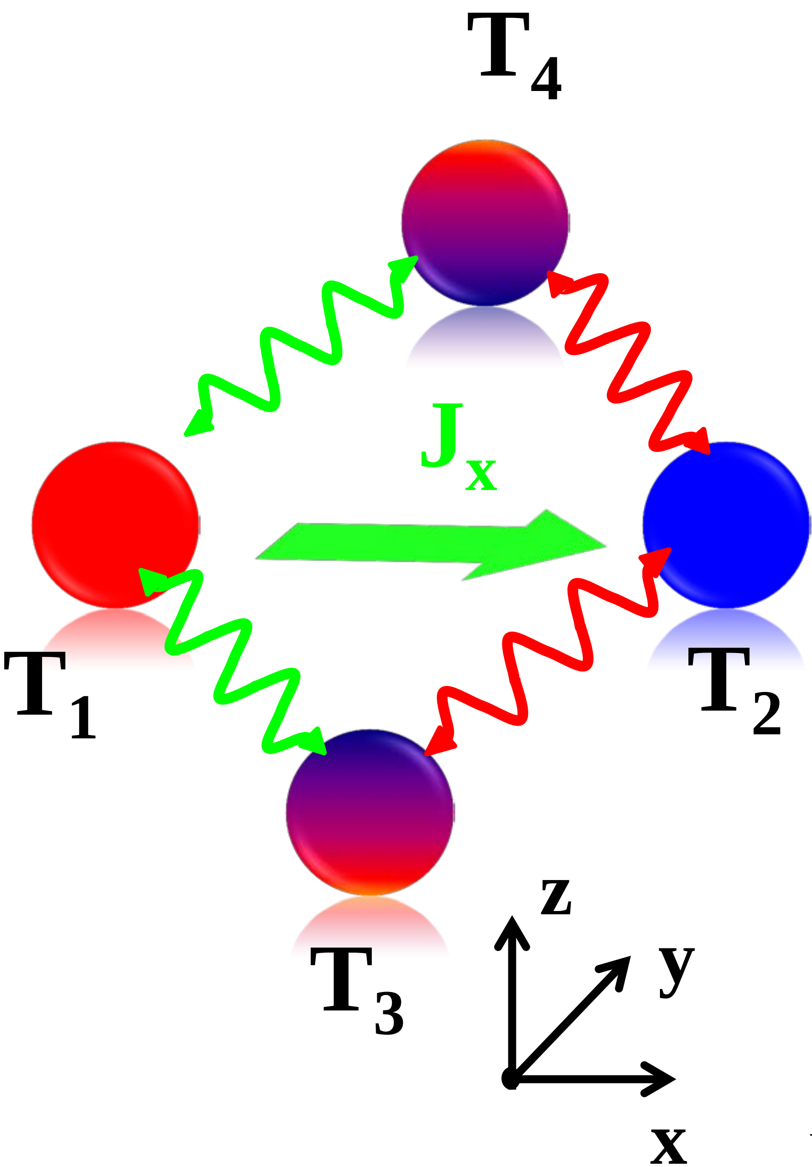


Strohm, 2005 (phonon Hall effect)



Mori et al., PRL, 113, 265901 (2014)

Photon thermal Hall effect



4-terminal InSb (magneto-optical) junction

B=0 ➡ $\varepsilon_{InSb} = \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_1 \end{pmatrix}$

$$\varepsilon_1(H) = \varepsilon_\infty \left(1 + \frac{\omega_L^2 - \omega_T^2}{\omega_T^2 - \omega^2 - i\Gamma\omega} + \frac{\omega_p^2(\omega + i\gamma)}{\omega[\omega_c^2 - (\omega + i\gamma)^2]}\right)$$

with $\omega_c = \frac{eB}{m^*}$ cyclotron frequency

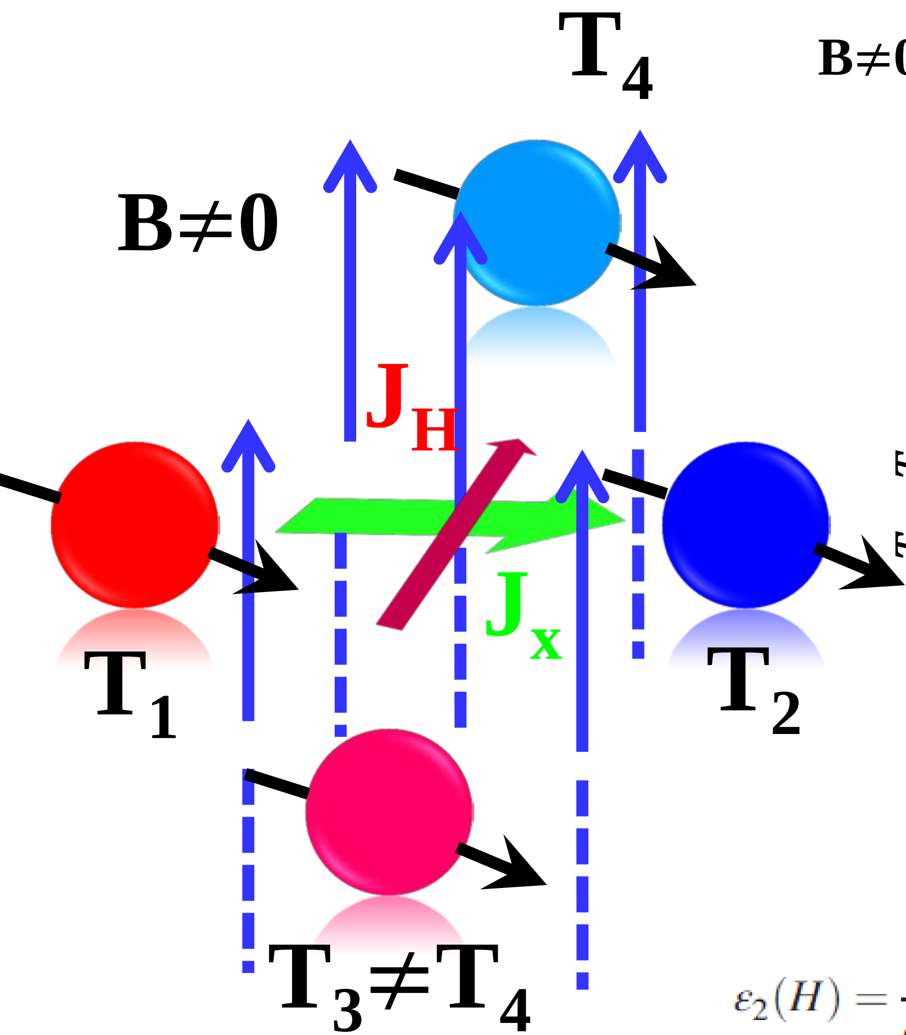
T_3=T_4 ➡ **J_H=J_y=0**

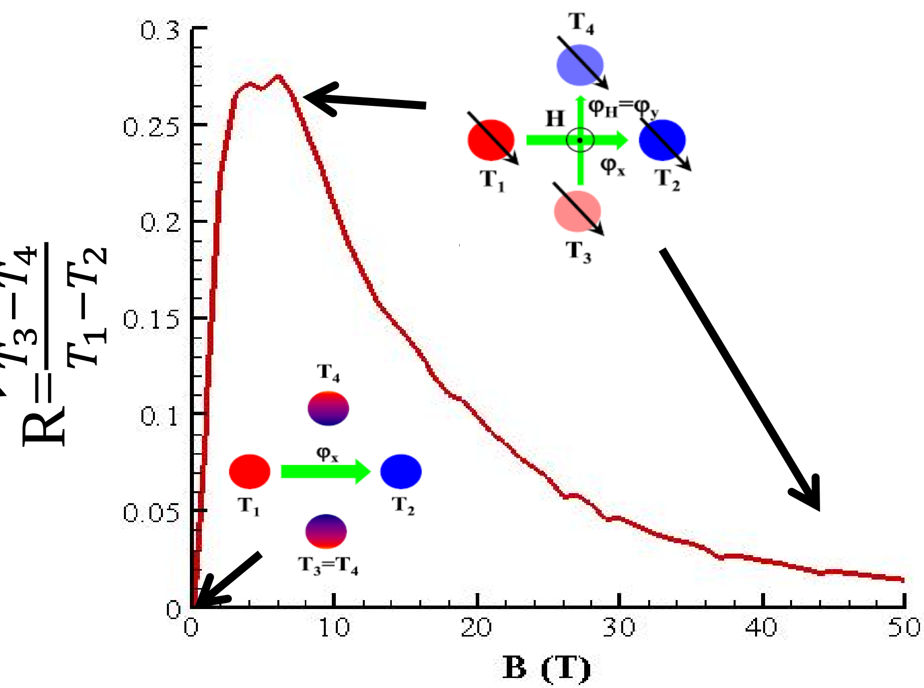
No Hall flux

PRL 116, 084301 (2016)

Photon thermal Hall effect

B≠0 → InSb anisotropic (symmetry breaking) → **$J_H \neq 0$**





$$\varepsilon = \begin{pmatrix} \varepsilon_1 & -i\varepsilon_2 & 0 \\ i\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix}$$

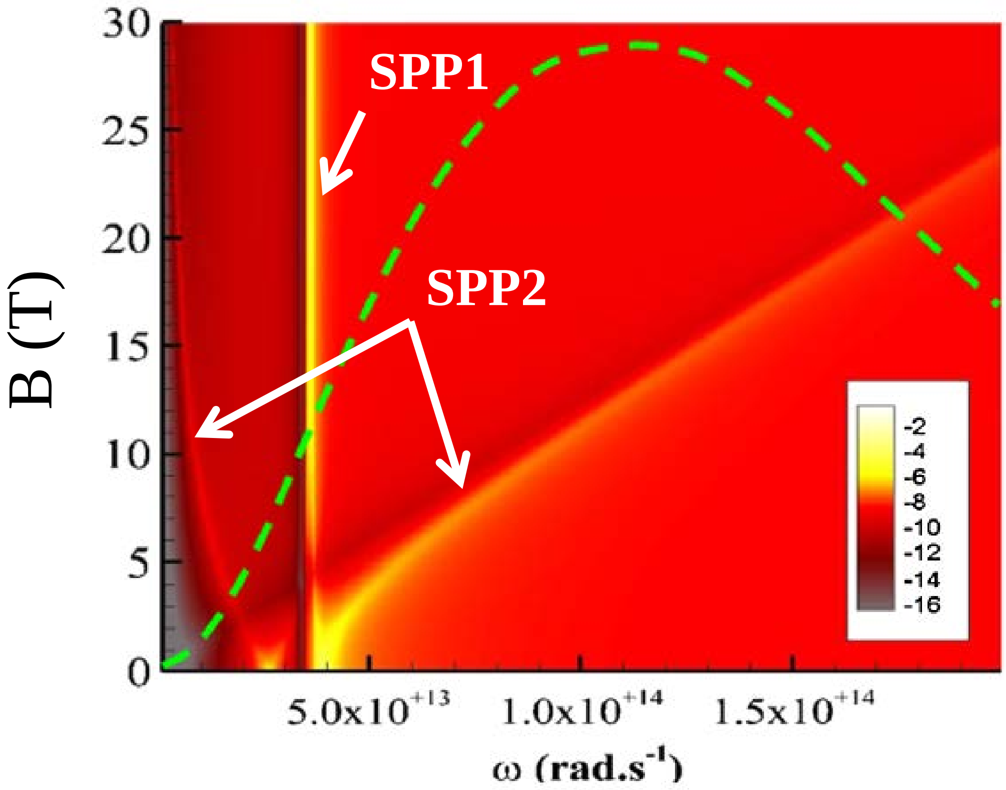
$$\varepsilon_2(H) = \frac{\varepsilon_\infty \omega_p^2 \omega_c}{\omega[(\omega + i\gamma)^2 - \omega_c^2]}$$

$$\varepsilon_3 = \varepsilon_\infty \left(1 + \frac{\omega_L^2 - \omega_T^2}{\omega_T^2 - \omega^2 - i\Gamma\omega} - \frac{\omega_p^2}{\omega(\omega + i\gamma)}\right)$$

Photon thermal Hall effect

Quasistatic polarizability:

$$\bar{\bar{\alpha}}_{0i}(\omega) = 4\pi r^3(\bar{\bar{\varepsilon}} - \varepsilon_h \bar{\bar{1}})(\bar{\bar{\varepsilon}} + 2\varepsilon_h \bar{\bar{1}})^{-1} \longrightarrow \propto \Rightarrow \begin{cases} \varepsilon_3(\omega) + 2\varepsilon_h = 0 & \text{SPP1} \\ [\varepsilon_1(\omega) + 2\varepsilon_h]^2 - \varepsilon_2^2(\omega) = 0 & \text{SPP2} \end{cases}$$



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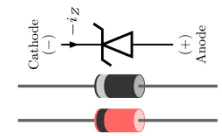
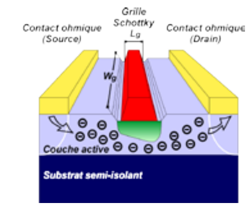
Summary

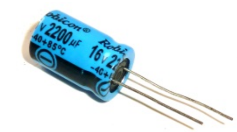
- New radiative effects and basic functionalities :



-strong thermal rectification with MIT materials ➡ diode



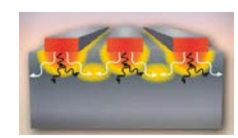
-high NDTR both in near and far-field regime ➡ transistor



-bistable thermal states ➡ memory

-SPP tunning with graphene or magnetic field ➡ heat flux splitter

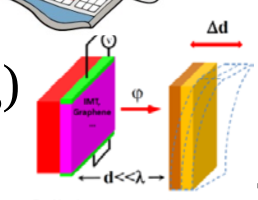
- Potential applications :



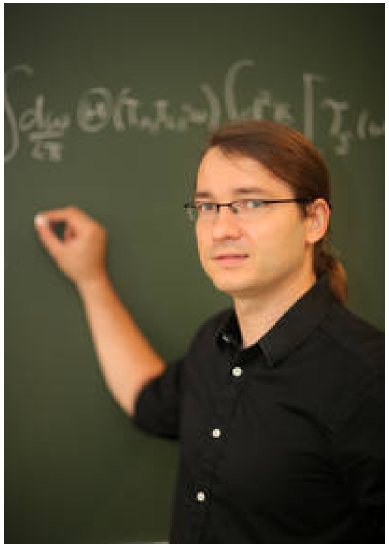
-thermal managment at nano and macroscale

- information treatment without electricity (low speed)

- Optomechanical systems (nanoheat engines and energy harvesting)



Acknowledgments



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