



Rectification Thermique Radiative

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Collaborations

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- Philippe Ben-Abdallah (Institut d'optique, Palaiseau)
- Domingos De Sousa Meneses (CEMHTI, Orléans)
- Benoît Rousseau (LTN Nantes)

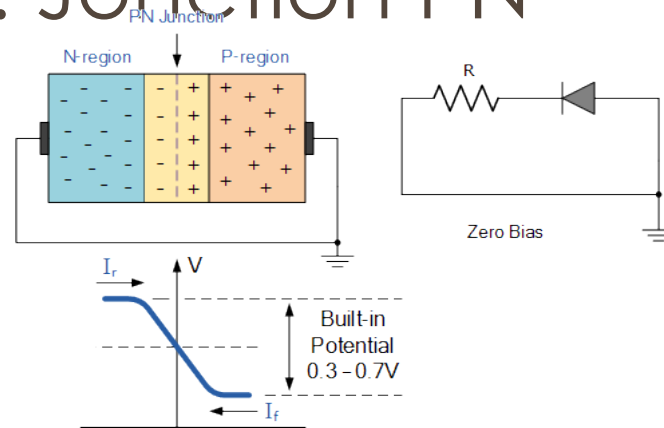
Motivations



- Réchauffement climatique
- Ressources en énergie limitées
- Récupération de la chaleur fatale

Composants en électronique

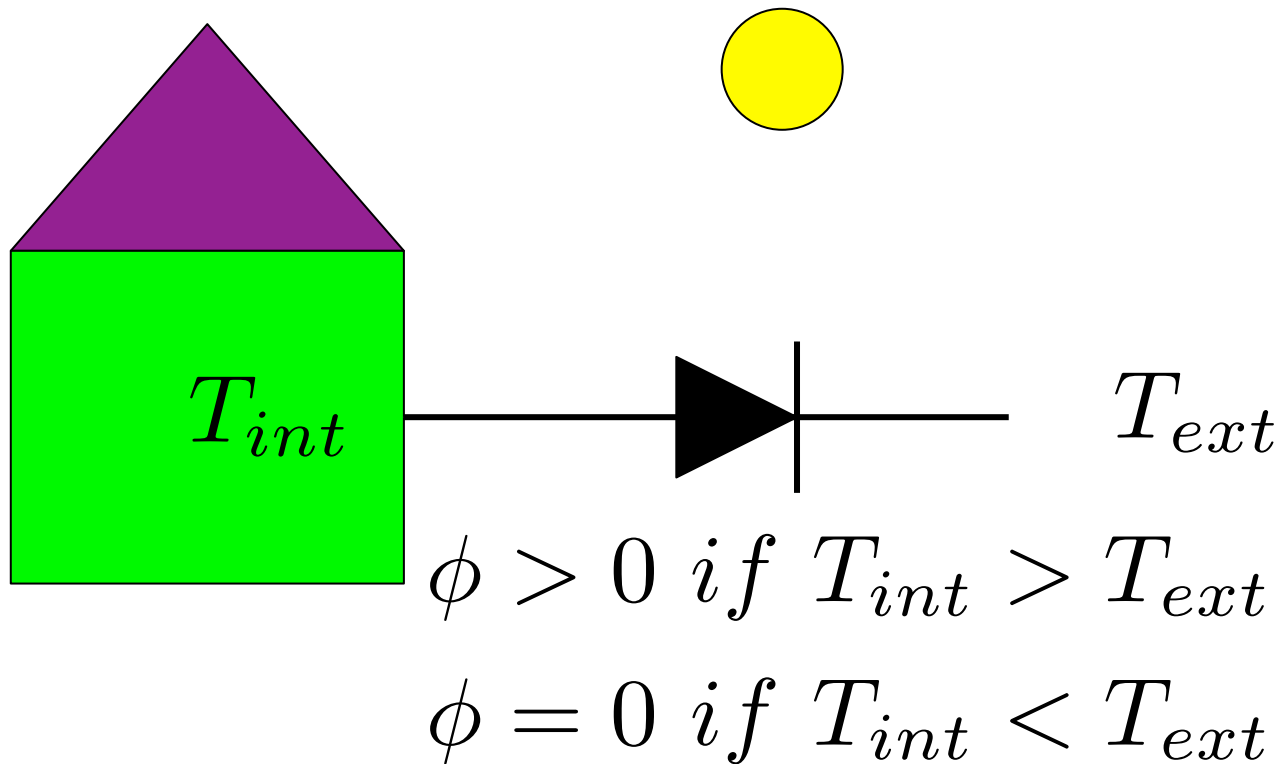
- Diode : Jonction PN



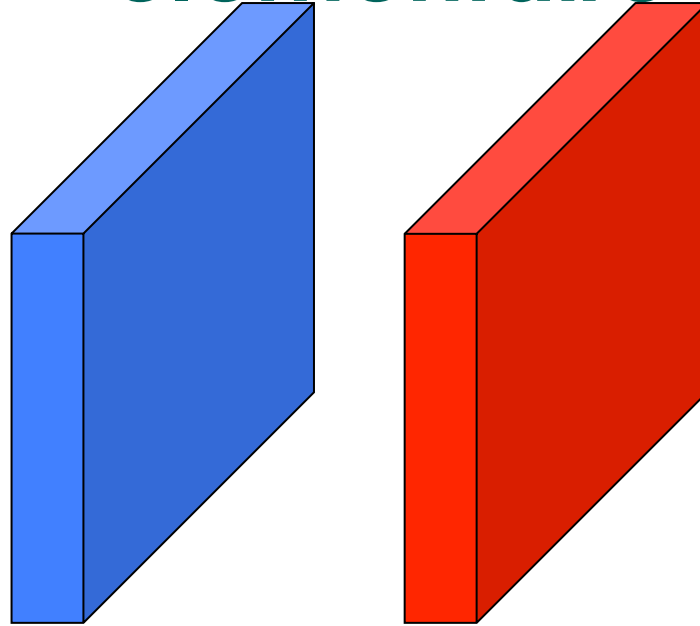
- Transistor (1947, Bardeen, Shockley, Brattain)
 - Modulateur, amplificateur et interrupteur d'électricité.

Analogie thermique des composants électronique

- Diode thermique



Diode thermique radiative élémentaire



Matériau 1

T_A

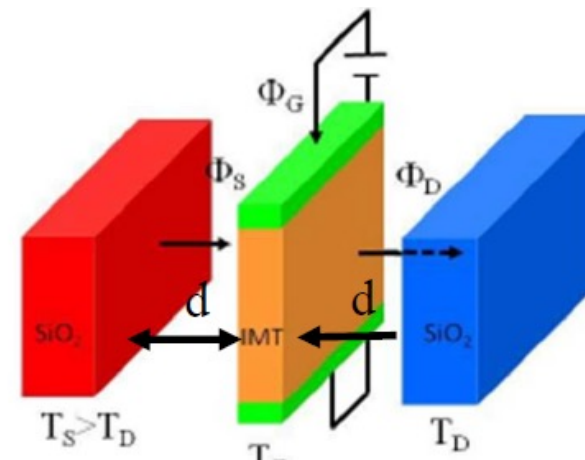
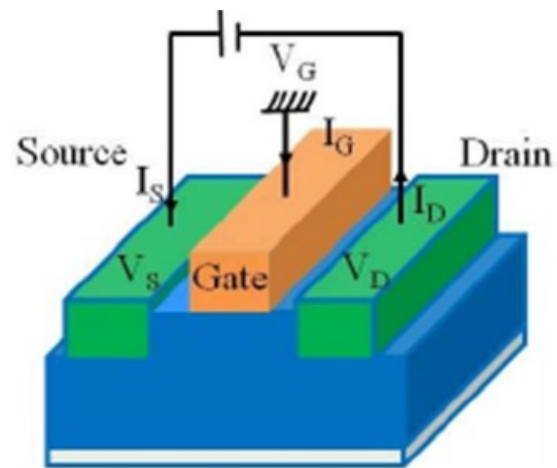
Matériau 2

T_B

Est ce que le flux est différent lorsque l'on échange T_A et T_B ?

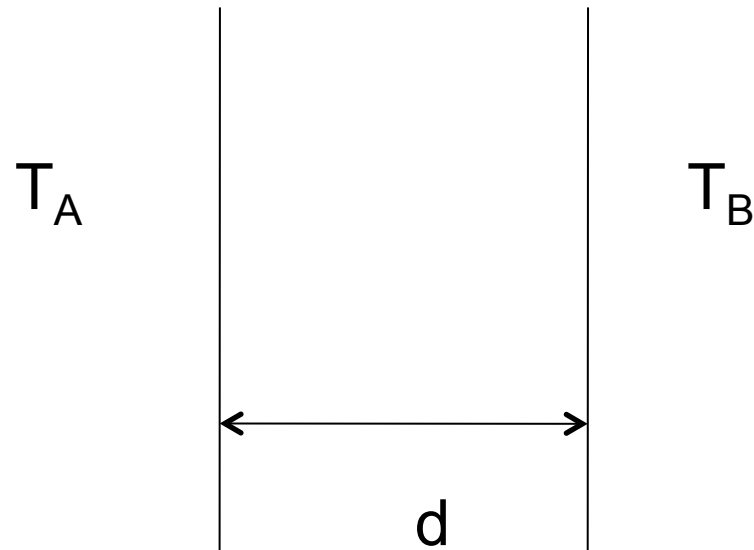
Analogie thermique de composants électroniques

- Transistor thermique.



Ben-Abdallah and Biehs, PRL, 112, 044301 (2014)

Transfert radiatif entre deux plans



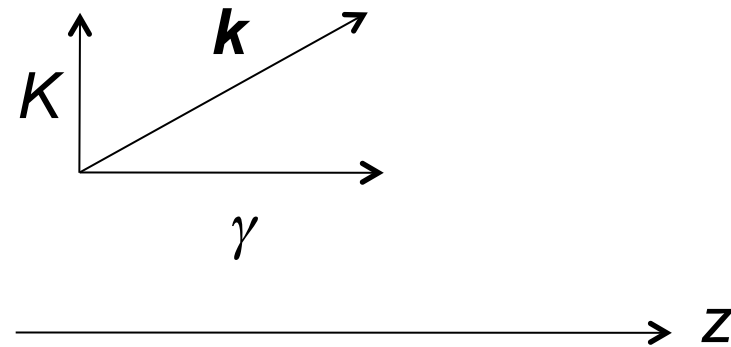
Mode électromagnétique : onde plane (ω, \mathbf{K})

Mode électromagnétique

- Onde propagative

$$K^2 + \gamma^2 = \omega^2 / c^2$$

$$\gamma \in \mathbb{R}$$



- Onde évanescente

$$\gamma \in i\mathbb{R}$$



Transfert thermique entre A et B

- Chaleur émise en A and transmise à B

$$E_{A \rightarrow B} = \sum_{\omega, K} \Theta(\omega, T_A) \tau_{A \rightarrow B}(\omega, K)$$

- Energie d'un mode à l'équilibre thermique

$$\Theta(\omega, T_A) = \hbar\omega / [\exp(\hbar\omega / k_b T_A) - 1]$$

- Probabilité de transmission d'un mode

$$\tau_{A \rightarrow B}(\omega, K)$$

Flux de chaleur échangé

- Densité de flux (Landauer)

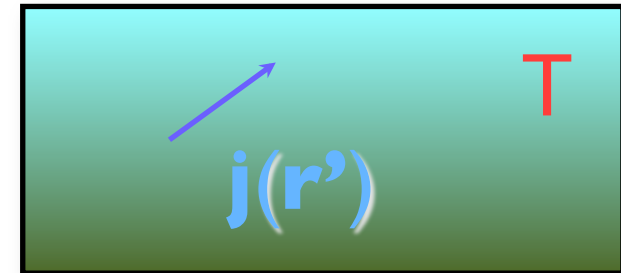
$$\varphi_{A \leftrightarrow B} = \int_0^{\infty} [\Theta(\omega, T_A) - \Theta(\omega, T_B)] d\omega \int_0^{\infty} \frac{K dK}{4\pi^2} \tau(\omega, K)$$

Electrodynamique Fluctuationnelle (S.M. Rytov)

$E(\mathbf{r})$



$$\mathbf{E}(\mathbf{r}) = \int \mathbf{G}(\mathbf{r}, \mathbf{r}') \cdot \mathbf{j}(\mathbf{r}') d^3 r'$$



Théorème de Fluctuation-dissipation

$$\langle j_n(\mathbf{r}) j_m(\mathbf{r}') \rangle = \frac{\omega \epsilon_0 \text{Im}(\epsilon)}{\pi} \Theta(\omega, T) \delta_{nm} \delta(\mathbf{r} - \mathbf{r}')$$

$$\Theta(\omega, T) = \frac{\hbar \omega}{e^{\hbar \omega / k_b T} - 1}$$

Flux de chaleur échangé

- Densité de flux

$$\varphi_{A \leftrightarrow B} = \int_0^\infty [\Theta(\omega, T_A) - \Theta(\omega, T_B)] d\omega \int_0^\infty \frac{K dK}{4\pi^2} \tau(\omega, K)$$

- Coef. Trans ondes propagatives

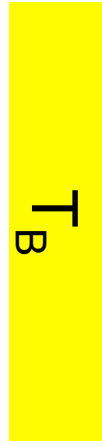
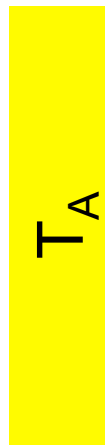
$$\tau(\omega, K) = \frac{(1 - |r_{vA}^{s,p}|^2)(1 - |r_{vB}^{s,p}|^2)}{|1 - r_{vA}^{s,p} r_{vB}^{s,p} e^{2i\gamma_v d}|^2}$$

- Coef. Trans. Ondes évanescentes

$$\tau(\omega, K) = \frac{4\text{Im}(r_{vA}^{s,p})\text{Im}(r_{vB}^{s,p})}{|1 - r_{vA}^{s,p} r_{vB}^{s,p} e^{2i\gamma_v d}|^2} e^{-2|\gamma_v|d}$$

Limites du transfert radiatif

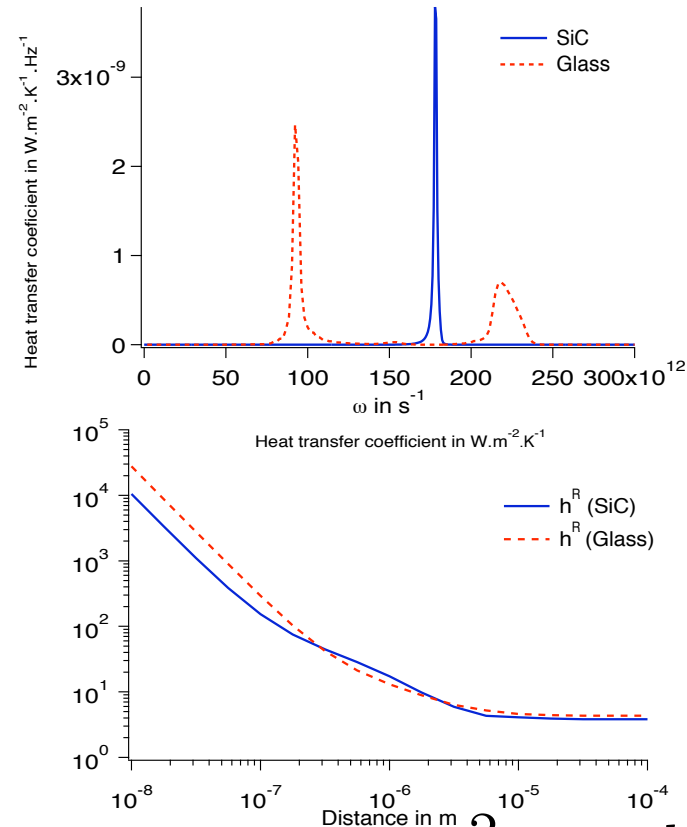
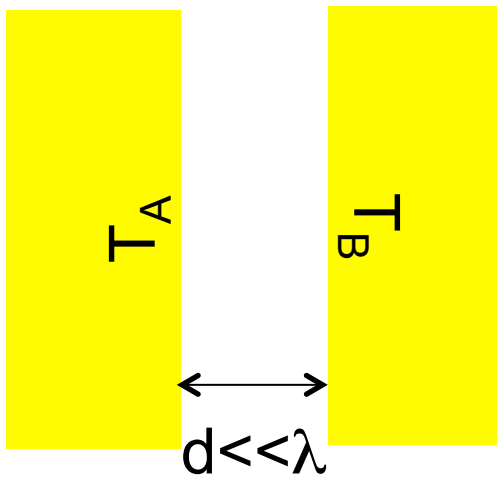
- Champ lointain



$$\varphi < \sigma(T_A^4 - T_B^4)$$

Limites du transfert radiatif

- Champ proche



$$h^R(\omega) \sim \frac{1}{d^2} \frac{\text{Im}(\epsilon_A)\text{Im}(\epsilon_B)}{|1 + \epsilon_A|^2 |1 + \epsilon_B|^2} k_B \left(\frac{\hbar\omega}{k_B T} \right)^2 \frac{e^{\hbar\omega/k_B T}}{(e^{\hbar\omega/k_B T} - 1)}$$

Rectification thermique radiative

- Densité de flux de chaleur

$$\varphi_{A \leftrightarrow B} = \int_0^\infty [\Theta(\omega, T_A) - \Theta(\omega, T_B)] d\omega \int_0^\infty \frac{K dK}{4\pi^2} \tau(\omega, K)$$

- Coef. Trans. ondes propagative

$$\tau(\omega, K) = \frac{(1 - |r_{vA}^{s,p}|^2)(1 - |r_{vB}^{s,p}|^2)}{|1 - r_{vA}^{s,p} r_{vB}^{s,p} e^{2i\gamma_v d}|^2}$$

- Coef. Trans. Ondes évanescentes

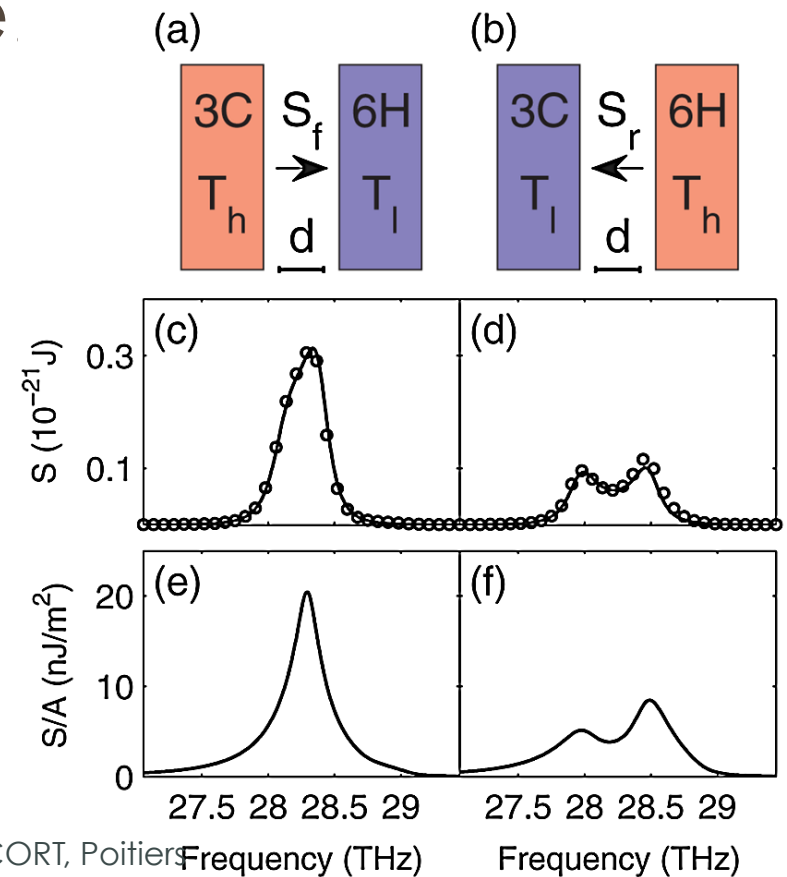
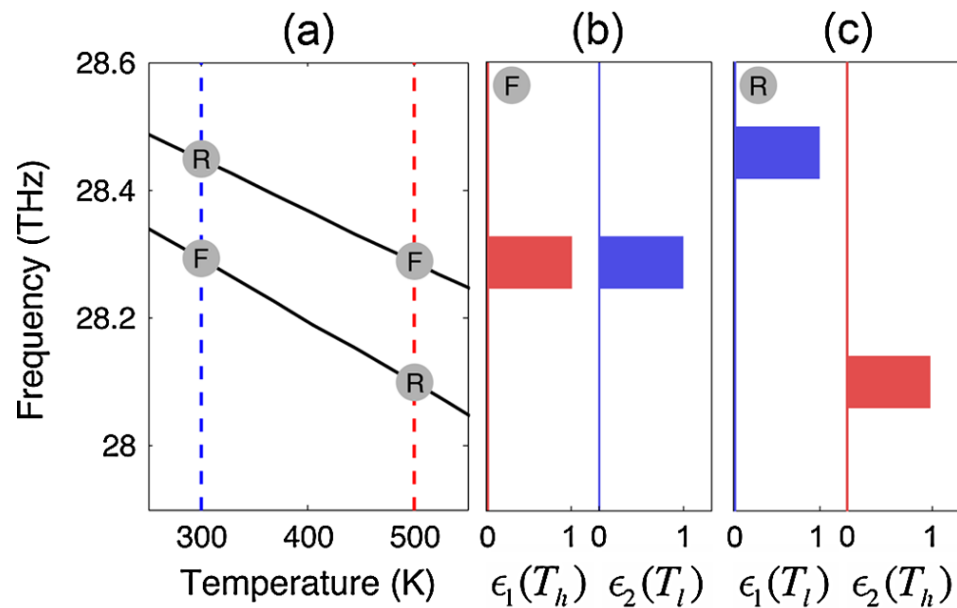
$$\tau(\omega, K) = \frac{4\text{Im}(r_{vA}^{s,p})\text{Im}(r_{vB}^{s,p})}{|1 - r_{vA}^{s,p} r_{vB}^{s,p} e^{2i\gamma_v d}|^2} e^{-2|\gamma_v|d}$$

- Rectification si $\epsilon_A(T) \neq \epsilon_B(T)$

$$R(T_A, T_B) = \frac{|\varphi_{AB}(T_A, T_B) + \varphi_{AB}(T_B, T_A)|}{\text{Max}(|\varphi_{AB}(T_A, T_B)|, |\varphi_{AB}(T_B, T_A)|)}$$

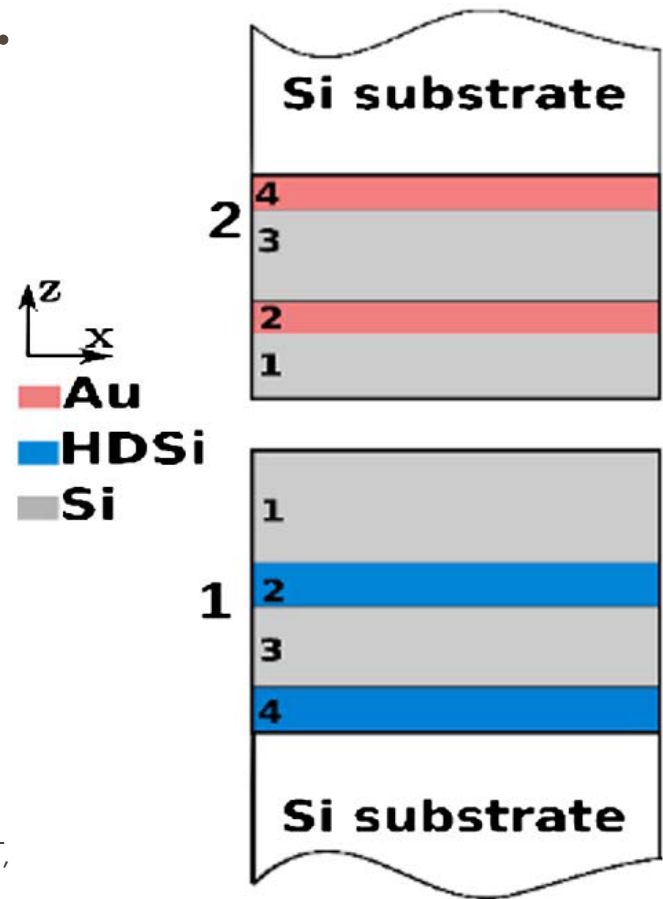
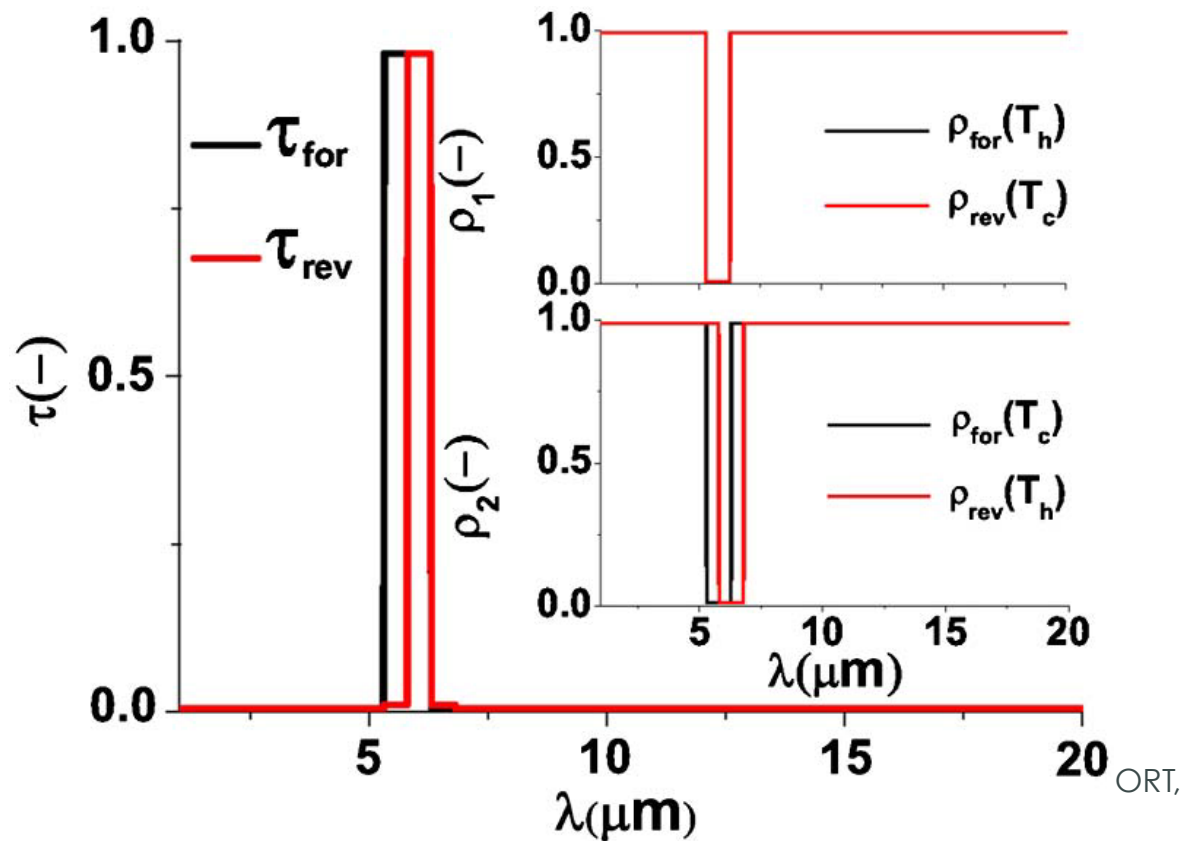
Rectification thermique radiative

- Otey, Lau and Fan, PRL, 104, 153301 (2010). Champ proche

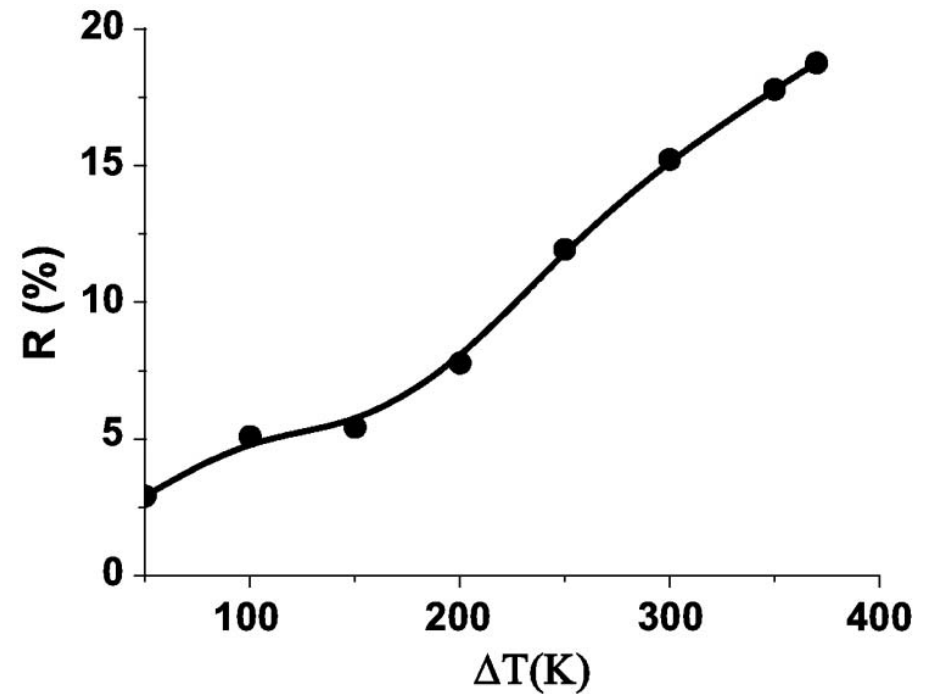
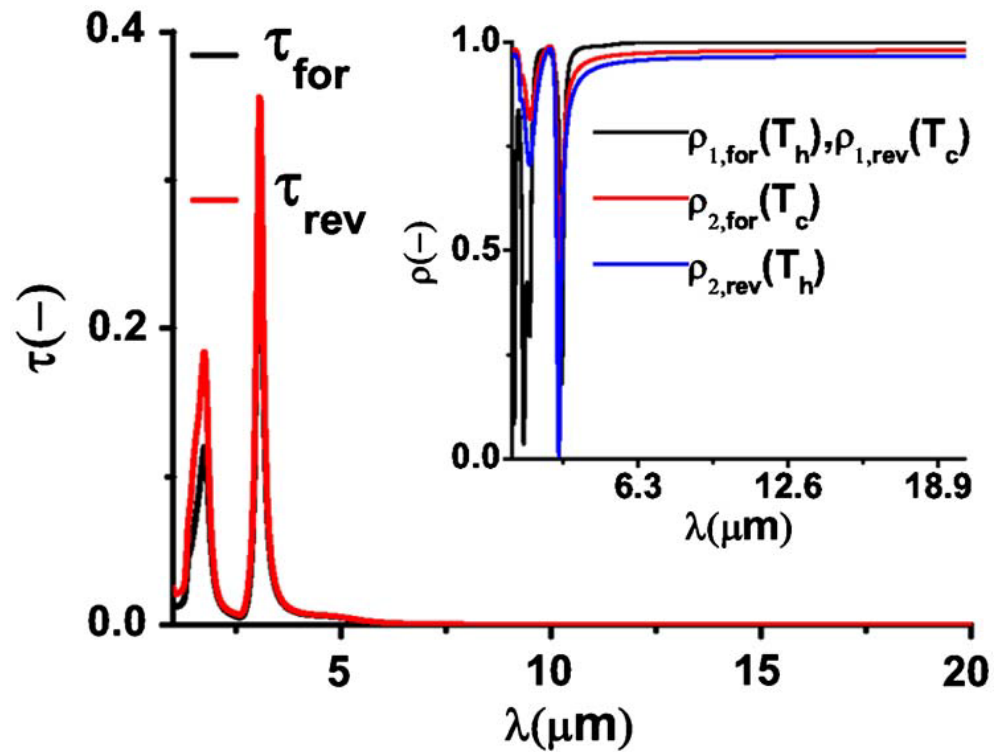


Cavités Fabry-Perot

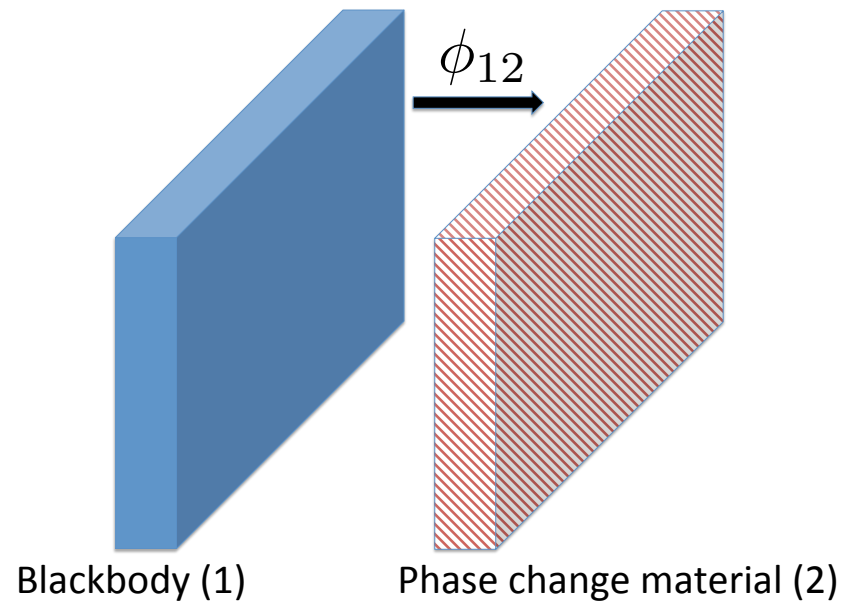
- Nefzaoui et al. Appl. Opt., 53, 3479 (2014). Champ lointain.



Cavités Fabry-Perot

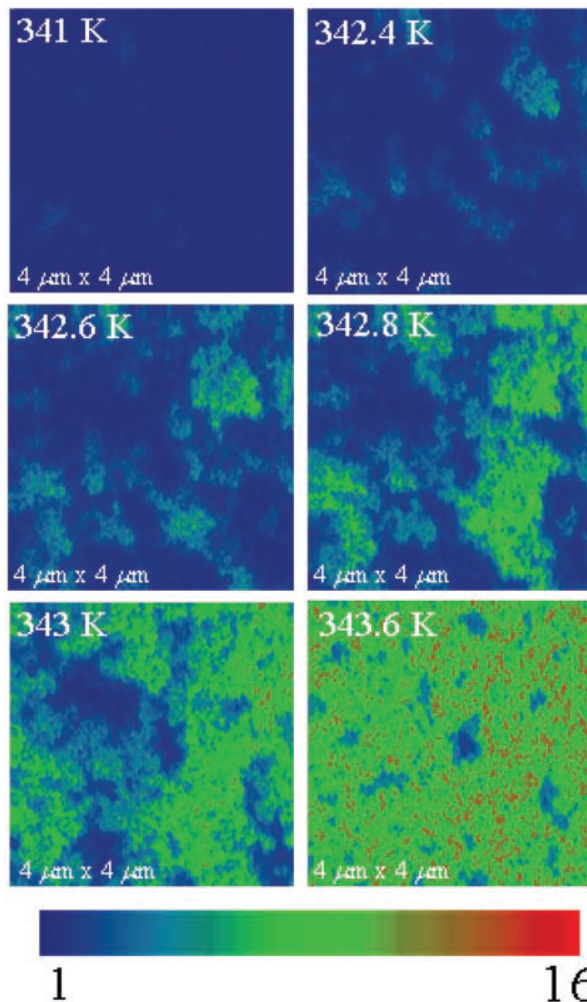


Matériaux à changement de phase

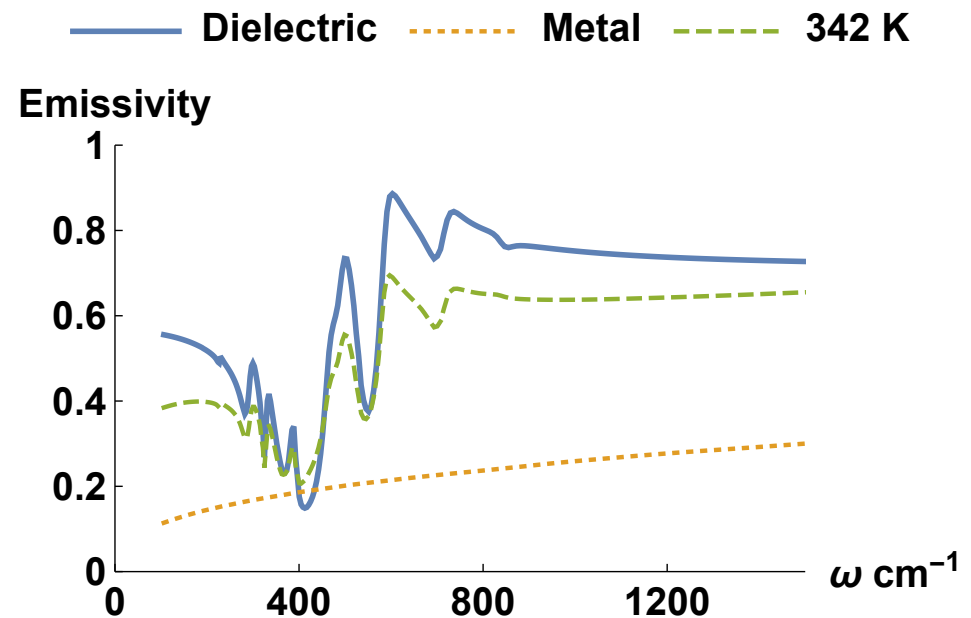


Matériaux à changement de phase

- VO₂



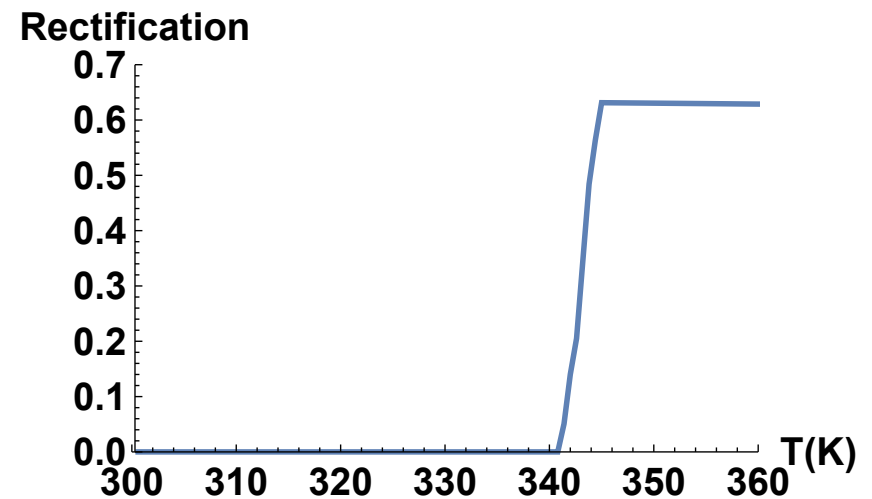
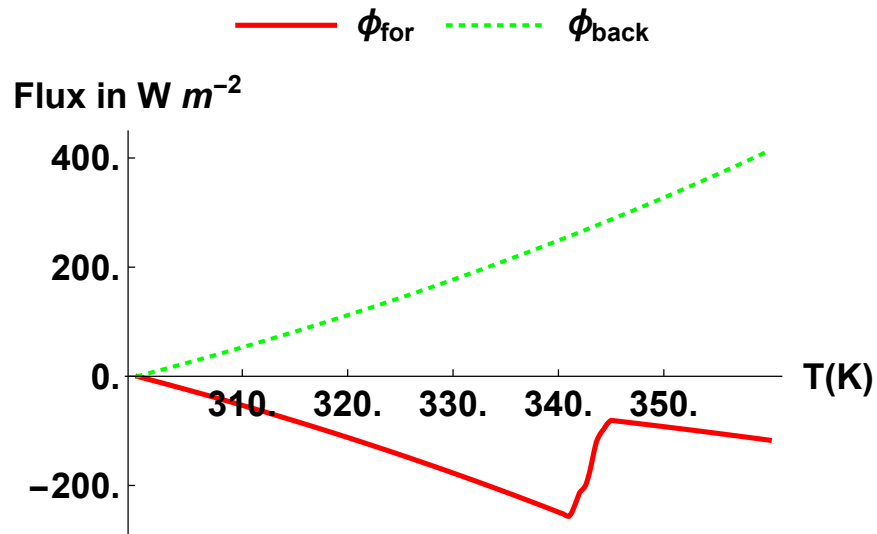
Emissivity VO₂



Qazilbash, Science, 318,1750 (2007)

Matériaux à changement de phase

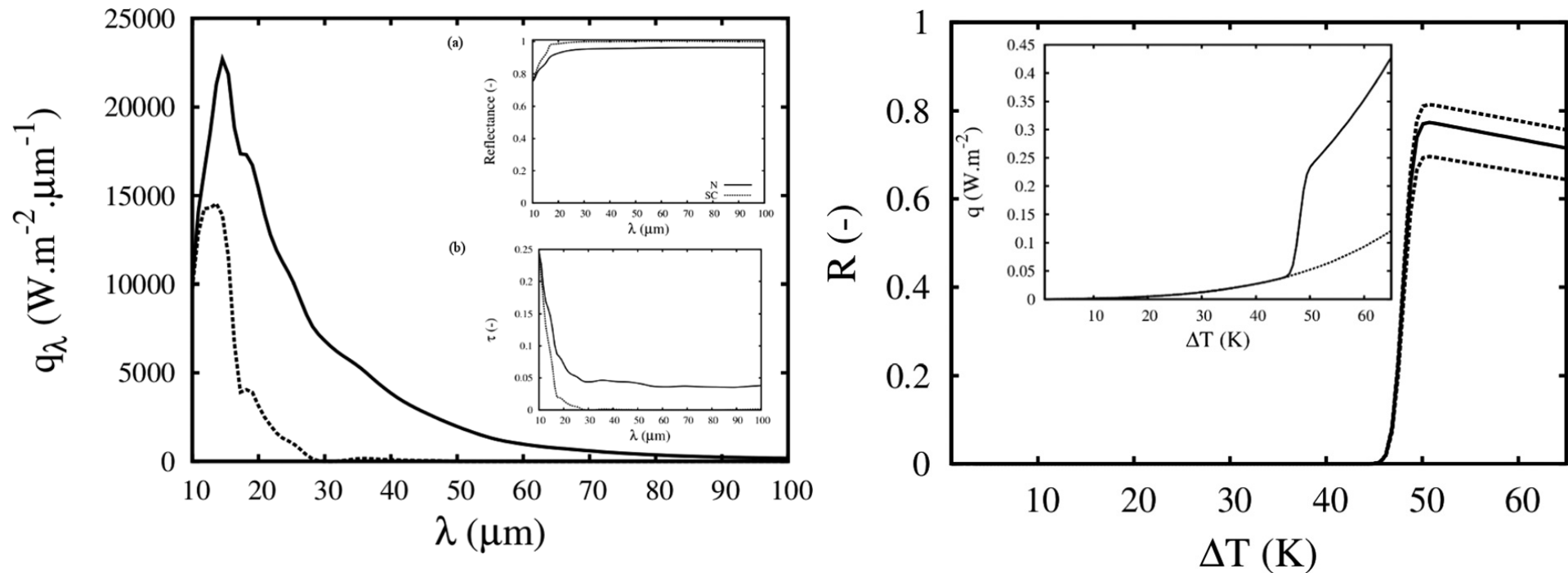
- VO₂



Ben-Abdallah et al., APL, 103,191907 (2013)

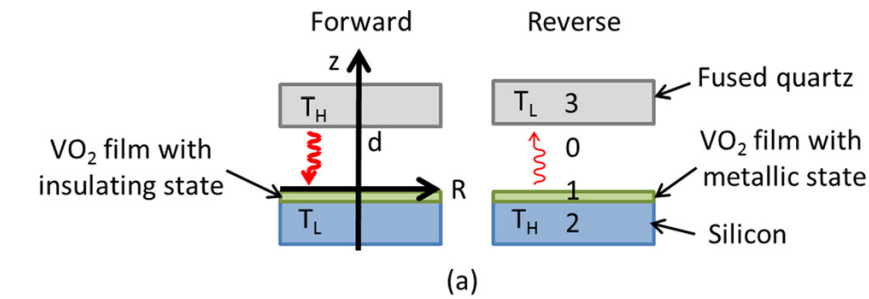
Matériaux à changement de phase

- Superconductors ($\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$)

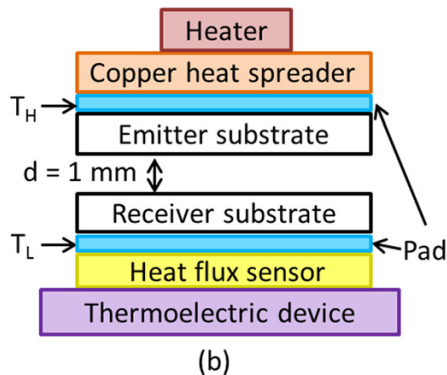


Nefzaoui et al, APL, 104, 103905 (2014)

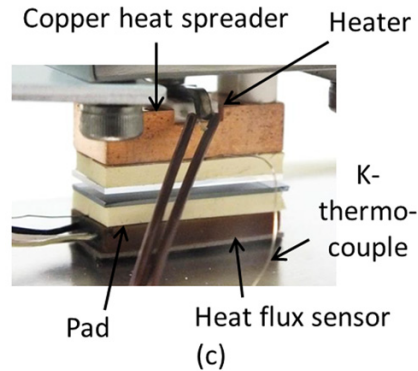
Diode thermique expérimentale



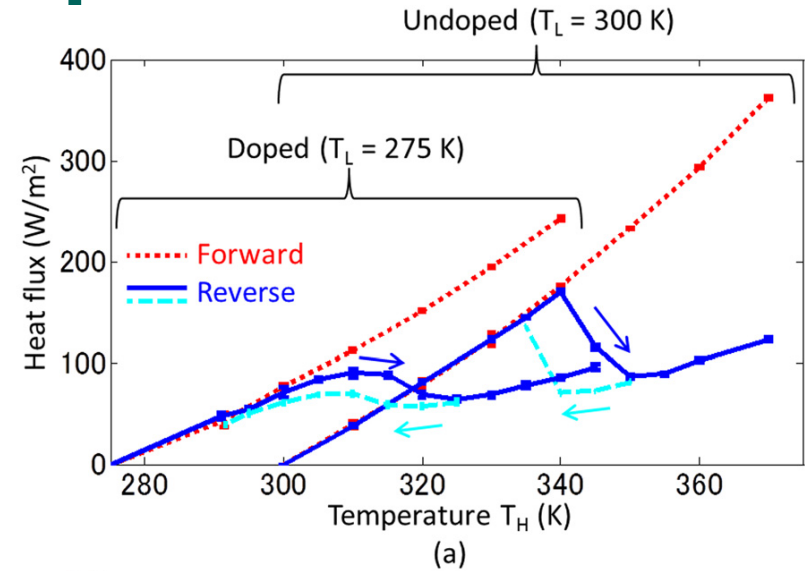
(a)



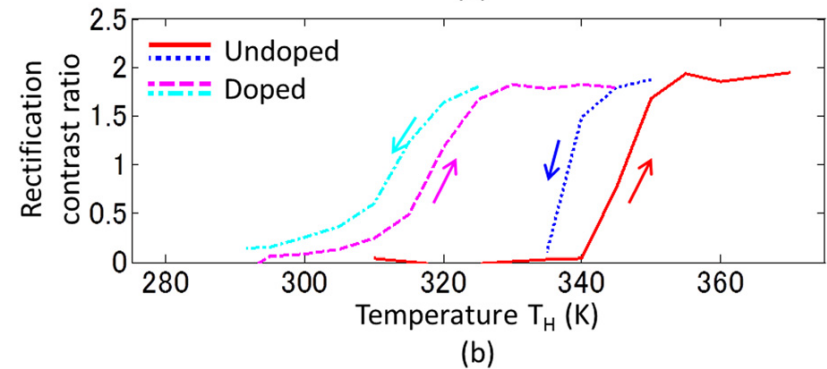
(b)



(c)



(a)

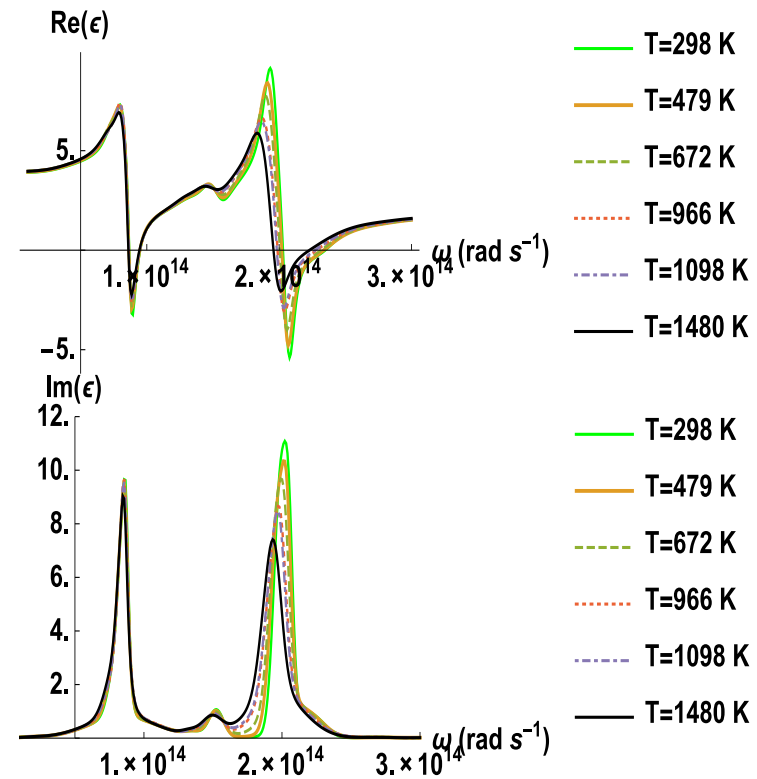
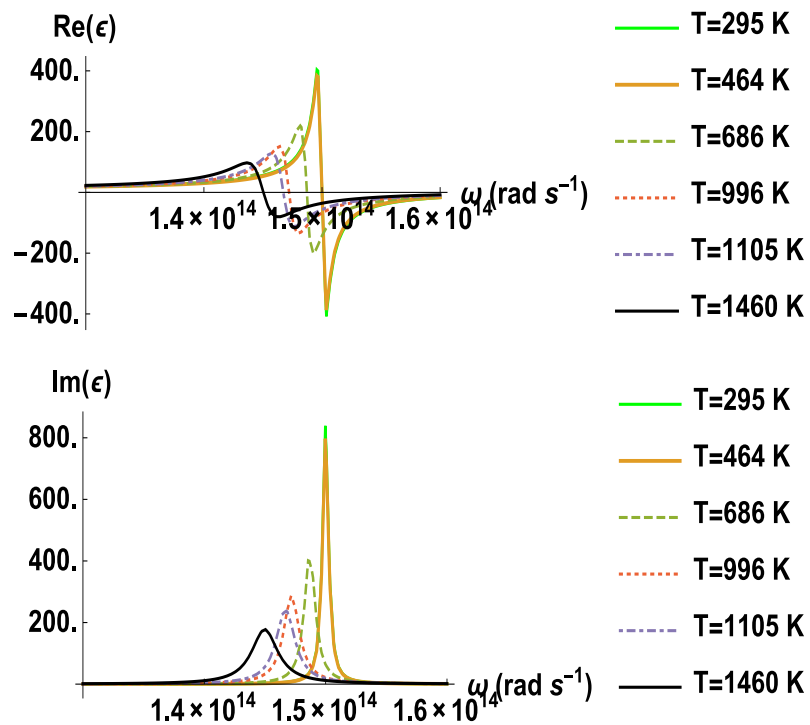


(b)

Ito et al., APL, 105, 253503 (2014)

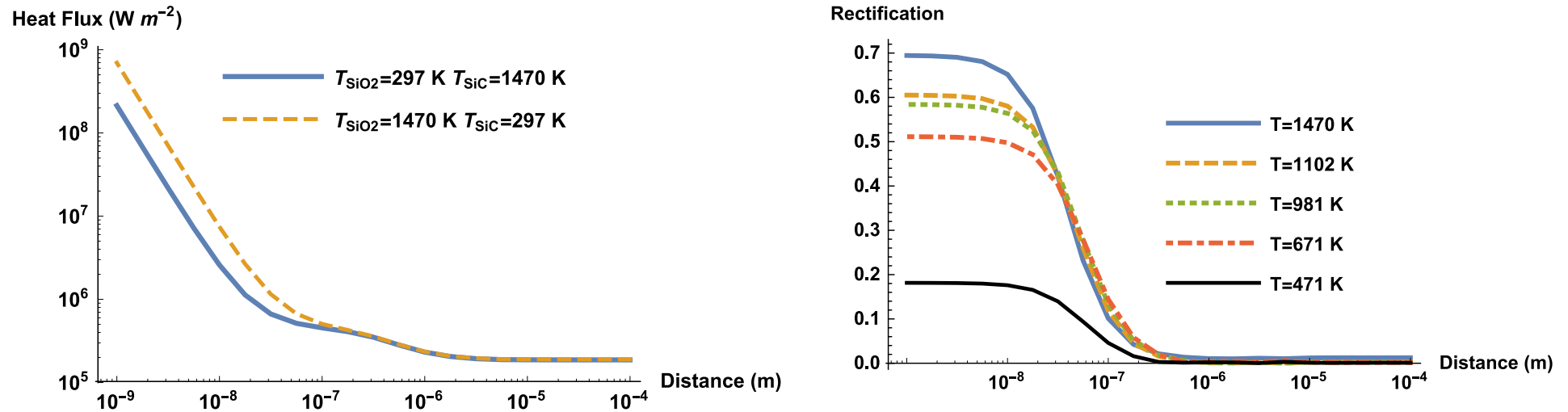
Rectification entre SiC et SiO₂

- Constante diélectrique du SiC et SiO₂(CEHMTI)



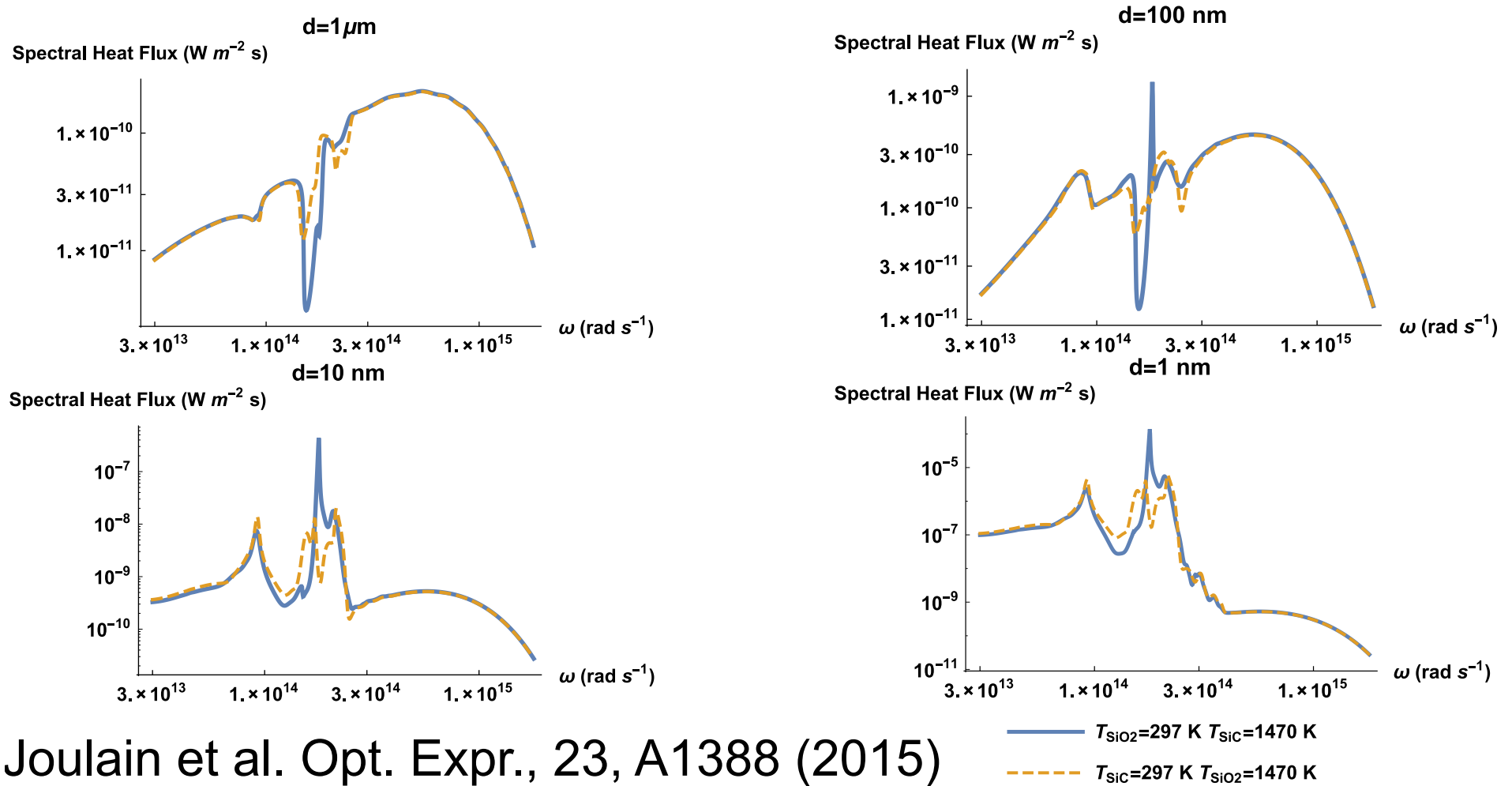
Joulain et al. Opt. Expr., 23, A1388 (2015)

Rectification between SiC and SiO₂



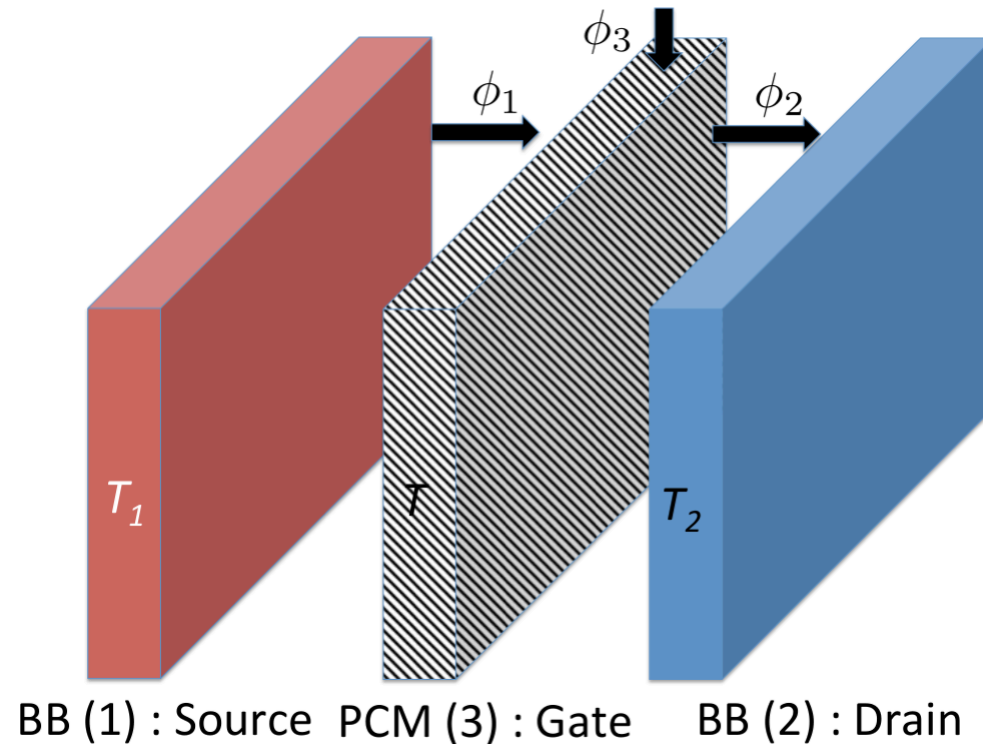
Joulain et al. Opt. Expr., 23, A1388 (2015)

Rectification entre SiC et SiO2



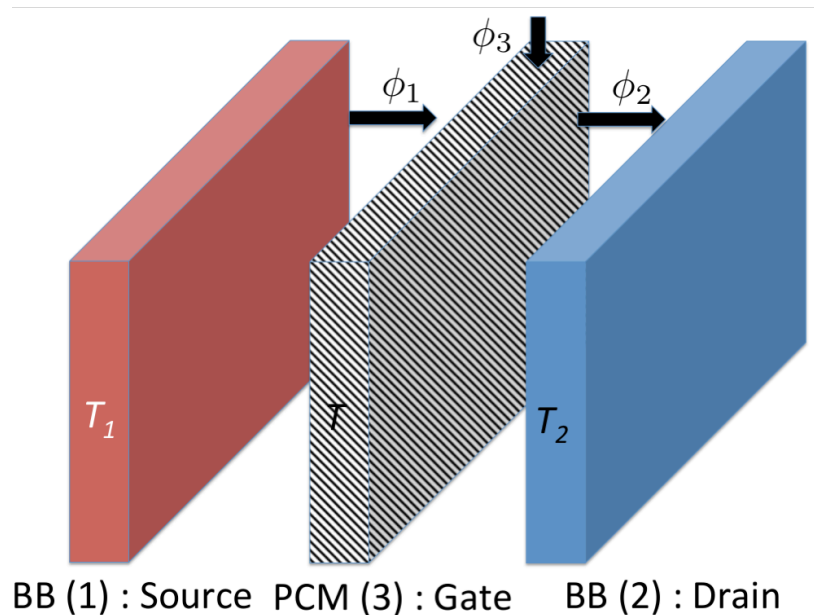
Joulain et al. Opt. Expr., 23, A1388 (2015)

Transistor thermique



Near-field : Ben-Abdallah and Biehs, PRL, 112, 044301 (2014)
Far-Field : Joulain et al., APL, 106, 133505 (2015)

Transistor Thermique en champ lointain pour matériaux gris



$$\phi_1 = \varepsilon(T)\sigma(T_1^4 - T^4)$$

$$\phi_2 = \varepsilon(T)\sigma(T^4 - T_2^4)$$

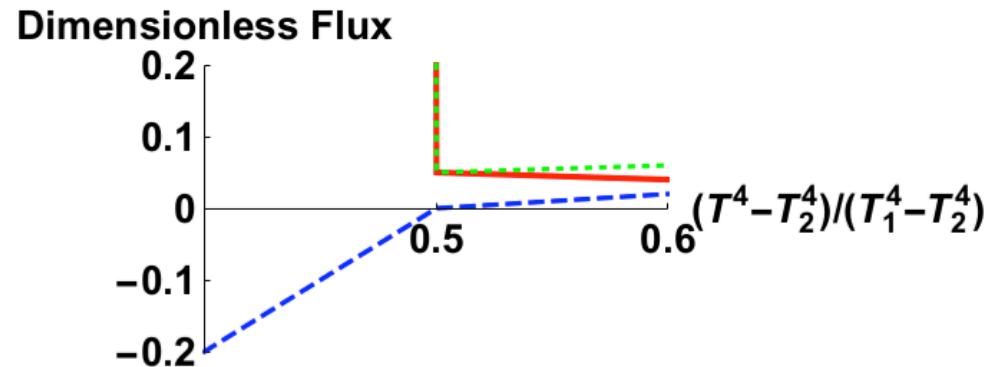
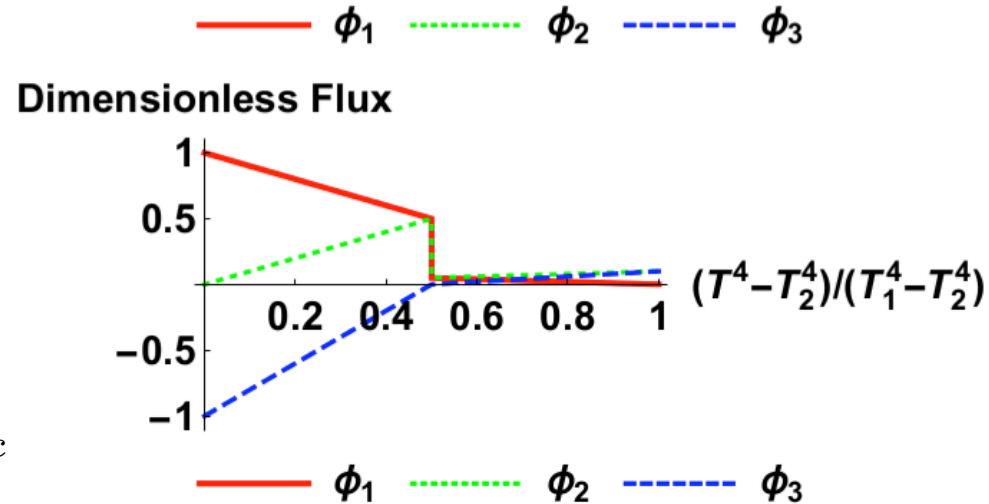
$$\phi_3 = \phi_2 - \phi_1 = \varepsilon(T)\sigma(2T^4 - T_1^4 - T_2^4)$$

Meilleure situation : $T_c = \left(\frac{T_1^4 + T_2^4}{2} \right)^{1/4}$

Transistor Thermique

$$\varepsilon = \begin{cases} \varepsilon^< = 1 & T < T_c \\ \varepsilon^> = 0.1 & T > T_c \end{cases}$$

$$R = 1 - \frac{\varepsilon^<}{\varepsilon^>}$$



Joulain et al., APL, 106, 133505 (2015)

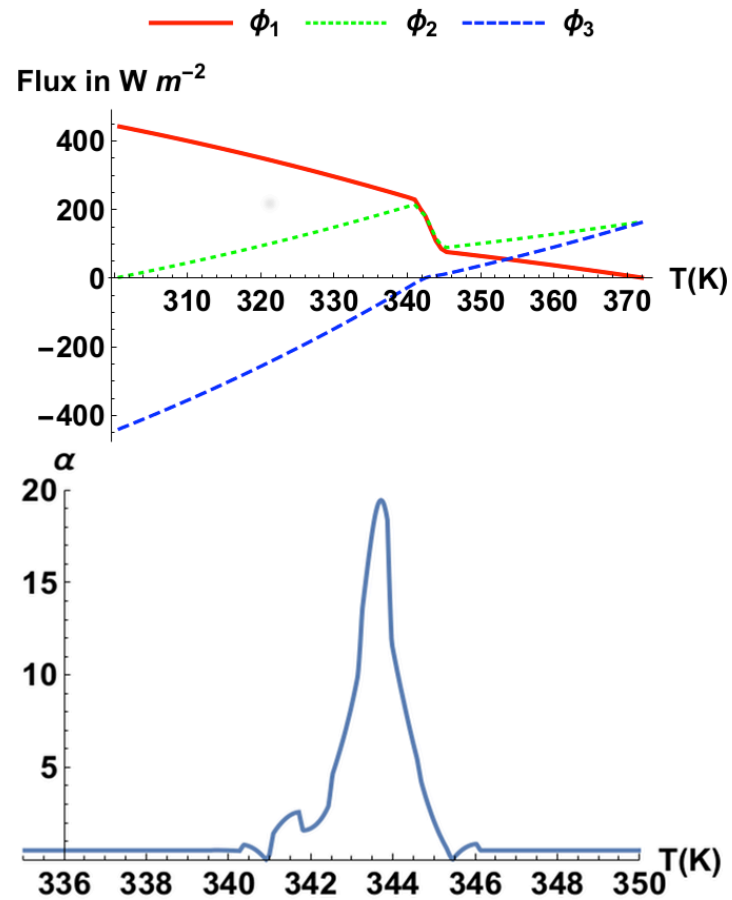
Facteur d'amplification

$$\alpha = \left| \frac{\partial \phi_2}{\partial \phi_3} \right| = \frac{1}{\left| 1 - (d\phi_2/dT)/(d\phi_3/dT) \right|}$$

if $T_c = \left(\frac{T_1^4 + T_2^4}{2} \right)^{1/4}$

$$\alpha \simeq \Delta\varepsilon(T_1 - T_c)/(\Delta T(\varepsilon^> + \varepsilon^<))$$

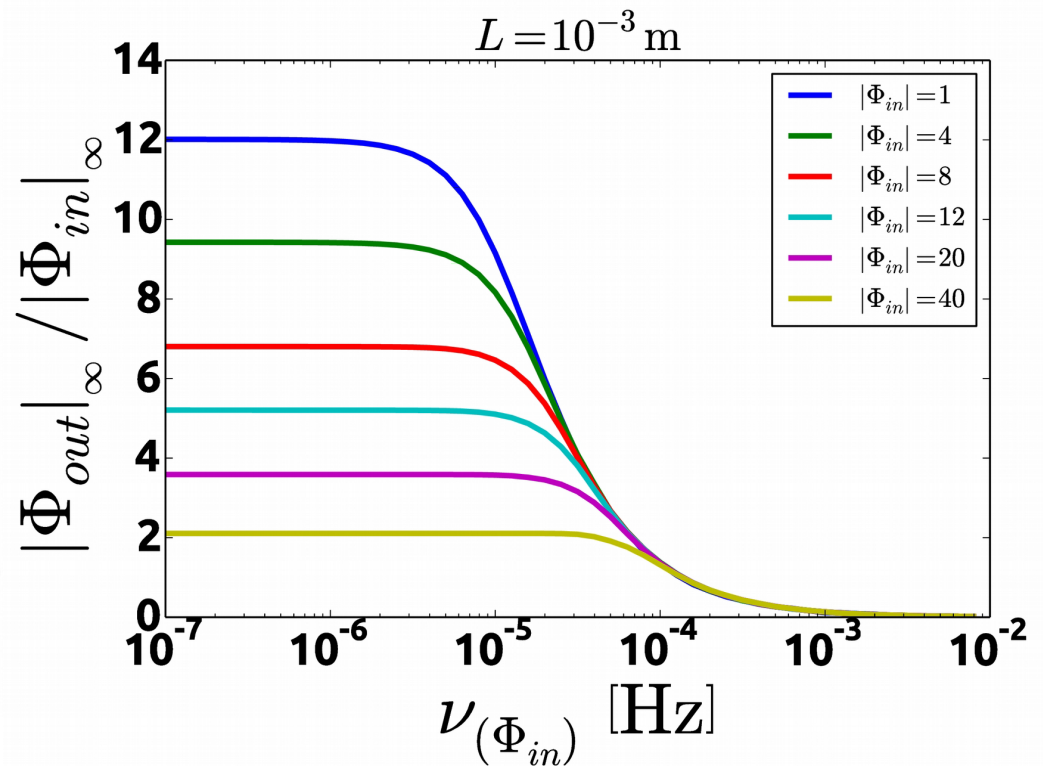
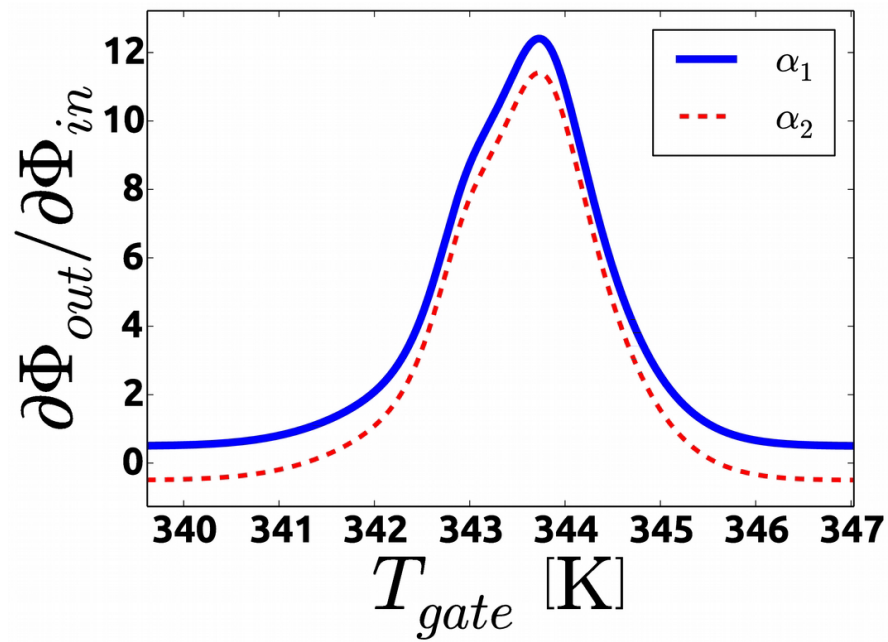
Transistor VO2



Joulain et al., APL, 106, 133505 (2015)

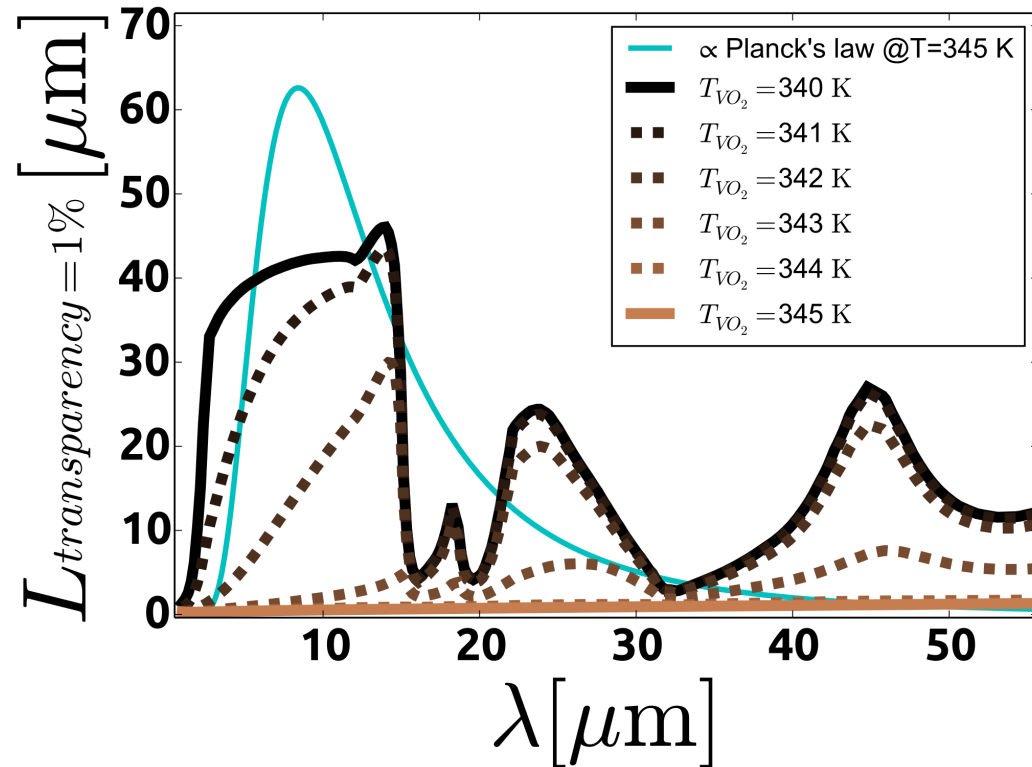
Transistor VO2 transistor en régime dynamique

Equation de la chaleur pour la grille



$$f_{cutoff} = 2.1 \cdot 10^{-5} \text{ Hz}$$

Epaisseur critique du VO2 pour être opaque



Epaisseur peut être réduite à 1 micron. Temps de réponse critique autour de la minute.

Perspectives

- Matériaux thermochromes.
- Fabriquer un transistor (en champ lointain)
- Aller dans le champ proche pour améliorer la dynamique
- Explorer les limites de la rectification dans des cas simples (systèmes à 2 niveaux)