Near-field heat transfer controlled by plasmons in graphene and applications in thermophotovoltaics

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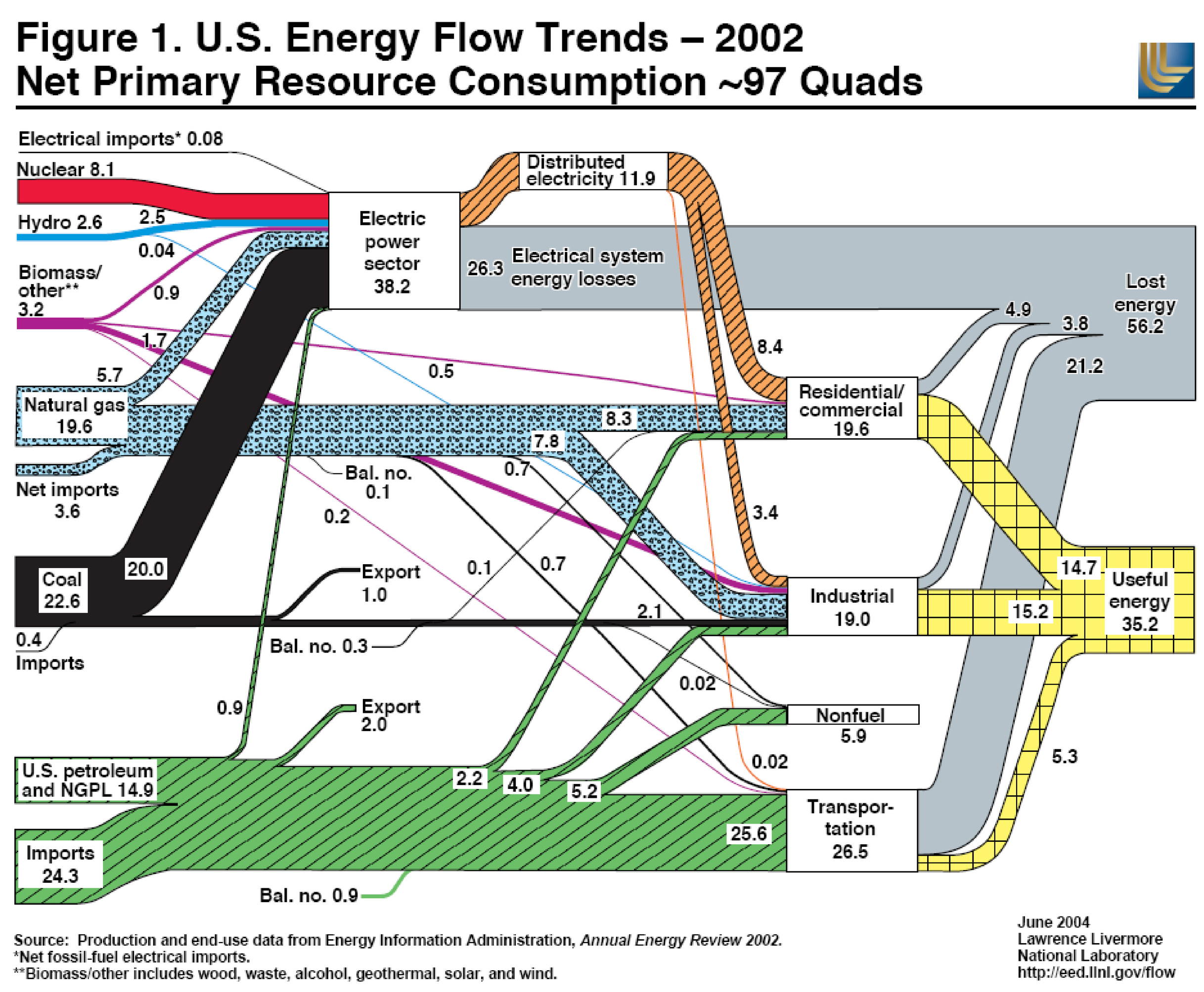
Main Point

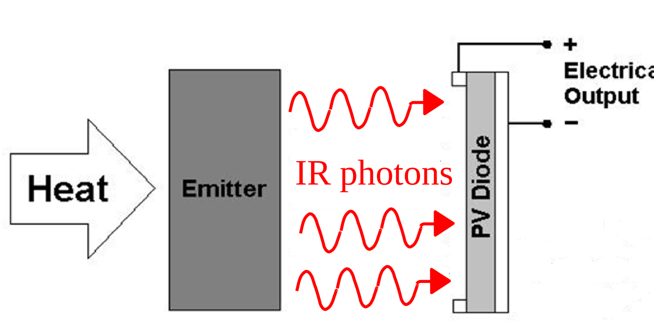
- Plasmon in graphene
- Large heat transfer in the near-field
- Large plasmon DOS ⟶ high power densities $\left(H_{gg} >> H_{BB}\right)$
- Thermophotovoltaics (heat to electricity)

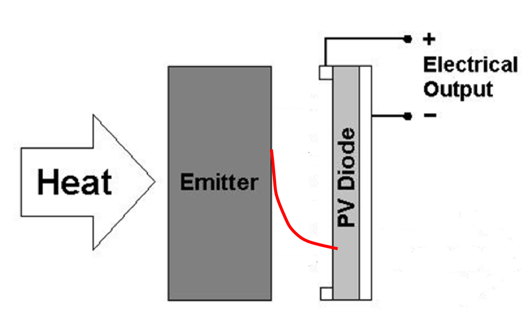
Motivation: heat losses (energy crisis)



Thermophotovoltaics (TPV): heat to electricity

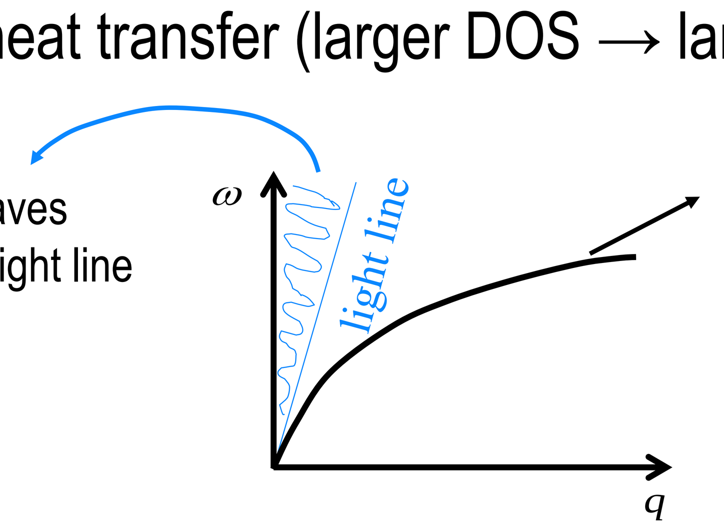
- Far field TPV
- Near field TPV





- Far field heat transfer: Stefan-Boltzman law $\frac{P_{BB}}{A}=\frac{\pi^2 k_B^4}{60\hbar^3 c^2}T^4$
- Near field heat transfer (larger DOS ⟶ larger power density)

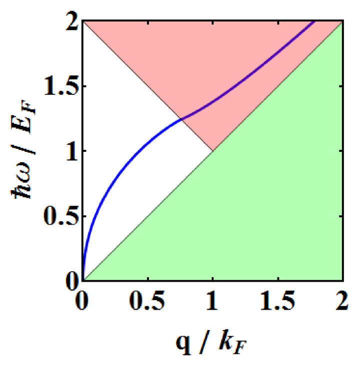
> Propagating waves
> Limited by the light line
> Small DOS
> Far field



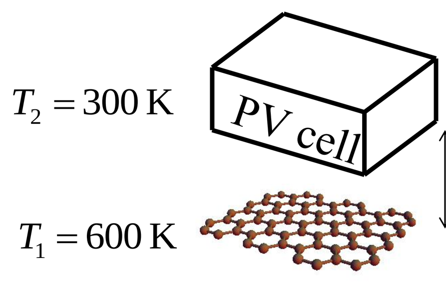
> Evanescent (surface waves)
> $q >> \omega / c$
> Large DOS
> Small (subwavelength) separation

- Plasmon in graphene:

$q \approx 100 \cdot \omega / c$

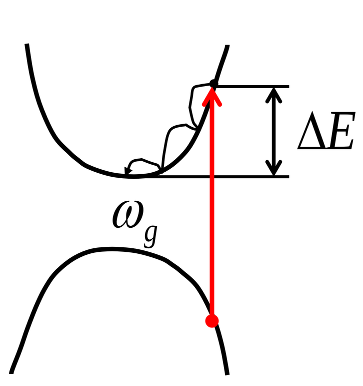


Near field TPV using graphene as a thermal emitter [1]



- PV cell (InSb): $\omega_g = 0.17\,\text{eV}$
- $D = 10\,\text{nm}$
- Graphene: $E_F = 0.25\,\text{eV}$

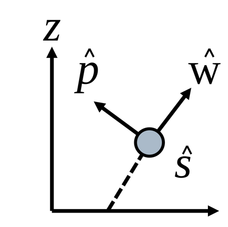
- Thermalization losses



biased voltage	near-field vs. far-field (BB)	power density	efficiency	Carnot efficiency
$V_0 = 0.08\text{V}$	$\frac{P^{gPV}_{rad}}{P^{BB}_{rad}} = 62$	$\frac{P_{PV}}{A} = 6\frac{\text{W}}{\text{cm}^2}$	$\eta = 35\%$	$\eta_C = 50\%$

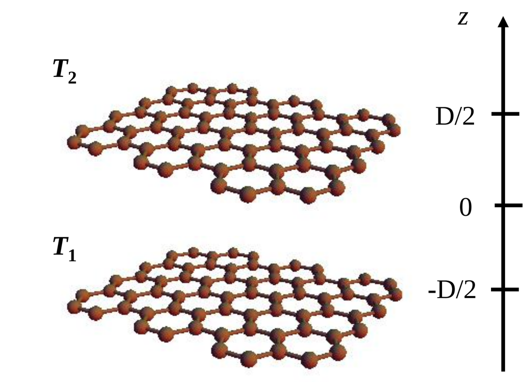
Radiative heat transfer

- Fluctuation-dissipation theorem



$$\left\langle j_{1\mu}(\mathbf{q},\omega)\, j^*_{1\mu}(\mathbf{q},\omega')\right\rangle = -\delta(\omega-\omega')\frac{1}{\pi}\frac{\hbar}{1-e^{-\beta_1\hbar\omega}}\operatorname{Im}\chi_{1\mu}(\mathbf{q},\omega)$$

- Fields above $z > D/2$



$$\mathbf{E}(\mathbf{q},\omega) = -\frac{\omega}{2\varepsilon_0 c^2 \gamma}\left(\hat{\mathbf{s}}T^s_{12}\hat{\mathbf{s}}+\hat{\mathbf{p}}T^p_{12}\hat{\mathbf{p}}\right)\cdot \mathbf{j}_1(\mathbf{q},\omega)$$

$$\gamma=\sqrt{\omega^2/c^2-q^2} \qquad T_{12}=\frac{t_1 t_2 e^{i\gamma D}}{1-r_1 r_2 e^{2i\gamma D}}$$

- Heat transfer = Ohmic losses

$$H_{1\to 2} = \int \mathbf{j}_2(\mathbf{r},t)\cdot\mathbf{E}(\mathbf{r},t)\,d\mathbf{r}$$

- Total heat transfer: $H = H_{ff} + H_{nf}$

$$H_{ff} = \frac{1}{(2\pi)^3}\int_0^\infty d\omega\left[\Theta(\omega,T_1)-\Theta(\omega,T_2)\right]\int_0^{\omega/c} 2\pi q\,dq\sum_\mu h^\mu_{ff}(q,\omega) \qquad (q<\omega/c)$$

$$H_{nf} = \frac{1}{(2\pi)^3}\int_0^\infty d\omega\left[\Theta(\omega,T_1)-\Theta(\omega,T_2)\right]\int_{\omega/c}^{\infty} 2\pi q\,dq\sum_\mu h^\mu_{nf}(q,\omega) \qquad (q>\omega/c)$$

- Boltzman factor: $\Theta(\omega,T)=\frac{\hbar\omega}{e^{\hbar\omega/kT}-1}$
- Far field spectral function: $h^\mu_{ff}(q,\omega)=\frac{|a_1^\mu|^2|a_2^\mu|^2}{4\left|1-r_1^\mu r_2^\mu e^{2i\gamma D}\right|^2}$

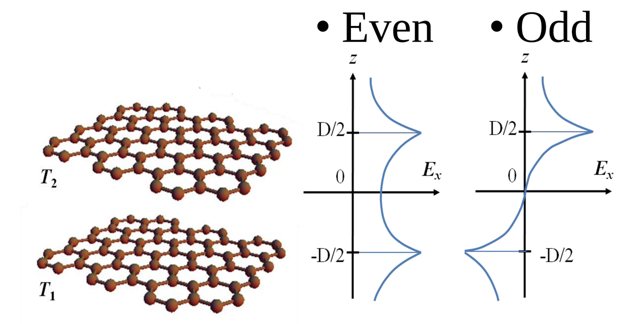
> Graphene absorption

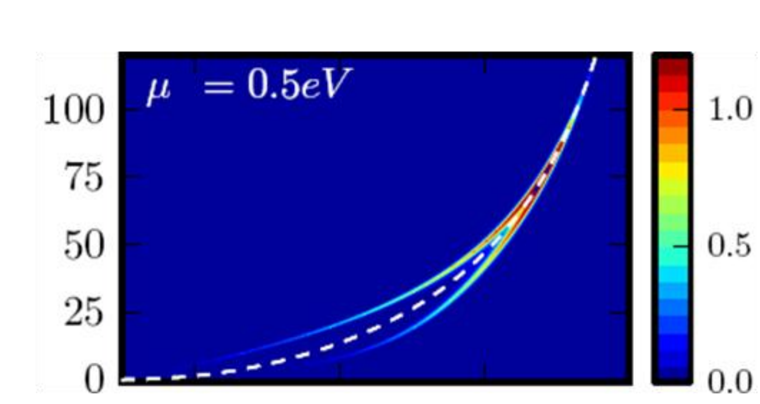
$|a|^2 \approx 2\% << |a_{BB}|^2 = 100\%$

- Near field spectral function: $h^\mu_{nf}(q,\omega)=\frac{\operatorname{Im} r_1^\mu \operatorname{Im} r_2^\mu e^{-2|\gamma|D}}{\left|1-r_1^\mu r_2^\mu e^{-2|\gamma|D}\right|^2}$

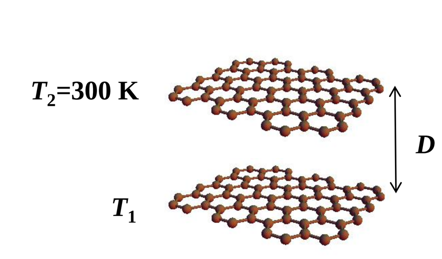
Near field heat transfer between two graphene sheets [2]

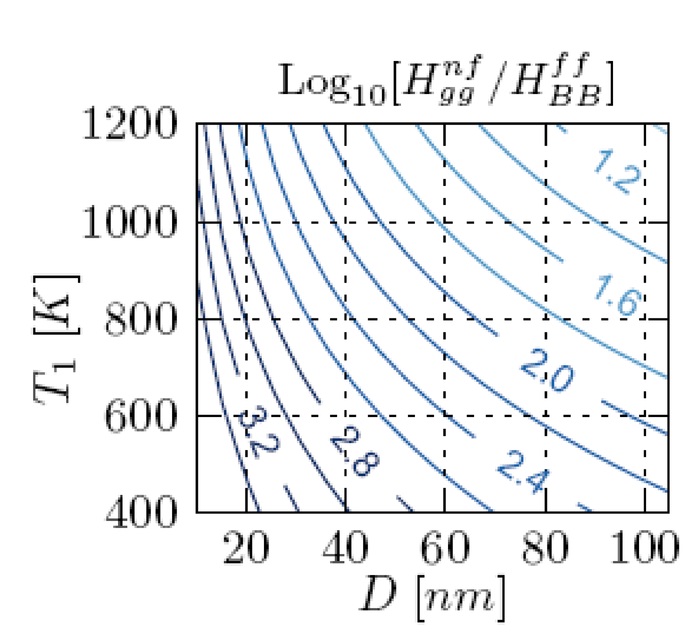
- Heat transfer dominated by TM modes (large DOS)
- Neglect TE modes (small DOS)
- Near field spectral function (identical sheets): $h^p_{nf}(q,\omega)=\frac{\left(\operatorname{Im} r^p\right)^2 e^{-2qD}}{\left|1-\left(r^p\right)^2 e^{-2qD}\right|^2}$
- Small separation: $h^p_{nf}(q,\omega) \propto e^{-2qD}$
- Coupled mode dispersion: $1-\left(r^p\right)^2 e^{-2qD}=0$





- Total heat transfer:





- Fermi level: $E_{F1,2} = 0.1\text{eV}$
- Relaxation time: $\tau_{1,2} = 10^{-13}\text{s}$

References

[1] O. Ilic, M. Jablan, J.D. Joannopoulos, I. Celanovic, M. Soljacic, Optics Express 20, A366 (2012).

[2] O. Ilic, M. Jablan, J.D. Joannopoulos, I. Celanovic, H. Buljan, M. Soljacic, Phys. Rev. B 85, 155422 (2012).

[3] P.J. van Zwol, S. Thiele, C. Berger, W.A. de Heer, J. Chevrier, Phys. Rev. Lett. 109, 264301 (2012).