Cooling and Seebeck effects in Double-Barrier Semiconductor Heterostructures

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Thematic day « Beyond Fourier »

The 9th of September 2022

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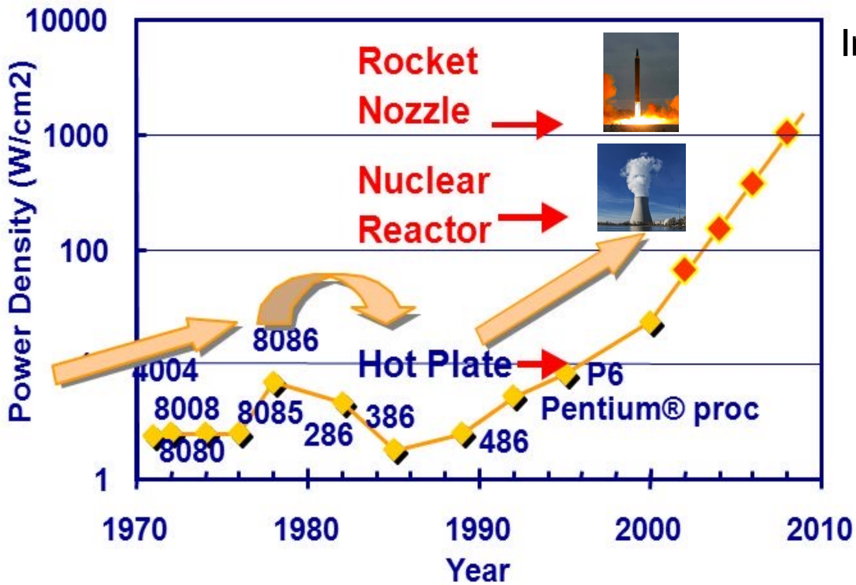
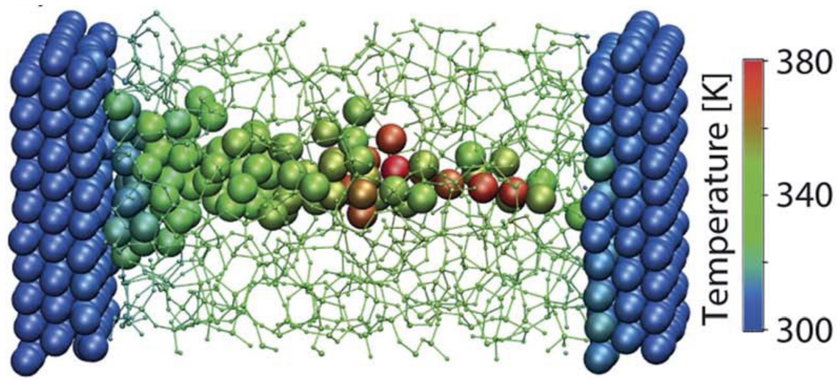
Cooling at the nanoscale

- **Self-heating: scientific and industrial issues**



Intel, 2004



CBRAM

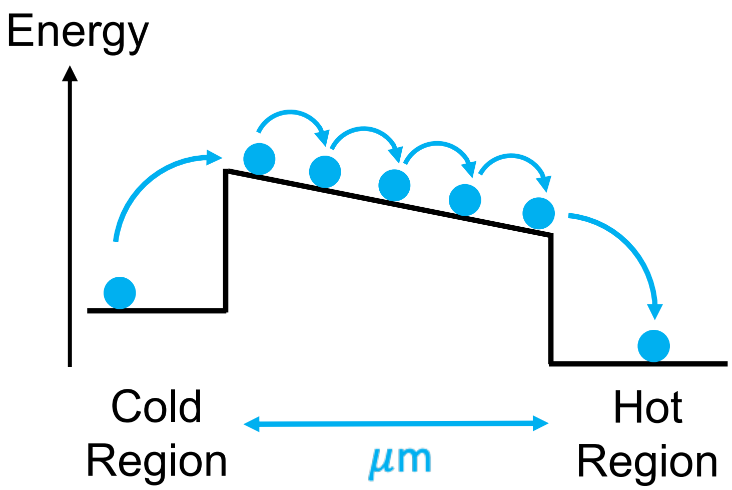
Nanoscale Adv., **2,** 2648 (2020)

M. Luisier, ETH Zurich

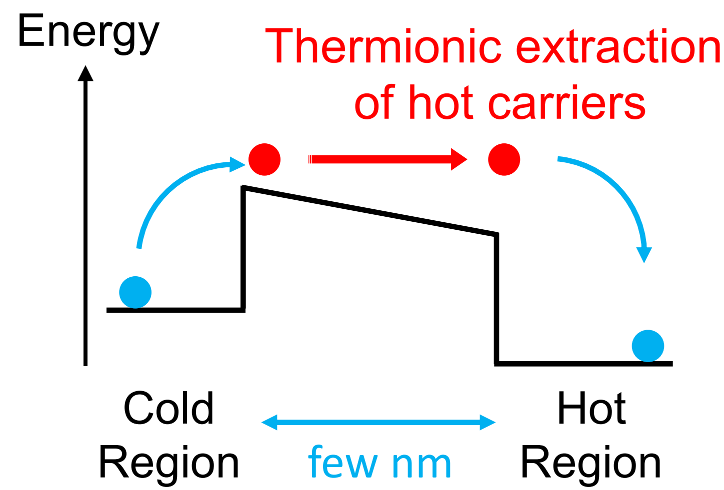
- Significant reduction of lifetimes and performances.
- “Bulk” refrigeration is extremely power consuming.

Urgent need of local source of cooling

Thermionic cooling*



Thermoelectric Peltier effect



Thermionic cooling

- ➢ Devices working in non-equilibrium regime.

Non-equilibrium ➜ Highest cooling power!

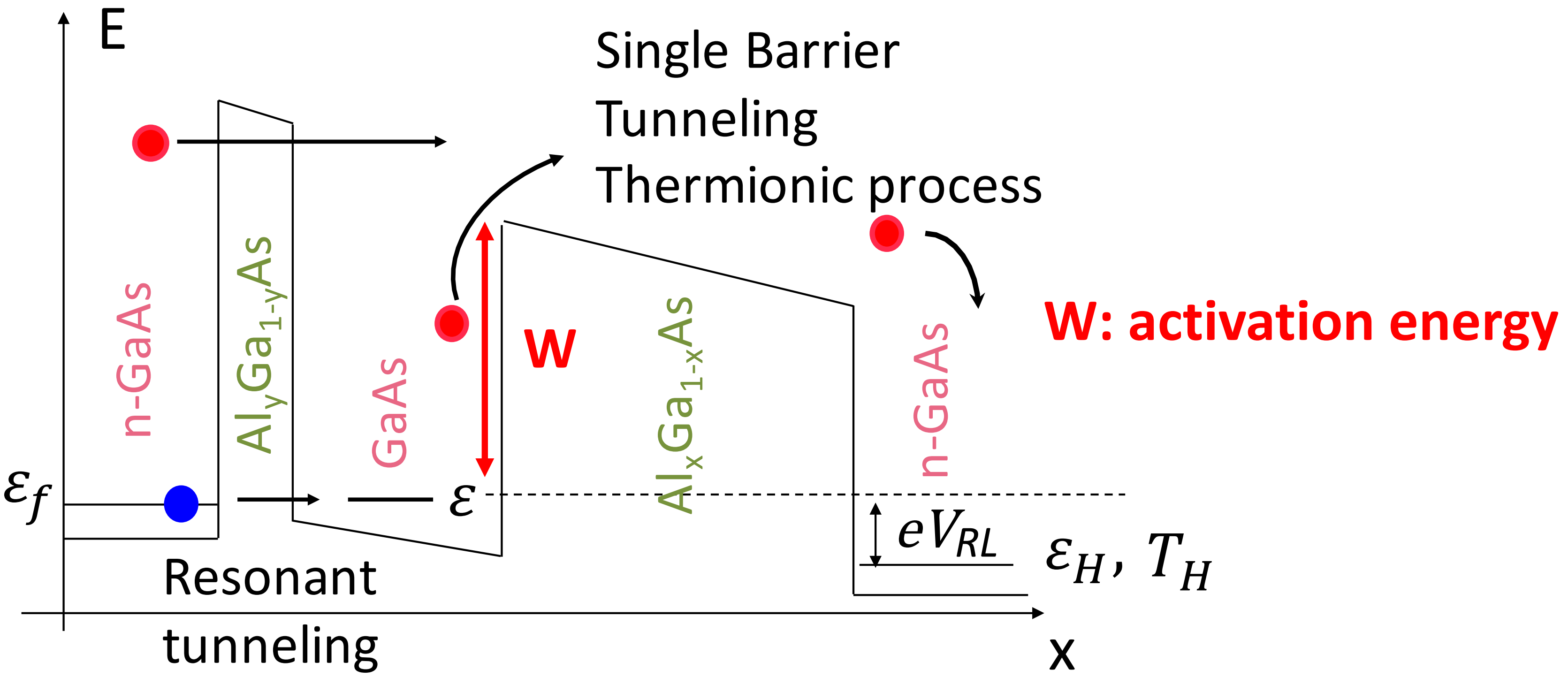
- ➢ Exploratory field: strong theoretical support.

Goal: use nano-structures to improve cooling efficiency.

*G. D. Mahan, *J. Appl. Phys.*, **76**, 4362 (1994).
*G. D. Mahan and L. M. Woods, *Phys. Rev. Lett.*, **80**, 4016 (1998).

Original thermionic cooling devices

➢ Coupling localized state and tunneling barrier*:



➢ Main idea: injecting cold electrons and extracting hot electrons.

➢ Investigate the concept of local temperature at the nanoscale.

*K. A. Chao, M. Larsson, and A. G. Mal'shukov, *Appl. Phys. Lett.*, **87**, 022103 (2005).

Simulations Requirements

Coupling of electron and heat transport

Electron transport

Treatment of quantum effects and non-equilibrium phenomena

Heat transport

- ➢ Electron → Non-Equilibrium Green's Function (NEGF) 👌
  - Effective mass approach, k.p, tight-binding, ab initio…
- ➢ Heat → Non-Equilibrium Green's Function (NEGF) 😅

Much less documented topic:
Harmonic (ballistic): N. Mingo and L. Yang, *Phys. Rev. B* **68**, 245406 (2003).

NEGF for phonon

- NEGF for electrons: Schrödinger equation

$$(E\mathbf{I} - \mathbf{H})\overline{\psi} = \bar{0} \quad \Rightarrow \quad \left[G^R(E)\right]$$

- NEGF for phonons: dynamical equation

$$\omega^2 \mathrm{M} + \Phi_{nm}^{ij} \bar{R} = \bar{O} \qquad \text{with} \qquad \Phi_{nm}^{ij} = \frac{\partial^2 V^{harm}}{\partial R_n^i \, \partial R_m^j}$$

Vibration frequency — Mass of the atoms (matrix) — 2^{nd} order FC — Displacement of the atoms

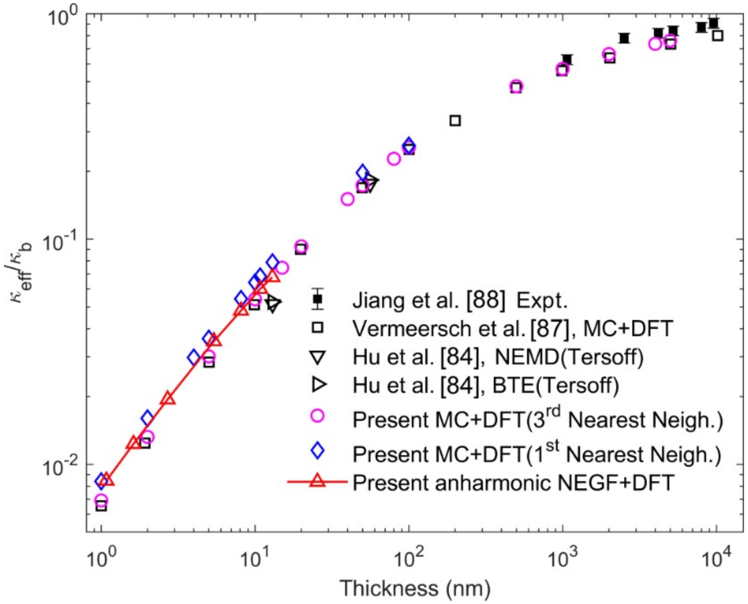
Retarded Green's function $\mathbf{G}^{\mathrm{R}}(\omega) = [\omega^2\mathbf{I} - \mathbf{\Phi} - \mathbf{\Sigma}^{\mathrm{R}}(\omega)]^{-1}$

- Anharmonic: N. Mingo, *Phys. Rev. B* **74**, 125402 (2006). (junctions)
  J. S. Wang, N. Zeng, J. Wang, and C. K. Gan, *Phys. Rev. E* **75**, 061128 (2007).
  M. Luisier, *Phys. Rev. B* **86**, 245407 (2012). (nanowires)
  K. Miao *et al., Appl. Phys. Lett*. **108**, 113107 (2016). (Büttiker Probes)
  J. H. Dai and Z. T. Tian, *Phys. Rev. B* **101**, 041301 (2020). (interfaces)
  R. Rhyner and M. Luisier, *Phys. Rev. B* **89**, 235311 (2014). (NEGF coupling e-/ph!!)

NEGF for phonon

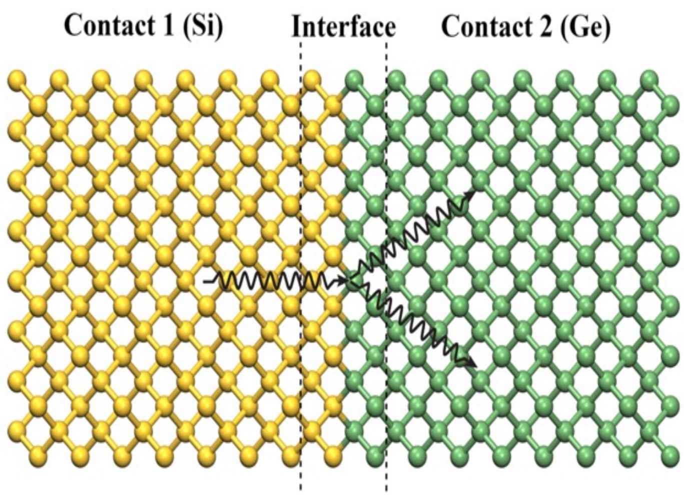
➢ Anharmonic phonon NEGF development: additional issues

Thermal conductivity Si film



Y. Guo, *et al., Phys. Rev. B*, **102**, 195412 (2020).

Si/Ge interface



Y. Guo, *et al., Phys. Rev. B* **103** (17), 174306 (2021).

➢ Anharmonicity:

1) Non-local treatment of the phonon-phonon self-energies!
2) 4th order force constant might be needed…

→ NEGF for phonons can be only applied to rather small (tens of nanometers) systems.

Alternative approach:

NEGF for electrons
+
Heat equation

→ M. Bescond *et al. J. Phys.: Condens. Matter* **30**, 064005 (2018).

NEGF + Heat equation

- **Non-equilibrium Green's function coupled to heat equation***

NEGF equations for electrons

$$G^r_{k_t} = \left[(E-V)I - H_{k_t} - \Sigma^r_{L,k_t} - \Sigma^r_{R,k_t} - \Sigma^r_{S,k_t}\right]^{-1}$$

Poisson equation

$$\nabla.(\epsilon \nabla V) = -\rho\left[G^{\lessgtr}\right]$$

Heat equation

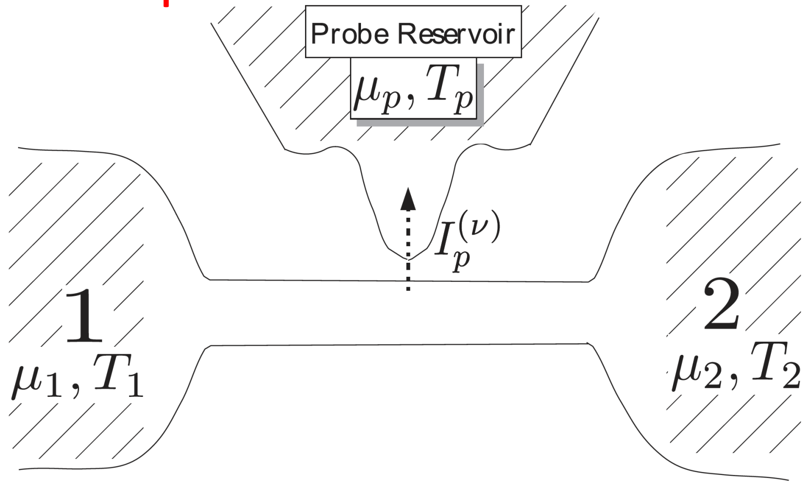
$$\left[-\frac{\partial}{\partial x}\left[\kappa_{\text{th}}(x)\frac{\partial}{\partial x}T_{AC}(x)\right]\right]_j = Q_j$$

- Most of physical properties: current, electron density, LDOS, local phonon temperatures, cooling power, efficiency…
- But… We are in a strong non-equilibrium regime… $T_{AC} \neq T_{POP} \neq T_e$
- Temperature of electrons in the active region???

Electronic temperature: virtual probe technique

- System out of equilibrium:
  Electronic and lattice temperatures usually not coincide.
- Accurate electronic temperature measurement (i.e. that follows the thermodynamic laws) requires simultaneously local voltage measurement.[1,2]
- Technique: vanish net charge current ($I_p^{(0)}$) **and** net heat current ($I_p^{(1)}$) into the probe.
  --> probe in local equilibrium with the sample.

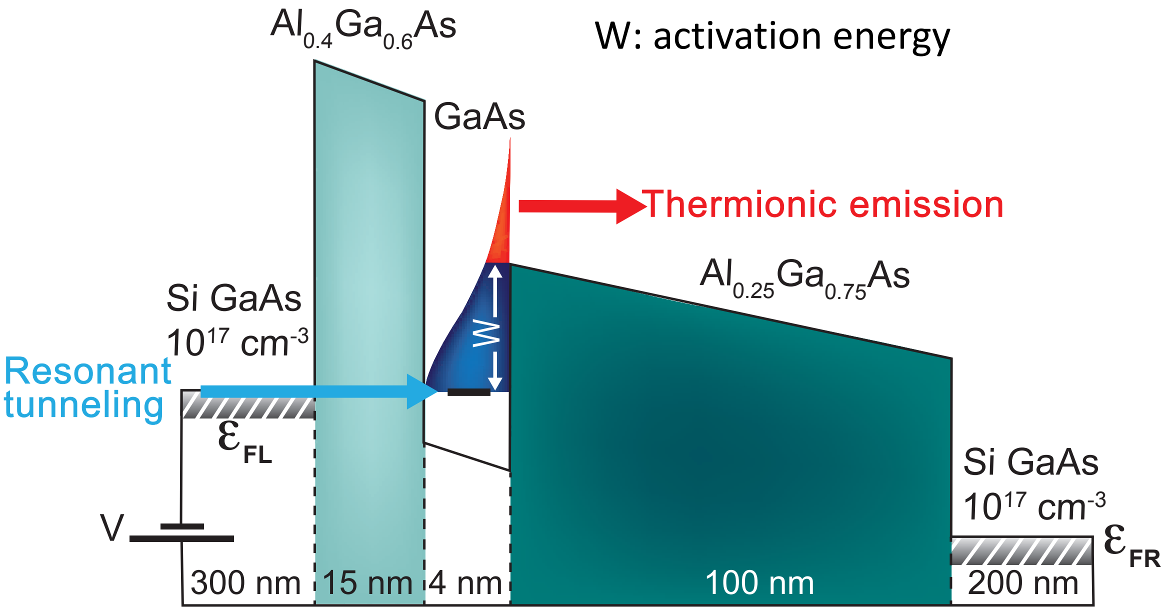
$$I_p^{(\nu)} = 0, \quad \nu \in \{0,1\}$$

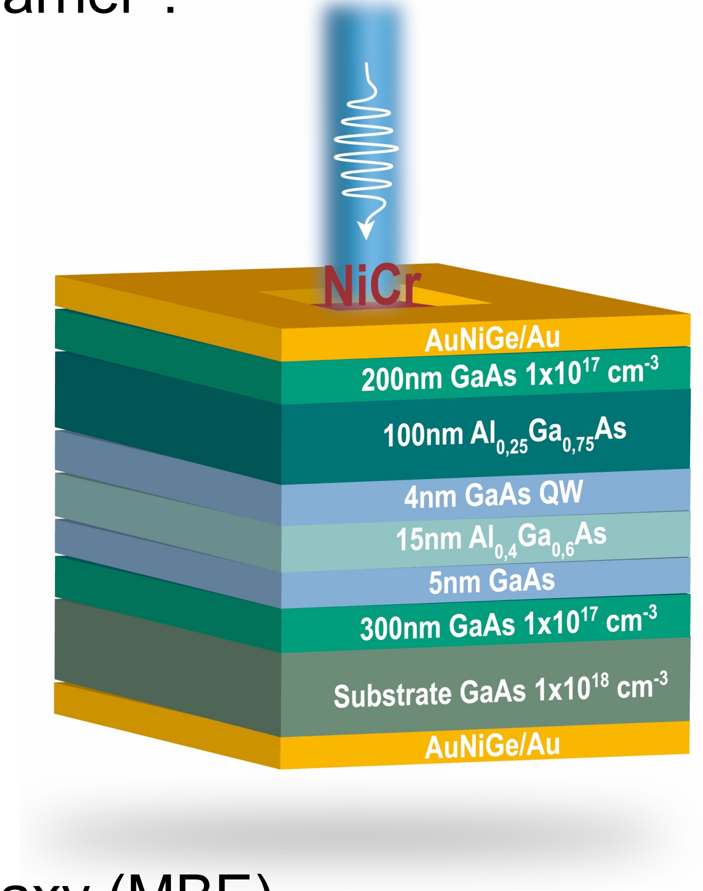


[1] C. A. Stafford, *Phys. Rev. B* **93**, 245403 (2016).
[2] A. Shastry and C. A. Stafford, *Phys. Rev. B* **94**, 155433 (2016).

Experimental implementation

- Coupling localized state and tunneling barrier*:

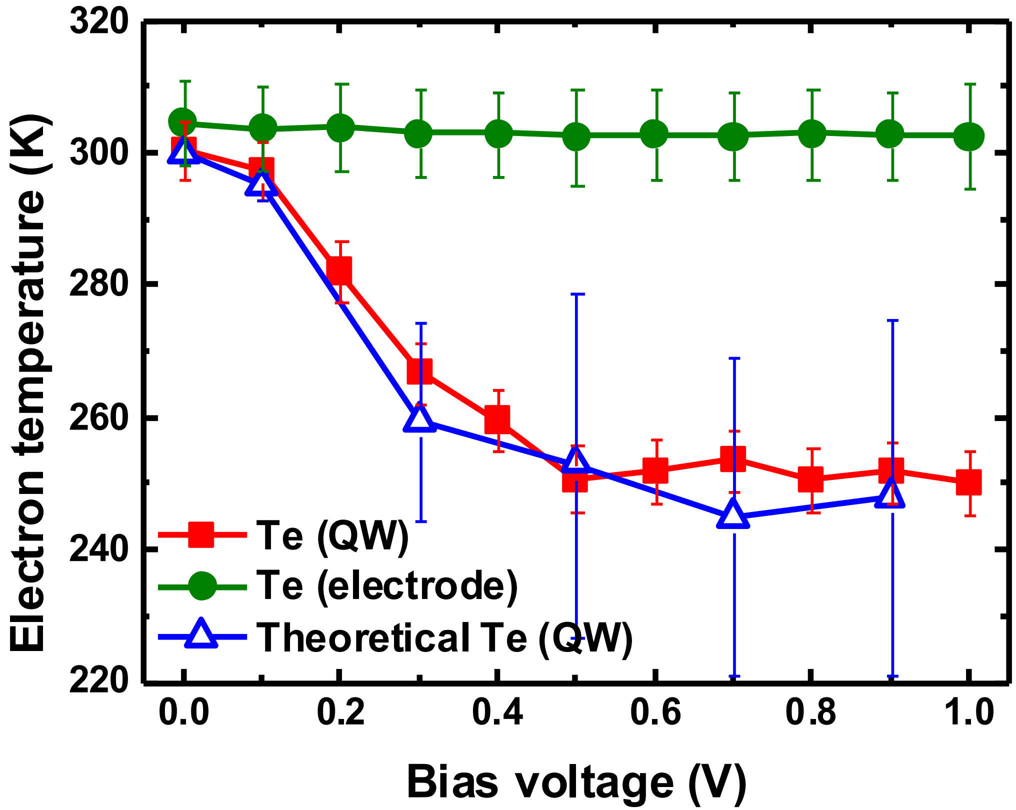


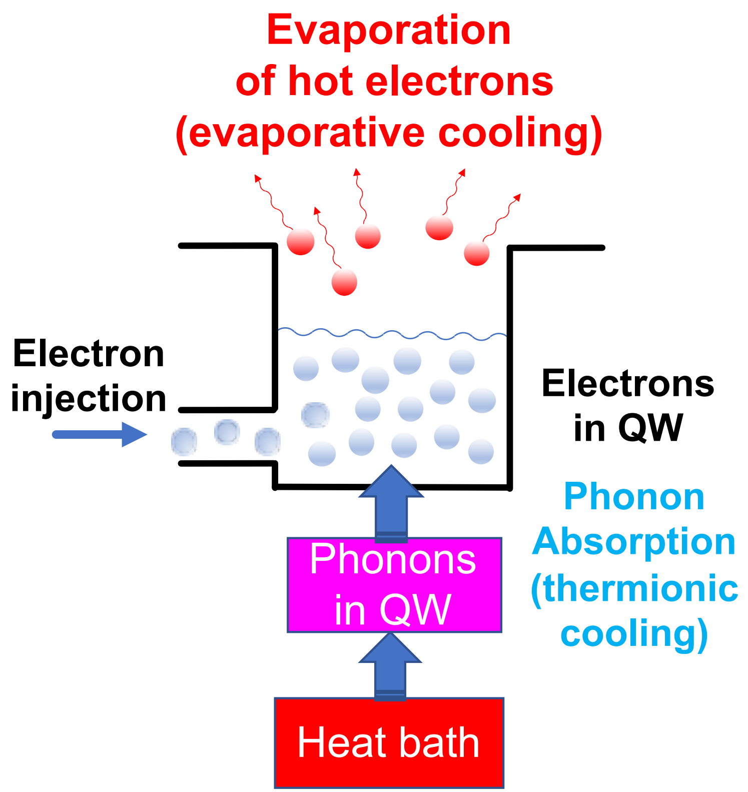


- Sample fabrication: Molecular beam epitaxy (MBE).
- Temperature of electron T_e in the quantum well (QW).

*A. Yangui, M. Bescond, T. Yan, N. Nagai, and K. Hirakawa, *Nature Commun*. **10**, 4504 (2019).

Electron Temperature(s)*

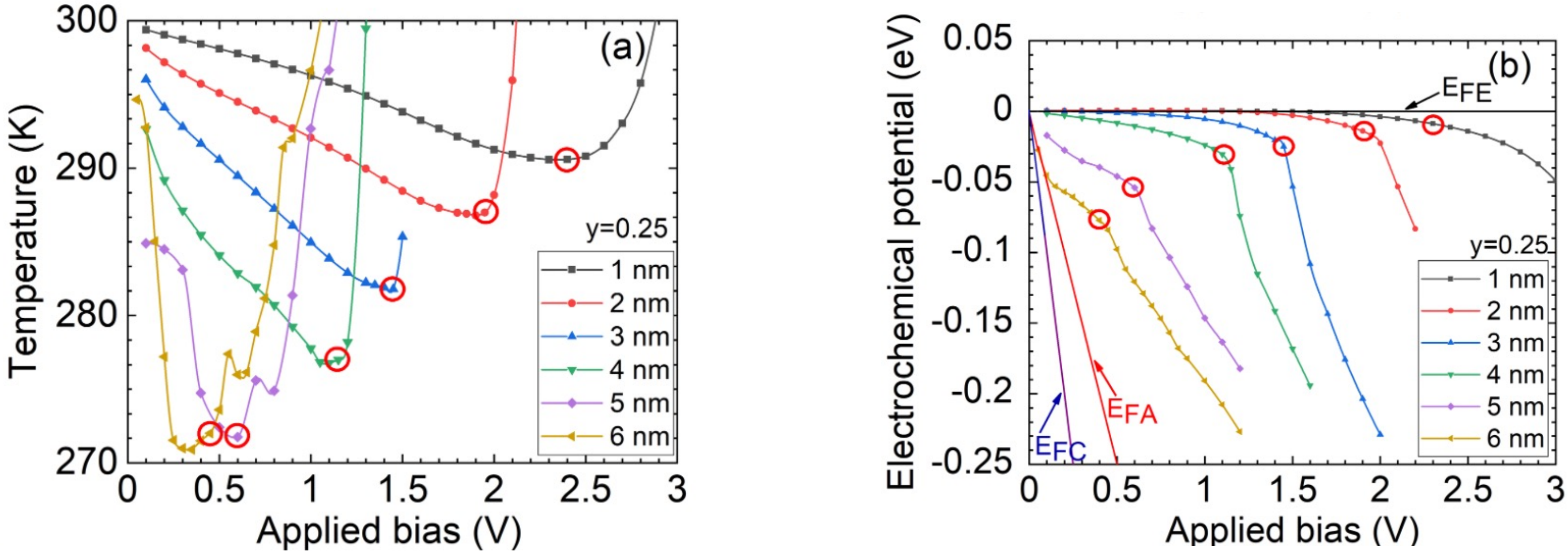




- T_e in electrodes constant.
- T_e in the QW decreases by 50K due to evaporative cooling.

*A. Yangui, M. Bescond, T. Yan, N. Nagai, and K. Hirakawa, *Nature Commun*. **10**, 4504 (2019).

Maximum electron cooling*



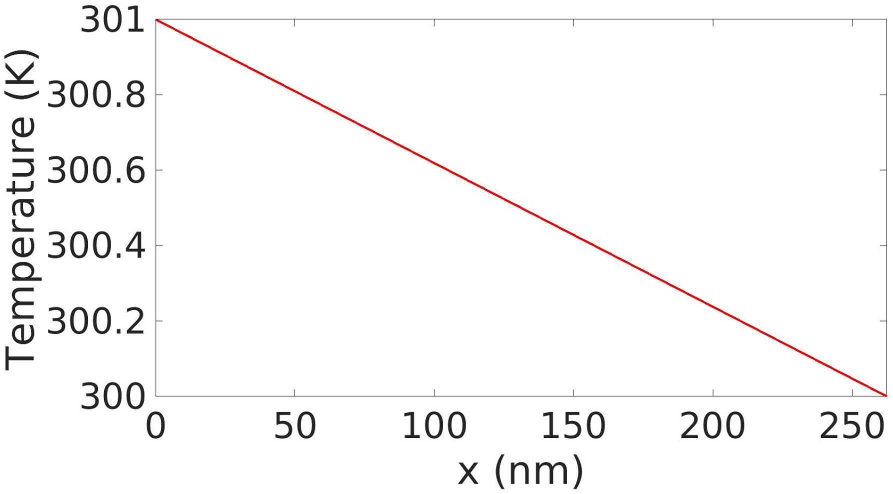
- Temperature minimum coincides very well with the resonance condition (highest current →best energy filtering).
- Temperature reduction increases with L_{Emit}.
- Electrochemical potential: best cooling when $R_{Emit} \approx R_{Coll}$.

*M. Bescond, *et al.*, *Phys. Rev. Appl.* **17,** 014001 (2022).

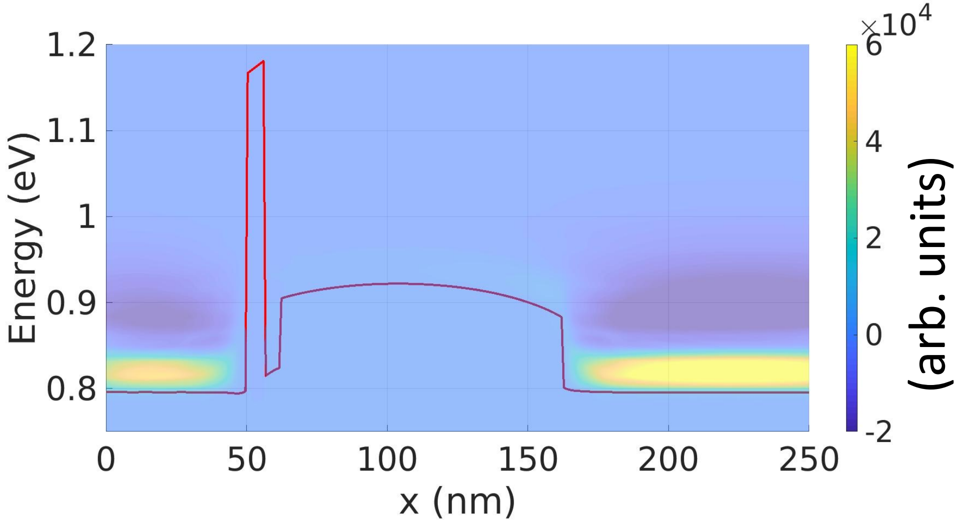
Thermoelectric properties

Lattice temperature gradient

ΔT=1 K



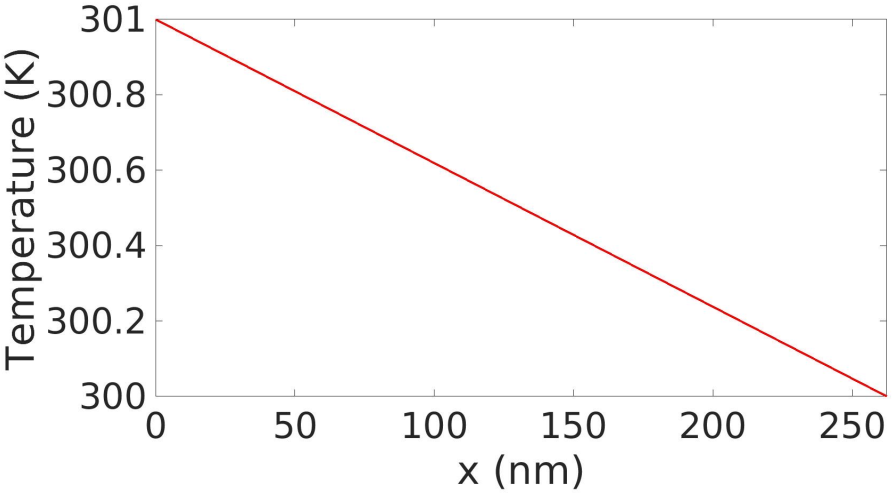
Current spectrum



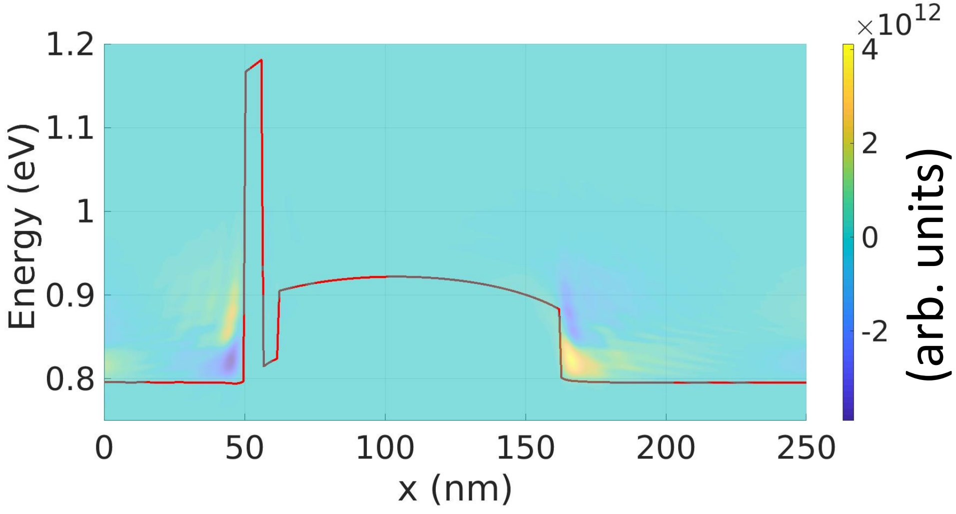
- Two current components in the access regions.
- At the barrier: phonon emission/absorption and back flow towards the contacts

Lattice temperature gradient

ΔT=1 K



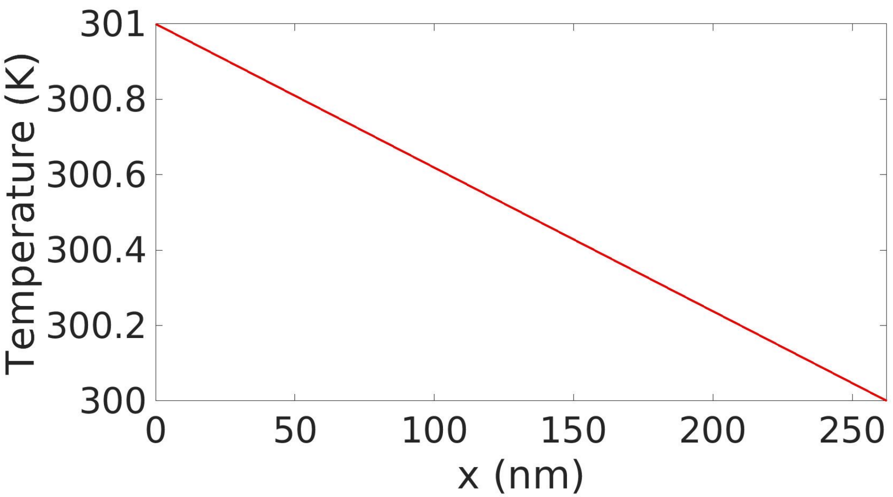
Derivative of energy current



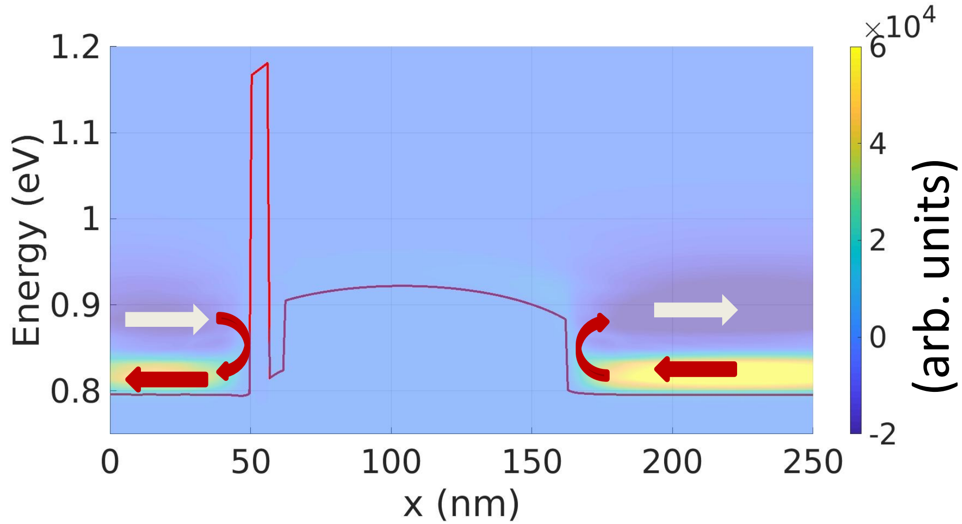
- Two current components in the access regions.
- At the barrier: phonon emission/absorption and back flow towards the contacts

Lattice temperature gradient

ΔT=1 K



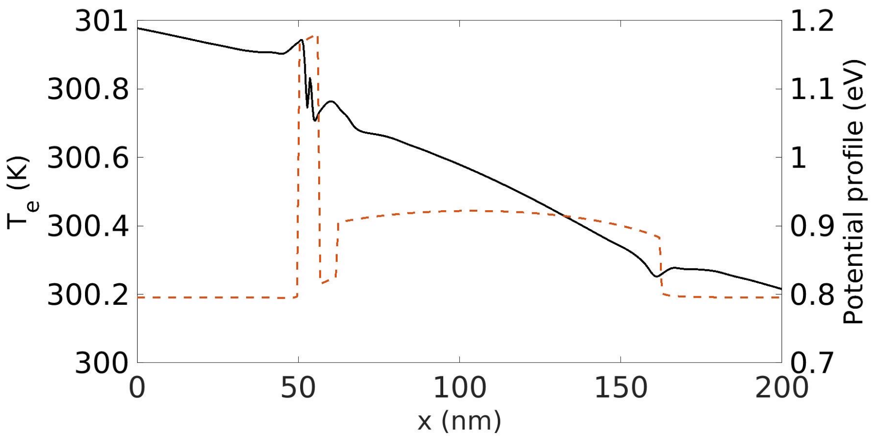
Current spectrum

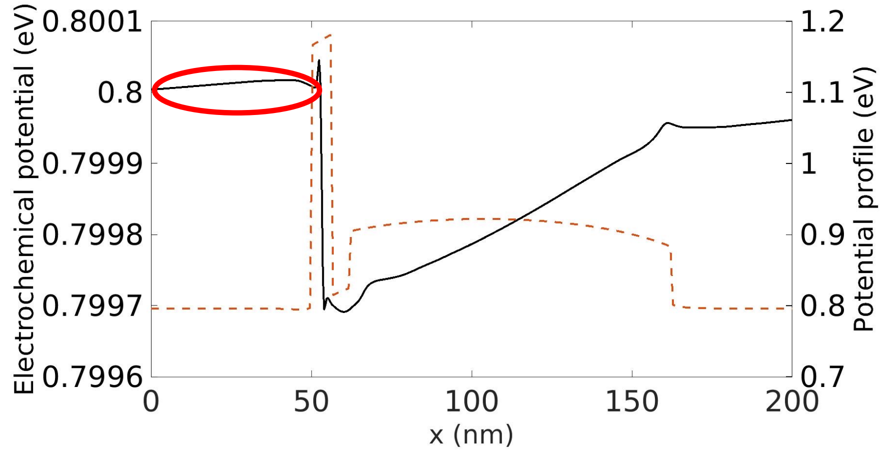


- Two current components in the access regions.
- At the barrier: phonon emission/absorption and back flow towards the contacts

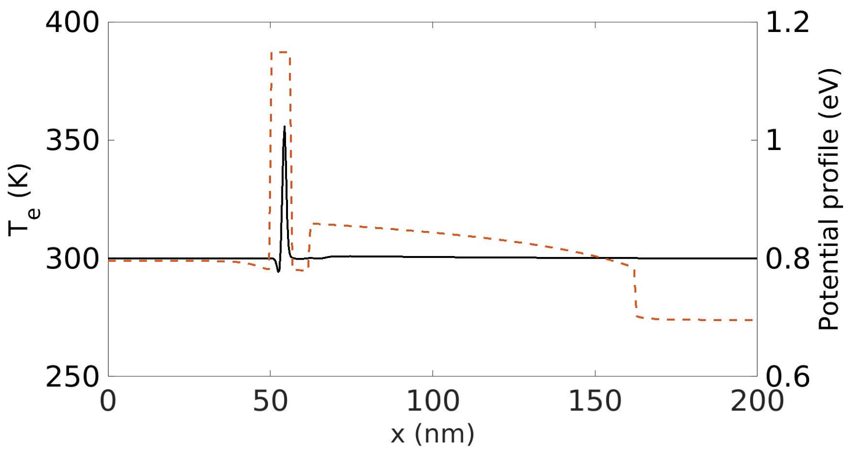
Electron temperature and Chemical potential

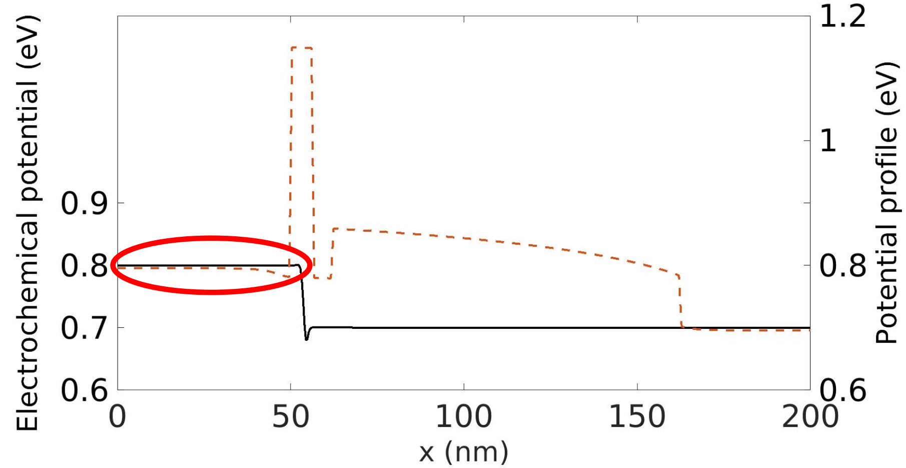
ΔT=1 K, ΔV=0 V





ΔT=0 K, ΔV=0.1 V

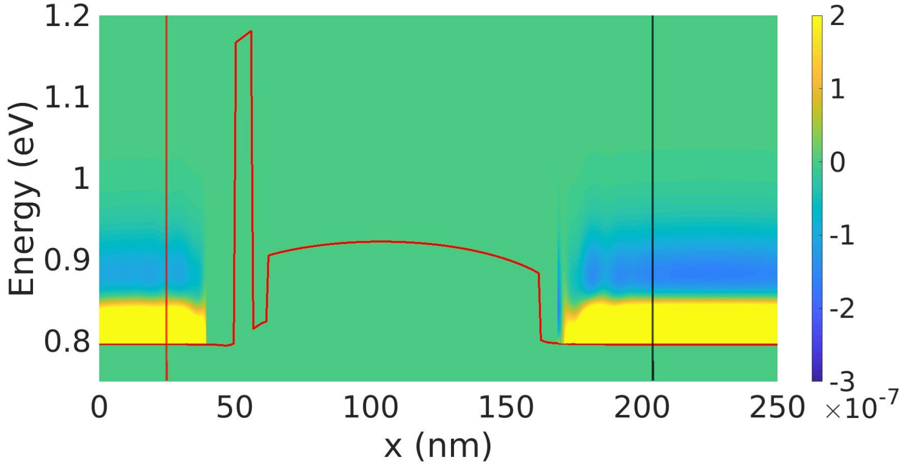




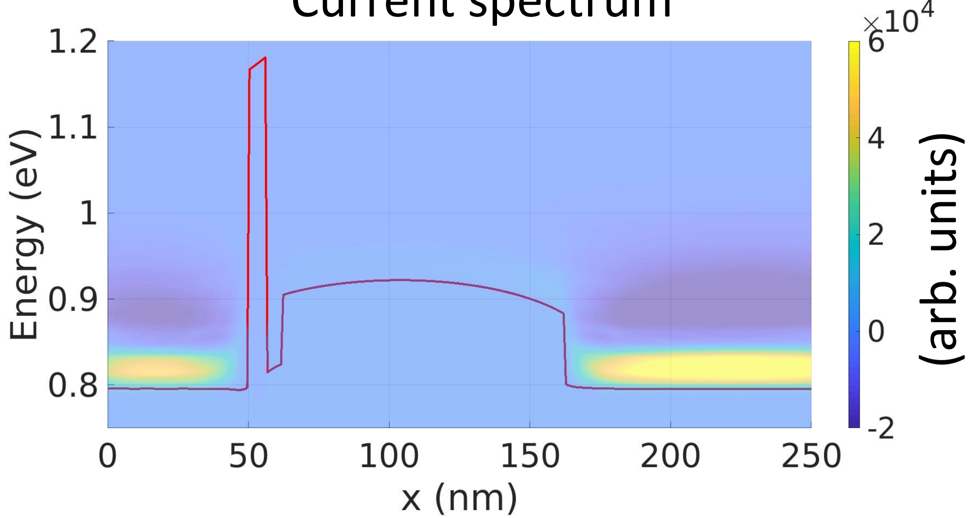
Difference of the Fermi-Dirac distributions

ΔT=1 K, ΔV=0 V

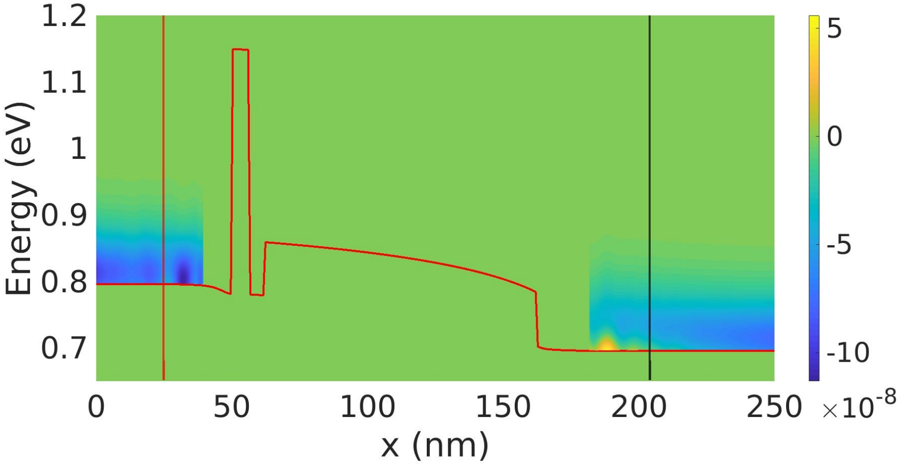
Δf_{FD}

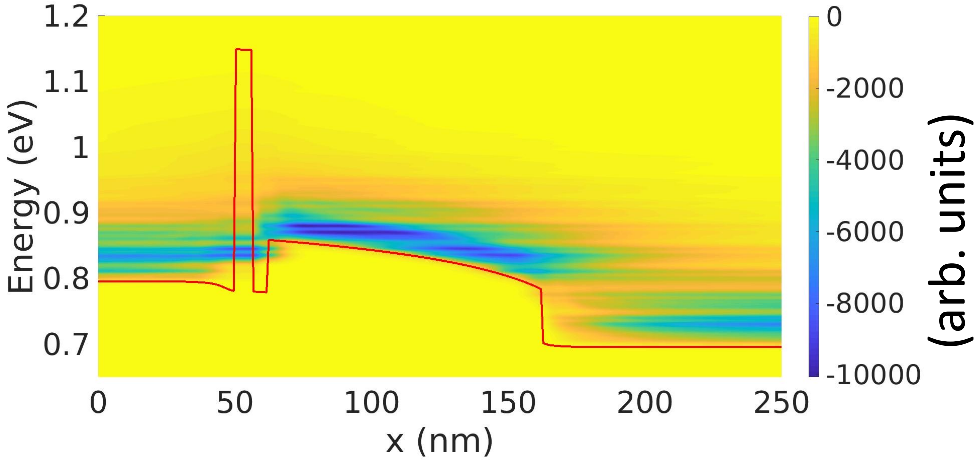


Current spectrum



ΔT=0 K, ΔV=0.1 V



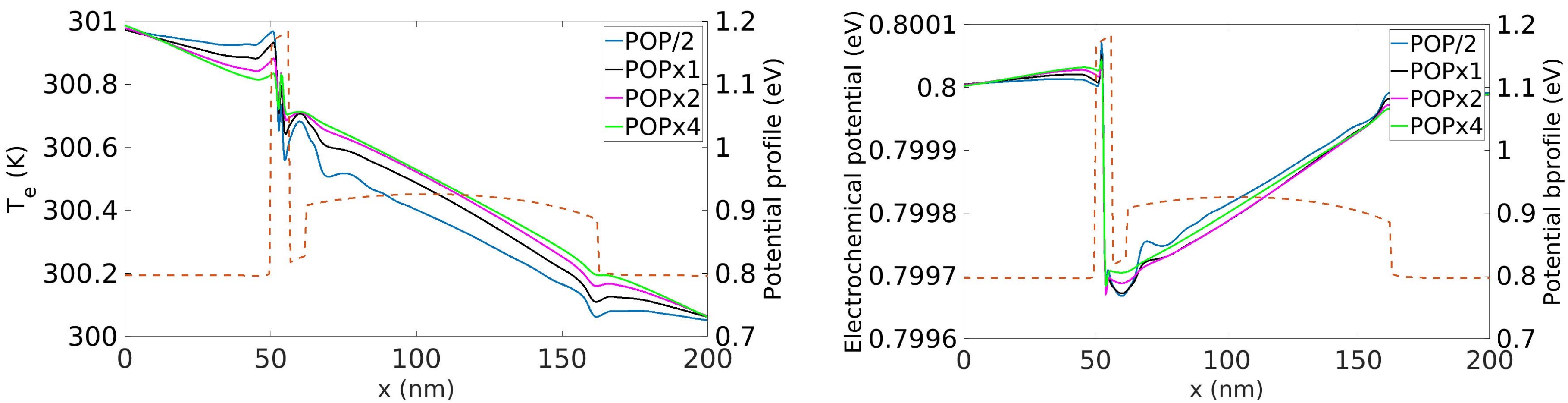


Origin of the reverse current component

- Reverse current: due to the variation of μ in the device.

- Increase of μ required to maintain the electron density with a ΔT_e.

Impact of the electron-phonon coupling



- Increasing coupling: T_e follow $T_{Lattice}$

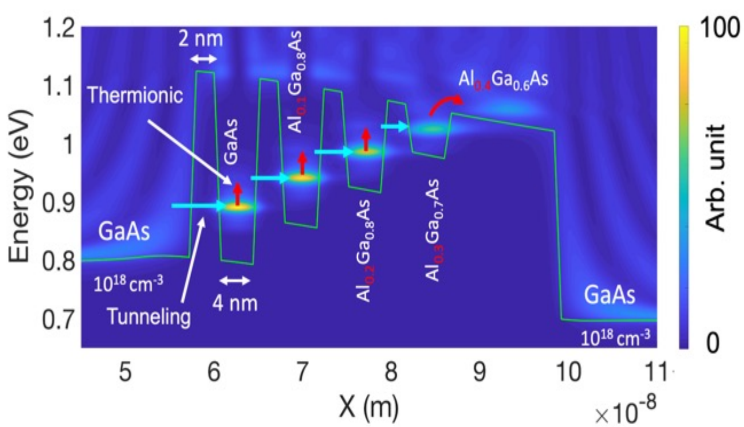
⟹ Larger T_e decrease

⟹ Larger μ increase

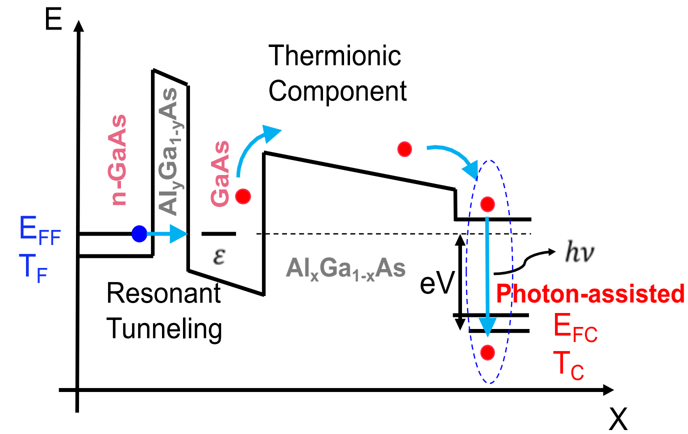
Conclusion

- Coupling NEGF and heat equation: good insight of the physical properties of the thermoelectric systems (good agreement with experiment).

- Conception and optimization of devices



Quantum cascade cooler



Opto-thermionic pumping

Novel generation of cooling devices

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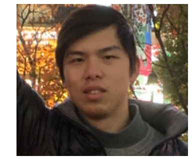
im2np Institut Matériaux Microélectronique Nanosciences de Provence
Aix*Marseille université initiative d'excellence
Institute of Industrial Science, The University of Tokyo

ANR GELATO (Oct. 2021- Apr.2025)

LIMMS, CNRS, IIS-University of Tokyo:

- Pr. Kazuhiko Hirakawa

Dr. Chloé Salhani
Post-doc



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Thank you!