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The Quantum Cascade Cooler: an NEGF analysis

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Outline:

- Context
- Cooling devices
  - Asymmetric double barrier
  - Quantum Cascade Cooler
- Self-consistent method
- Results
  - Performance comparison
  - Electron temperature oscillations

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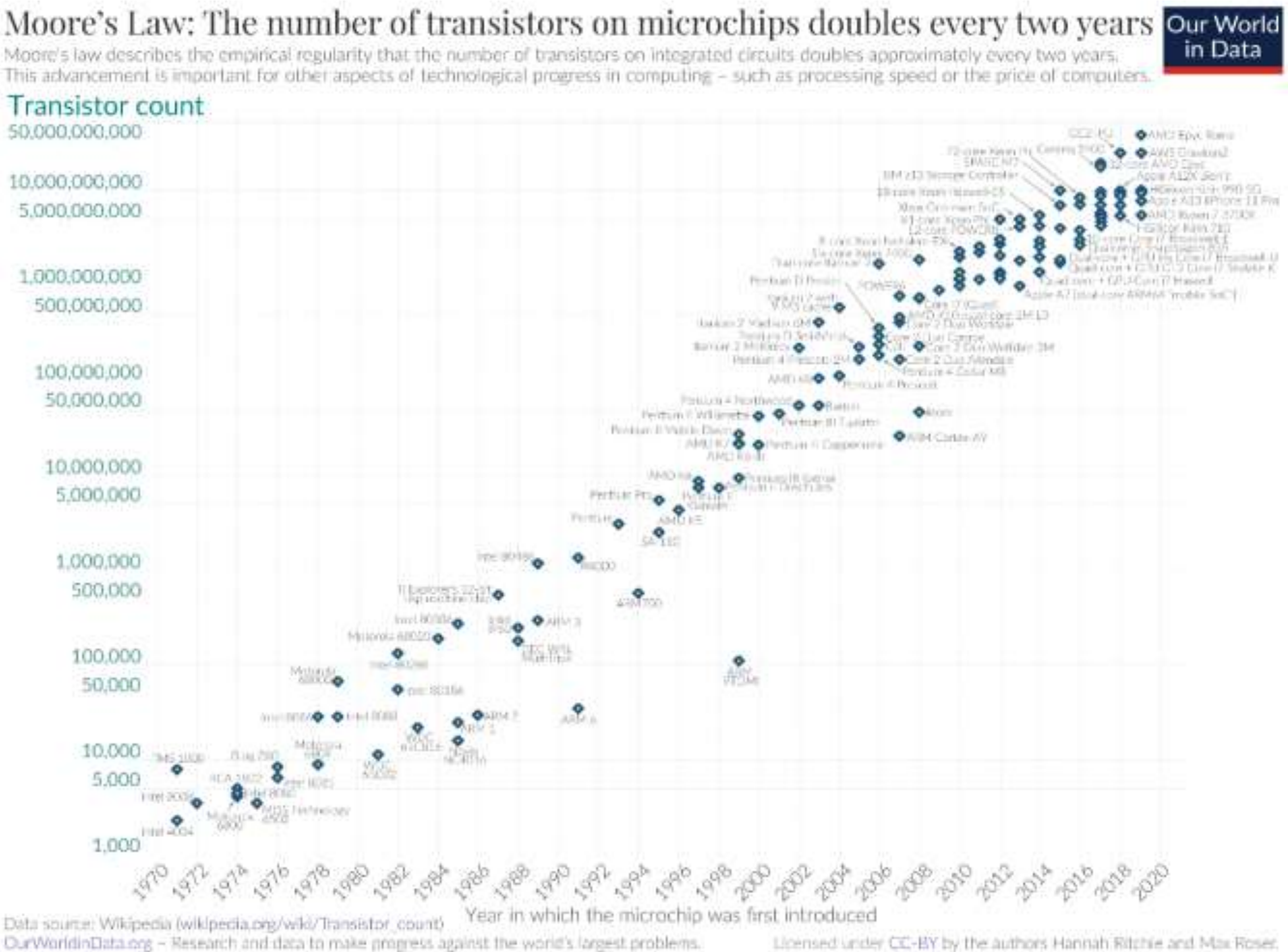
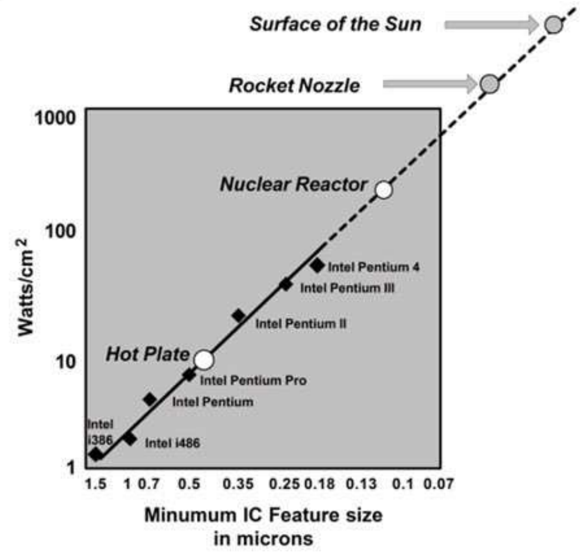
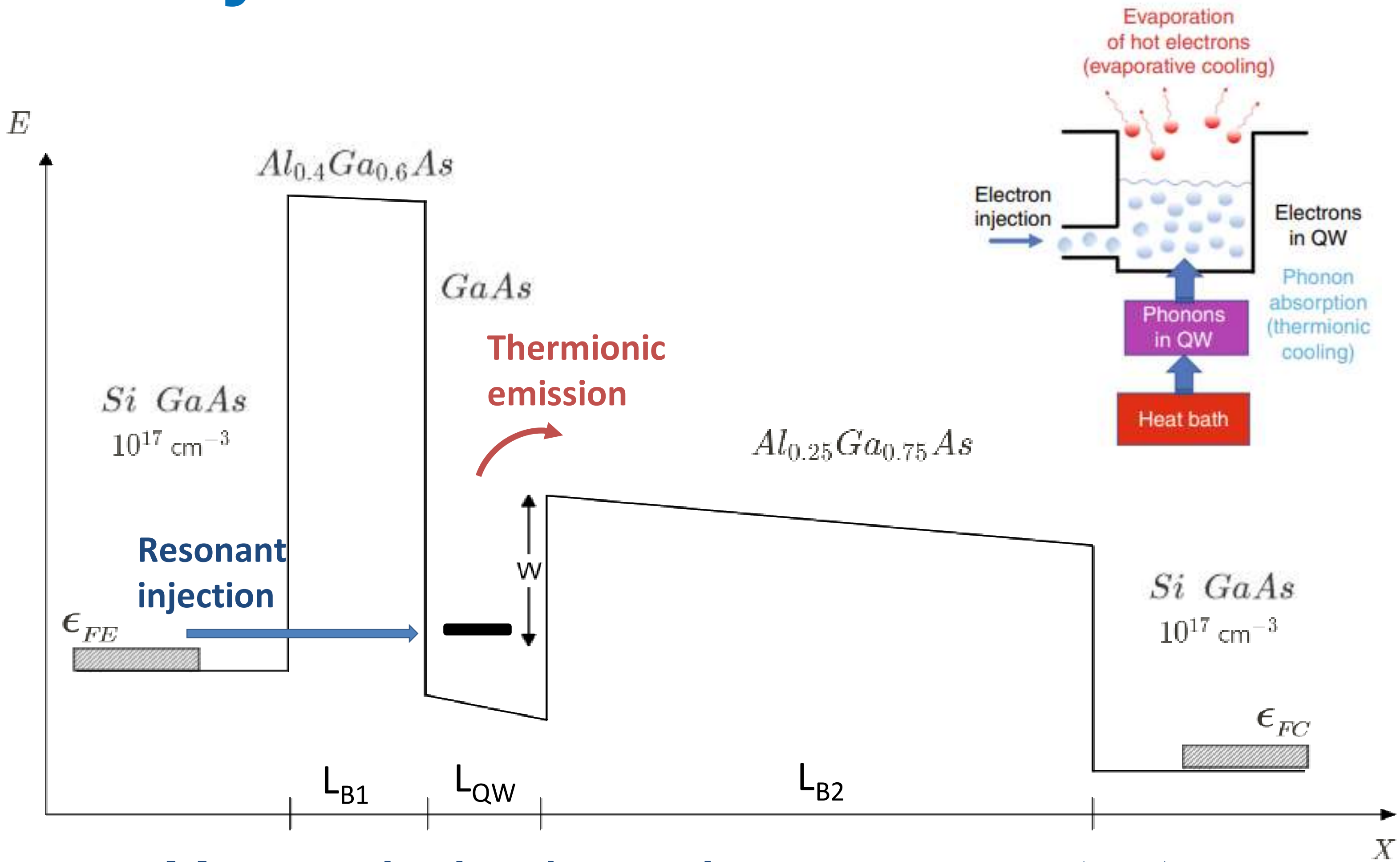
Context:

The need for new cooling devices:





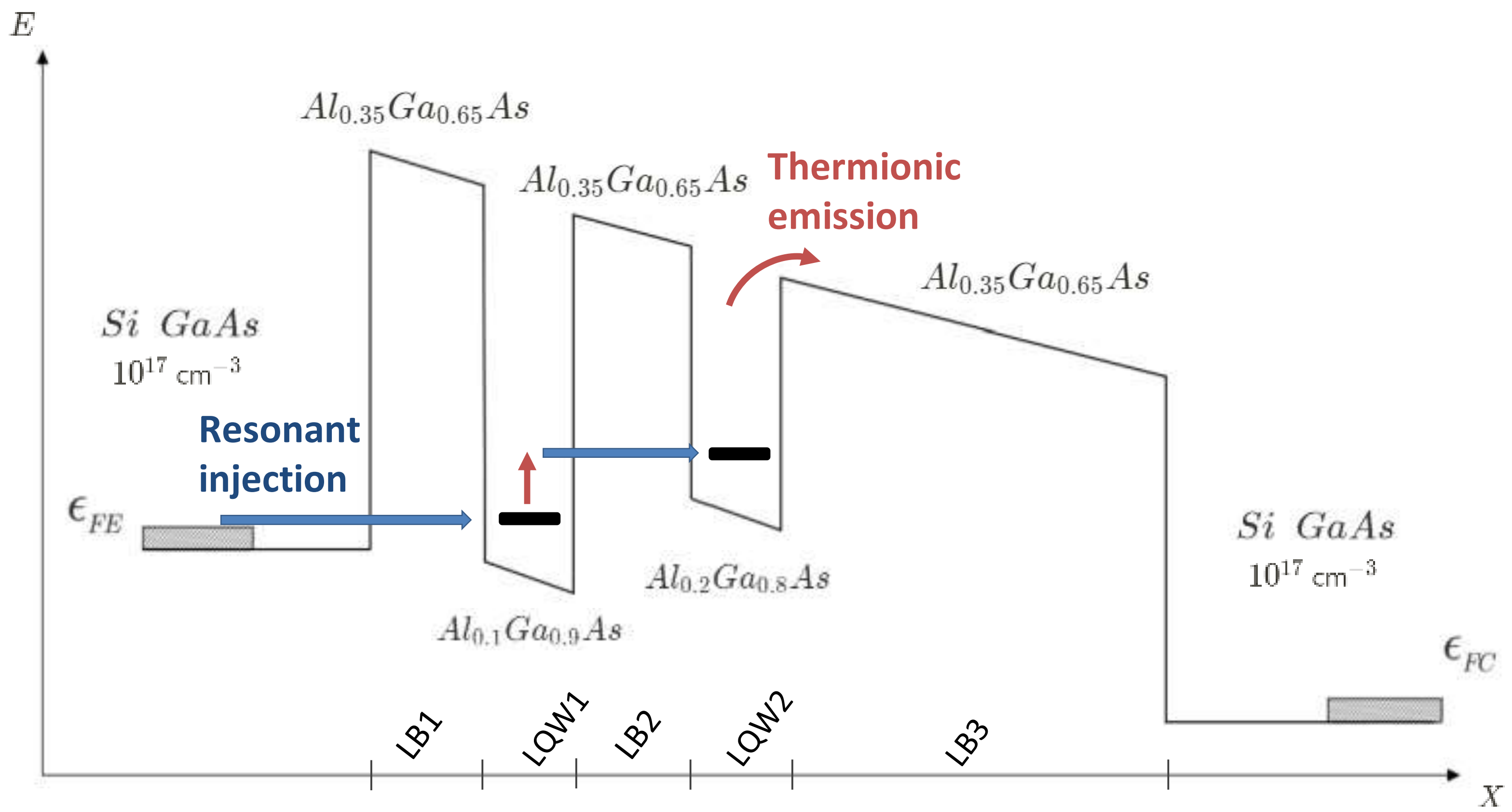
Asymmetric double barrier



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

- **Electron temperature reduced** by up to 50K. (evaporative cooling)

Quantum Cascade Cooler



- QCC consists of a periodic serie of the previous structure
- 1 **electron absorbs** several **phonons in cascade** along the structure

Self-consistent method

<u>Green's functions coupled to Heat and Poisson equations:</u>

NEGF equations for electrons

$$\left[EI - H - \Sigma_{\mathrm{C}} - \Sigma_{\mathrm{ph}}\right]G = I$$

Heat equation

$$-\nabla \cdot (\kappa_{th} \nabla T_{AC}) = Q\left[G^{\lessgtr}(T_{AC}, T_{OP})\right]$$

Poisson equation

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

<u>Including interactions with:</u>

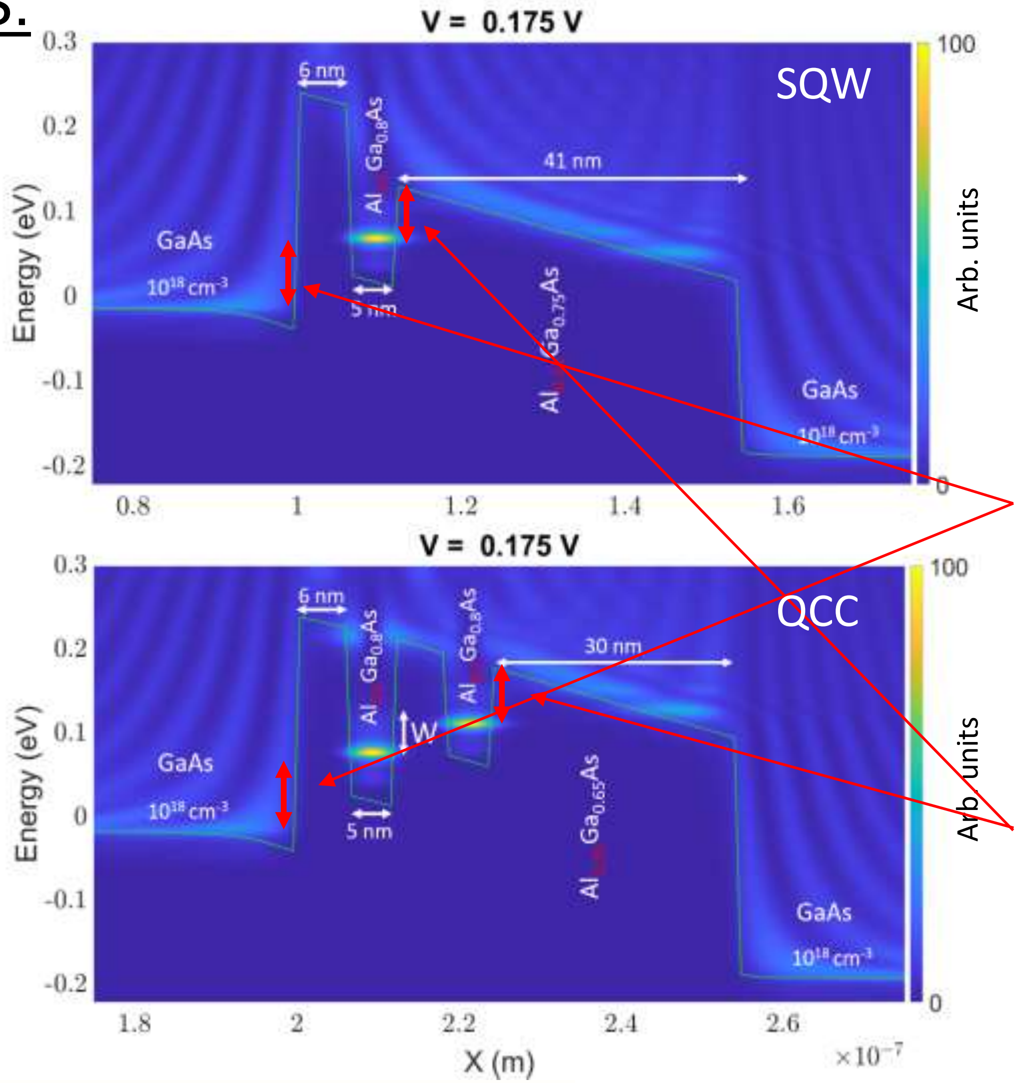
- Acoustic Phonons (AP) - elastic
- Polar optical phonons (POP) – inelastic [3]

Through the self-energies

[3] M.Moussavou, et. al. *Phys. Rev. Appl.*, **10**, 064023 (2018).

Performance comparaison

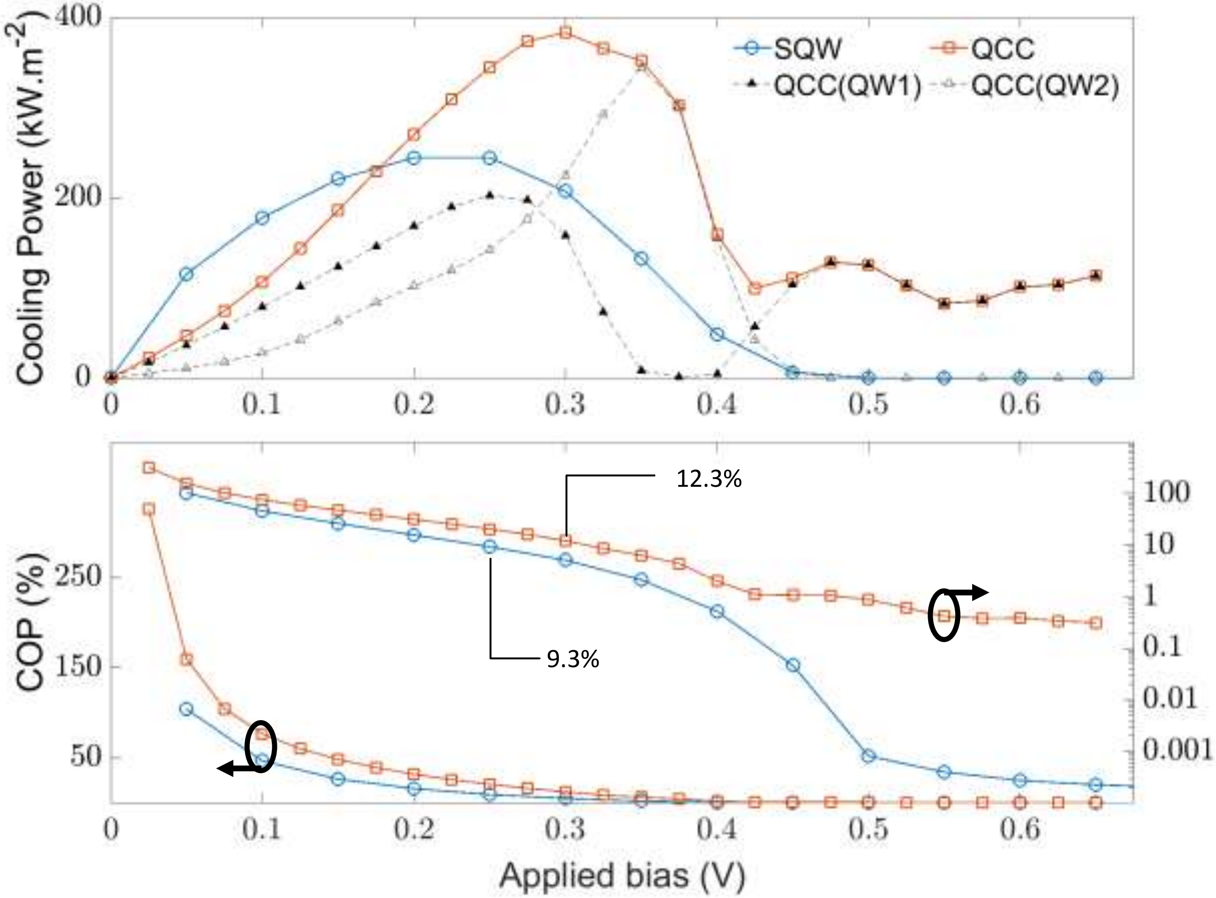
LDOS:



- **Both devices have same length**
- **Energy gap between emitter Fermi level and first QW ground state conserved**
- **Energy gap between last QW ground state and collector barrier conserved**

Performance comparaison

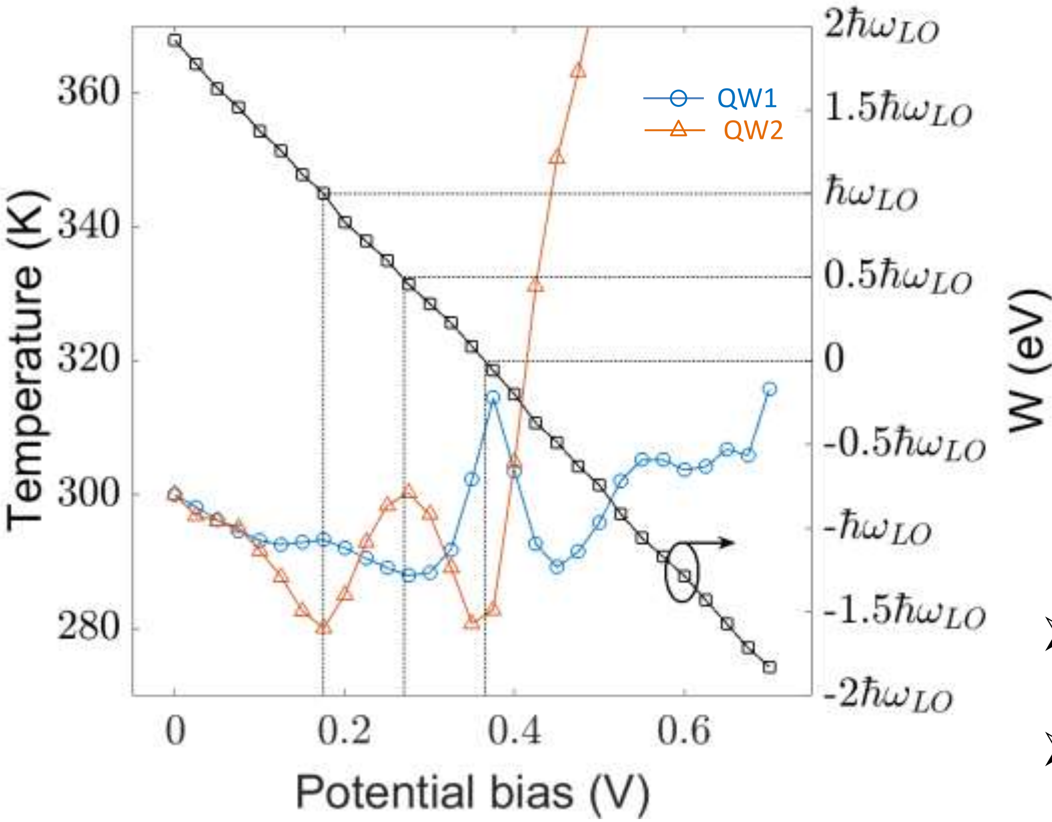
<u>SQW & QCC Cooling power and COP:</u>

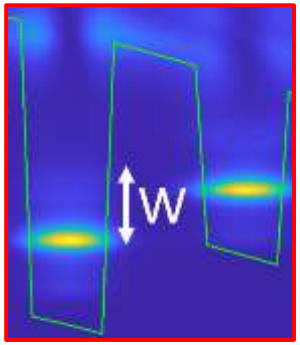


- **Higher** maximum **Cooling Power for QCC** than SQW (Single Quantum Well)
- **Higher COP** at max Cooling Power

Temperature oscillations

<u>Electron temperatures</u>





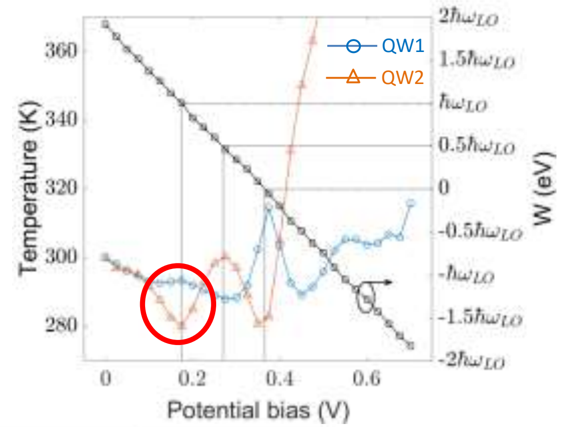
$\hbar\omega_{LO}$ = 35 meV

Polar optical phonon energy

- **Anticorrelation** between electron temperatures
- **Period of the oscillations** linked to the polar **optical phonon energy**

- **Analyze the injection and extraction current spectra, impacting the electron distribution**

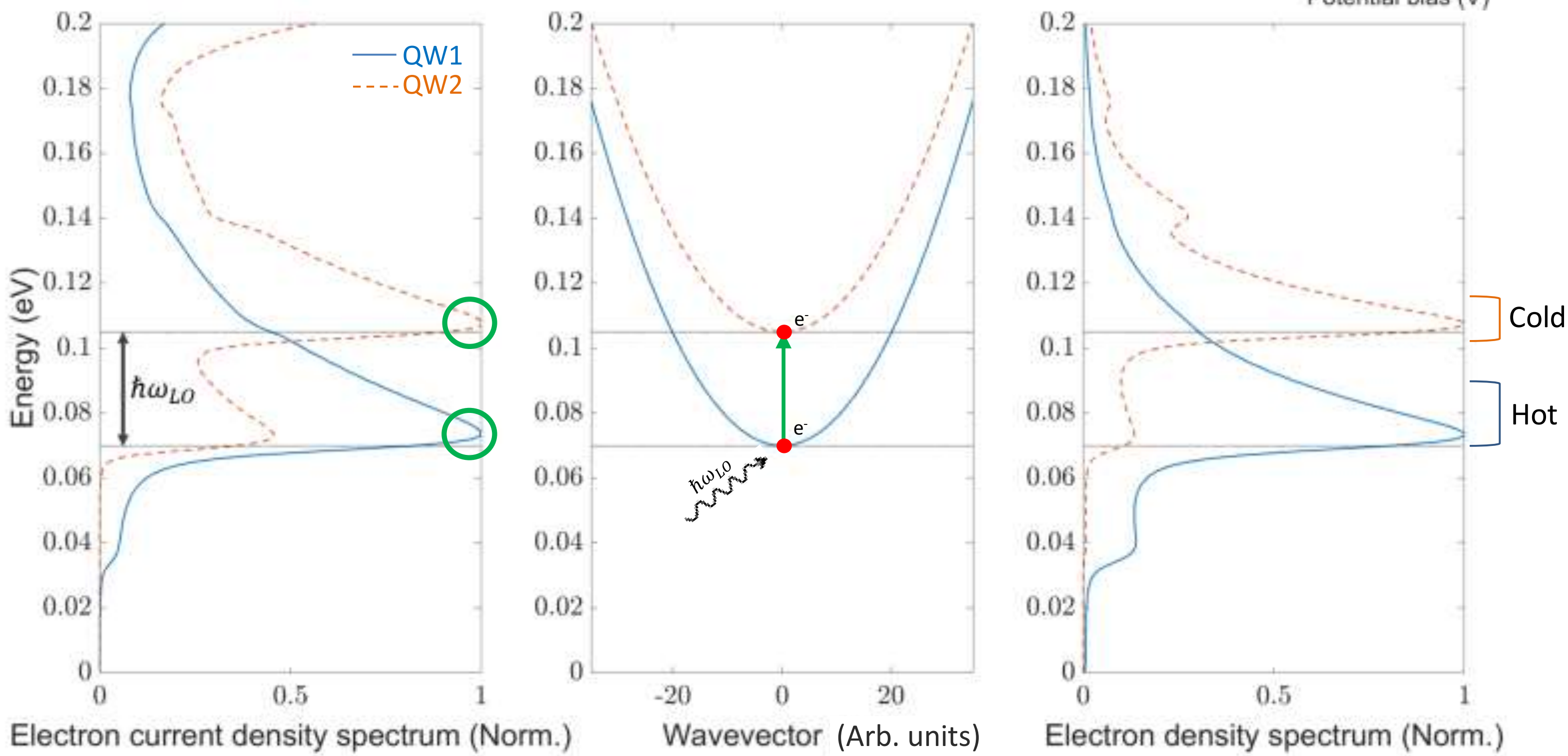
Temperature oscillations



0.175 V: $\begin{cases} W \approx \hbar\omega_{LO} > k_B T \approx 25meV \\ T_{QW1} \Rightarrow \text{local } \textbf{maximum} \\ T_{QW2} \Rightarrow \text{local } \textbf{minimum} \end{cases}$

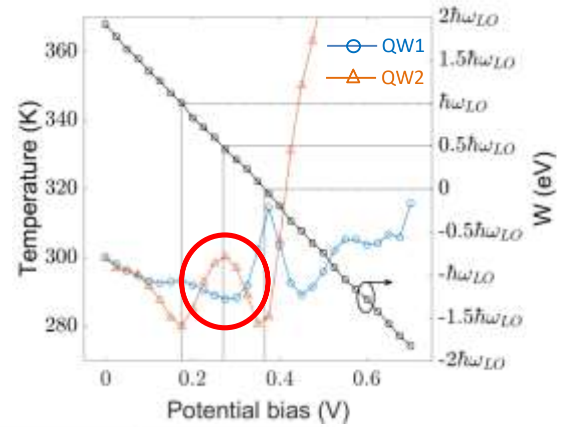
$\hbar\omega_{LO}$ = 35 meV

Polar optical phonon energy



- **Broad injection** in QW1 & **no selective extraction** of hot carriers → Heating QW1
- **Injection** in QW2 **@ ground state** energy & **Thermionic process** → Cooling QW2

Temperature oscillations

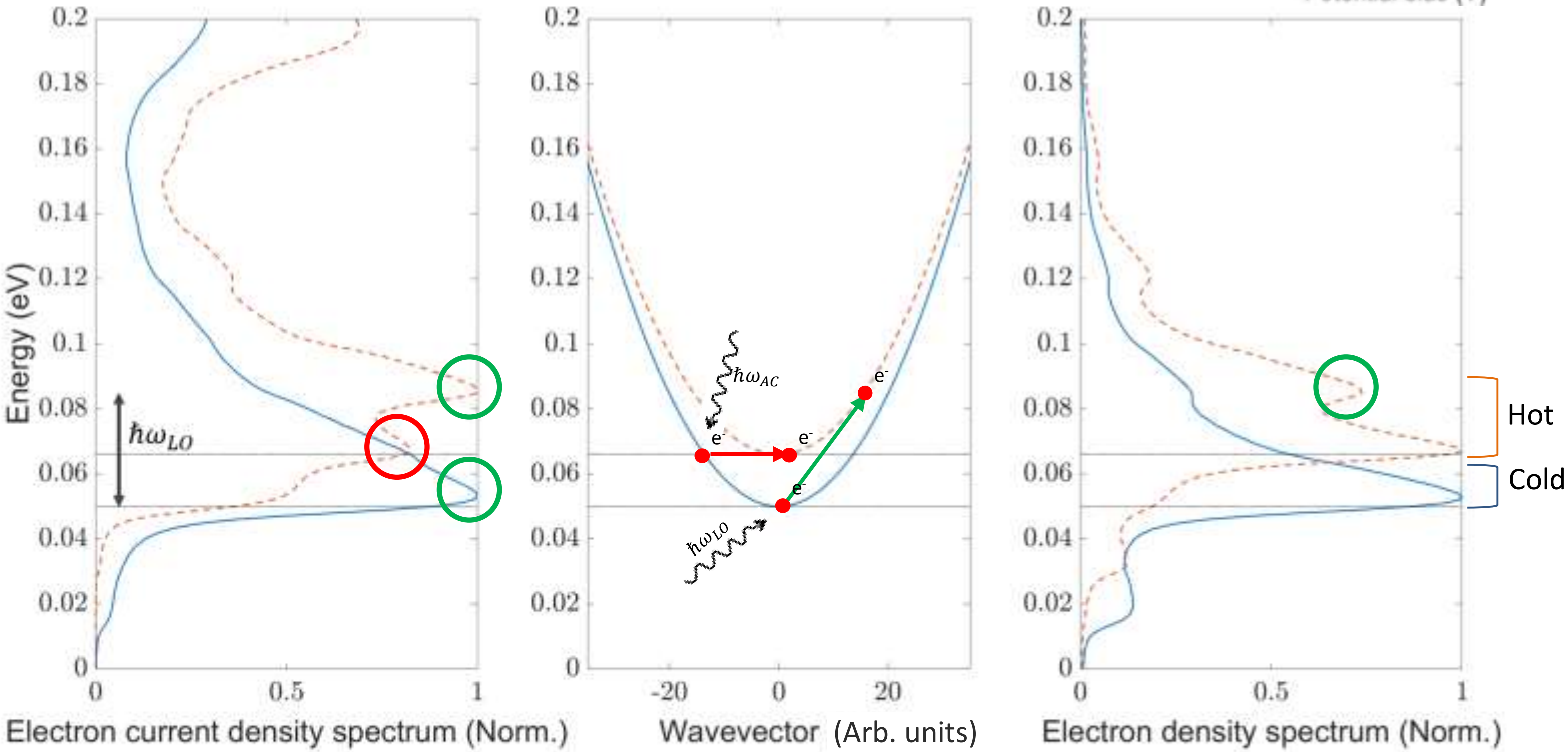


<u>0.275 V:</u>

- $W \approx 0.5\hbar\omega_{LO} < k_B T \approx 25meV$
- T_{QW1} =>local **minimum**
- T_{QW2} =>local **maximum**

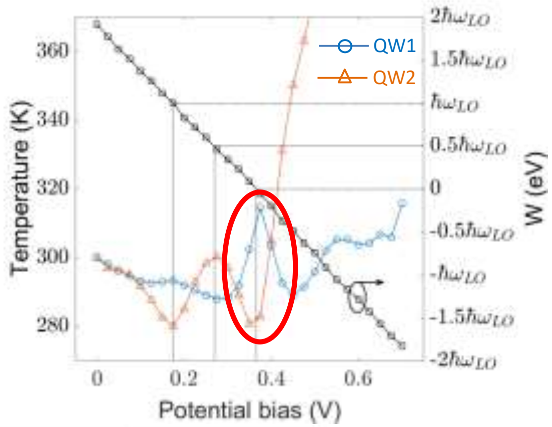
$\hbar\omega_{LO}$ = 35 meV

Polar optical phonon energy



- **Excited electrons extracted** from QW1 through **elastic scattering** → Cooling in QW1
- **Electron injected** in QW2 **above ground state** energy → Heating QW2

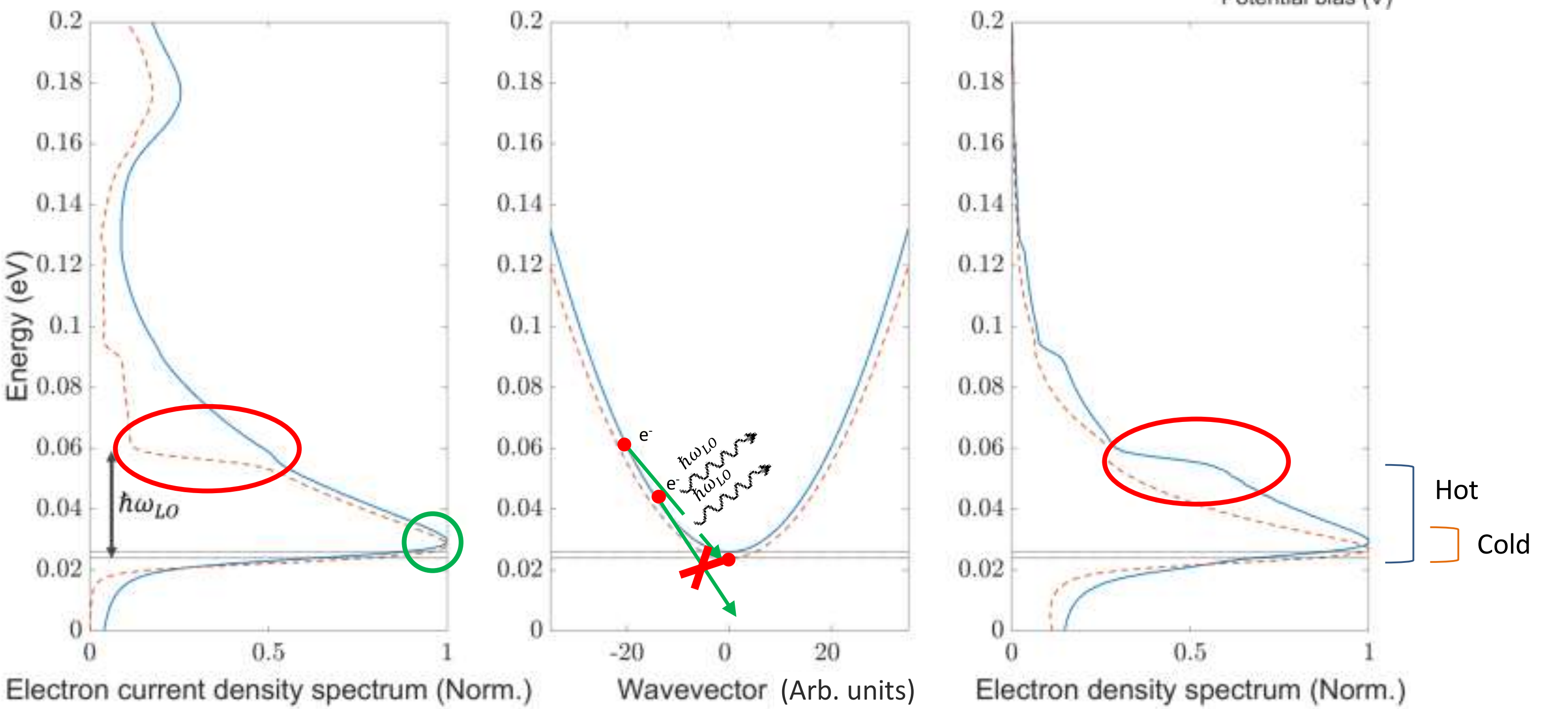
Temperature oscillations



0.375 V: $\begin{cases} W \approx 0 \\ T_{QW1} \text{ =>local } \textbf{maximum} \\ T_{QW2} \text{ =>local } \textbf{minimum} \end{cases}$

$\hbar\omega_{LO}$ = 35 meV

Polar optical phonon energy



- **Electron bottleneck** lead to a **shoulder at 0.055 eV** ➔ Heating QW1
- **Narrowed injection** & subsequent **thermionic emission** ➔ Cooling QW2

Conclusion

- Proof of concept for the Quantum Cascade Cooler, a new type of cooling nano-device
- Performances are increased when compared to the SQW
- Interpretation on the role of the optical phonon energy in multiple quantum well heterostructure

Thank you