Institut Matériaux Microélectronique
Nanosciences de Provence

A novel structure for Cooling Nano-devices: The Quantum Cascade Cooler

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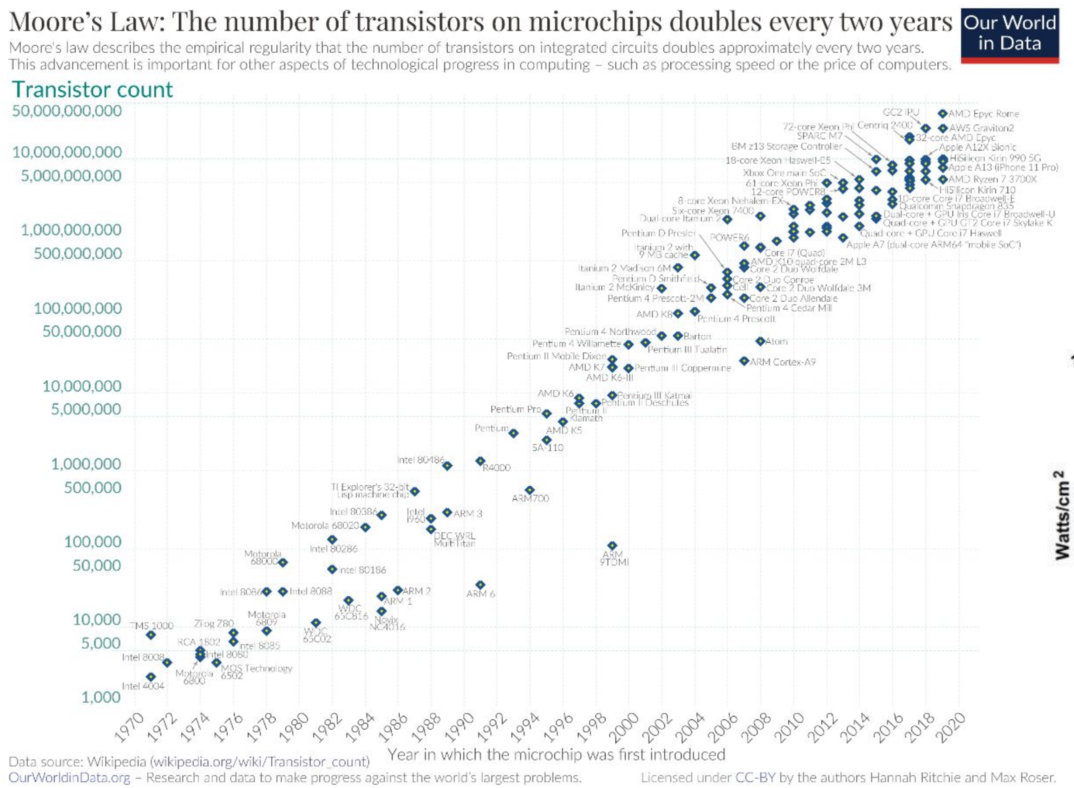
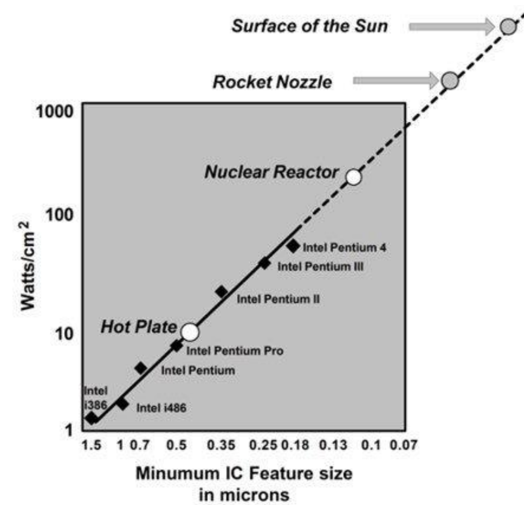
Summary:

- Context
- Quantum Cascade Cooler
- Self-consistent method
- Proof of Concept
- Electrons temperature oscillations

Context:

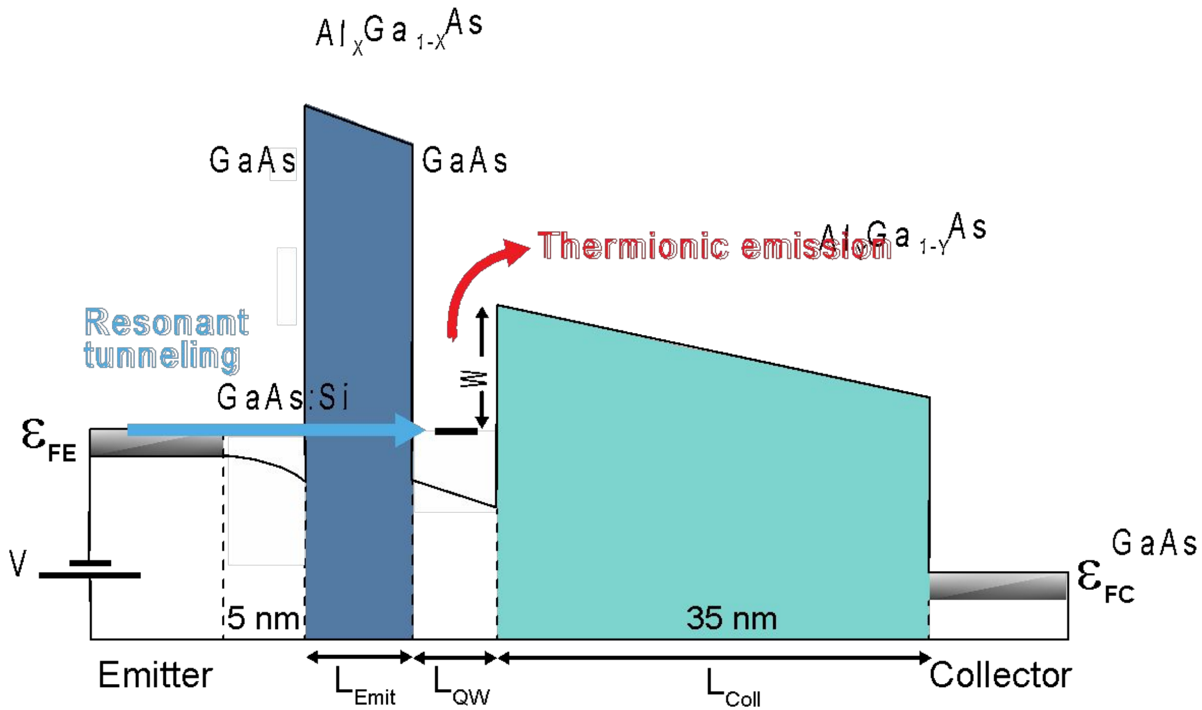
The need for new cooling devices:





Context:

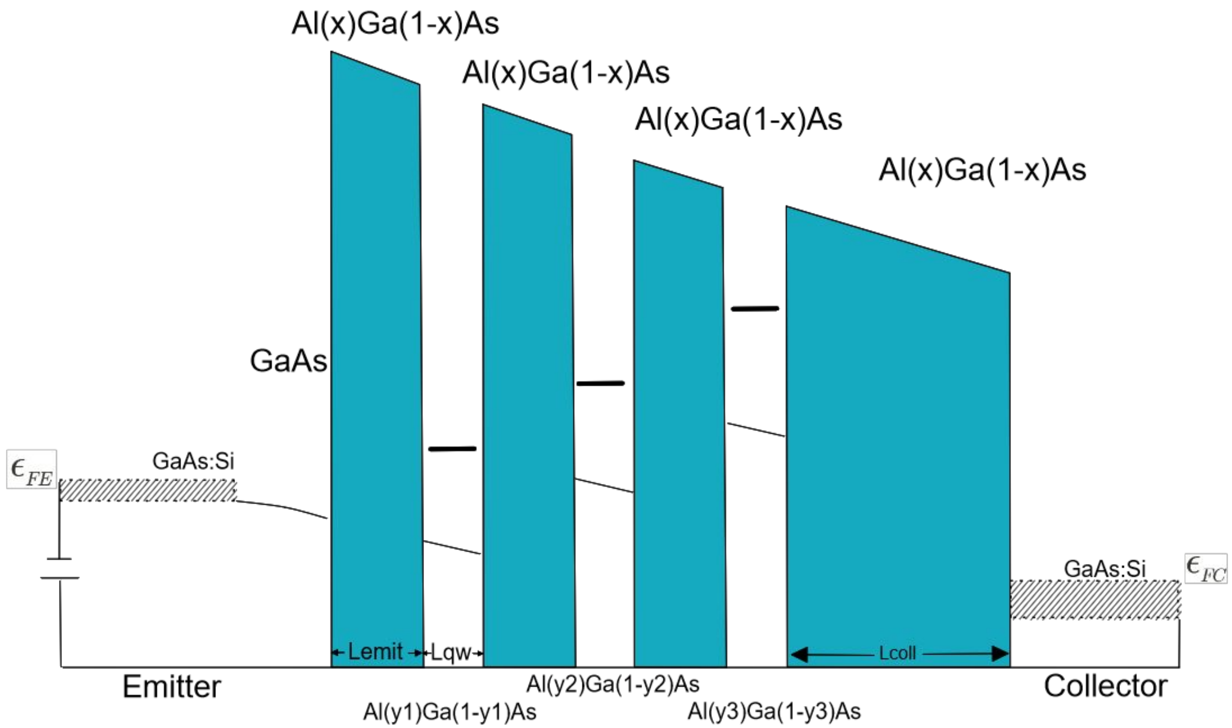
Cooling nano-device based on therminonic emission:



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

Injecting cold electrons by resonant tunelling and extracting hot electrons ⇒ Thermionic cooling

Quantum Cascade Cooler



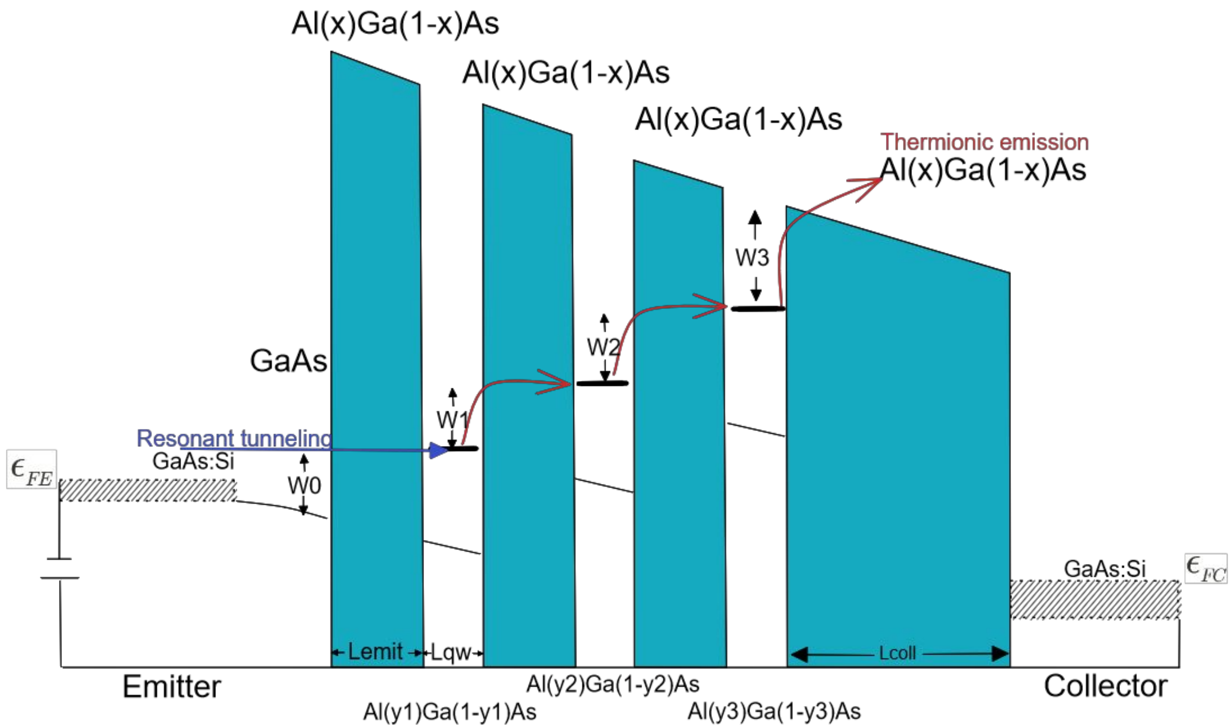
<u>Typical layer length:</u>

Lemit : 4nm

Lqw : 4nm

Lcoll : 12nm

Quantum Cascade Cooler



<u>Typical layer length:</u>

Lemit : 4nm

Lqw : 4nm

Lcoll : 12nm

Self-consistent method

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

NEGF equations for electrons

$$[EI - H - \Sigma_{\mathrm{c}} - \Sigma_{\mathrm{ph}}]\, G = I$$

Heat equation

$$-\nabla \cdot (\kappa_{\mathrm{th}} \nabla T_{\mathrm{ac}}) = Q\left[G^{\gtrless}(T_{ac}, T_{op})\right]$$

Poisson equation

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

<u>Including interactions with:</u>

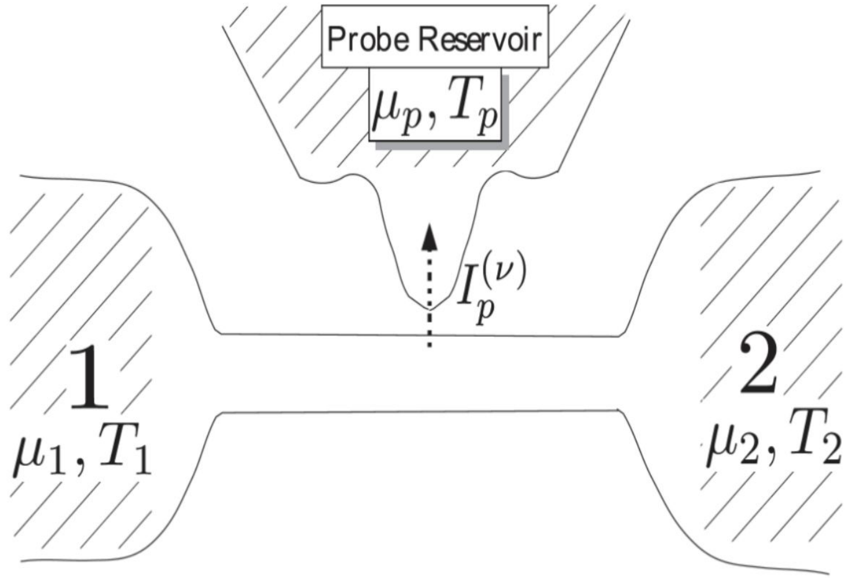
- Acoustic Phonons (AP) - elastic
- Polar optical phonons (POP) – inelastic [2]

Through the self-energies

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

Self-consistent method

Virtual Büttiker Probes [3]:



In out of equilibrium systems:

$$T_{electron} \neq T_{lattice}$$

Probe in local equilibrium with the system:

$$\begin{cases} I_p^{(0)} \\ I_p^{(1)} \end{cases} = 0 \Rightarrow \begin{cases} T_{probe} = T_{device} \\ \mu_{probe} = \mu_{device} \end{cases}$$

$I_p^{(0)}$: Charge current

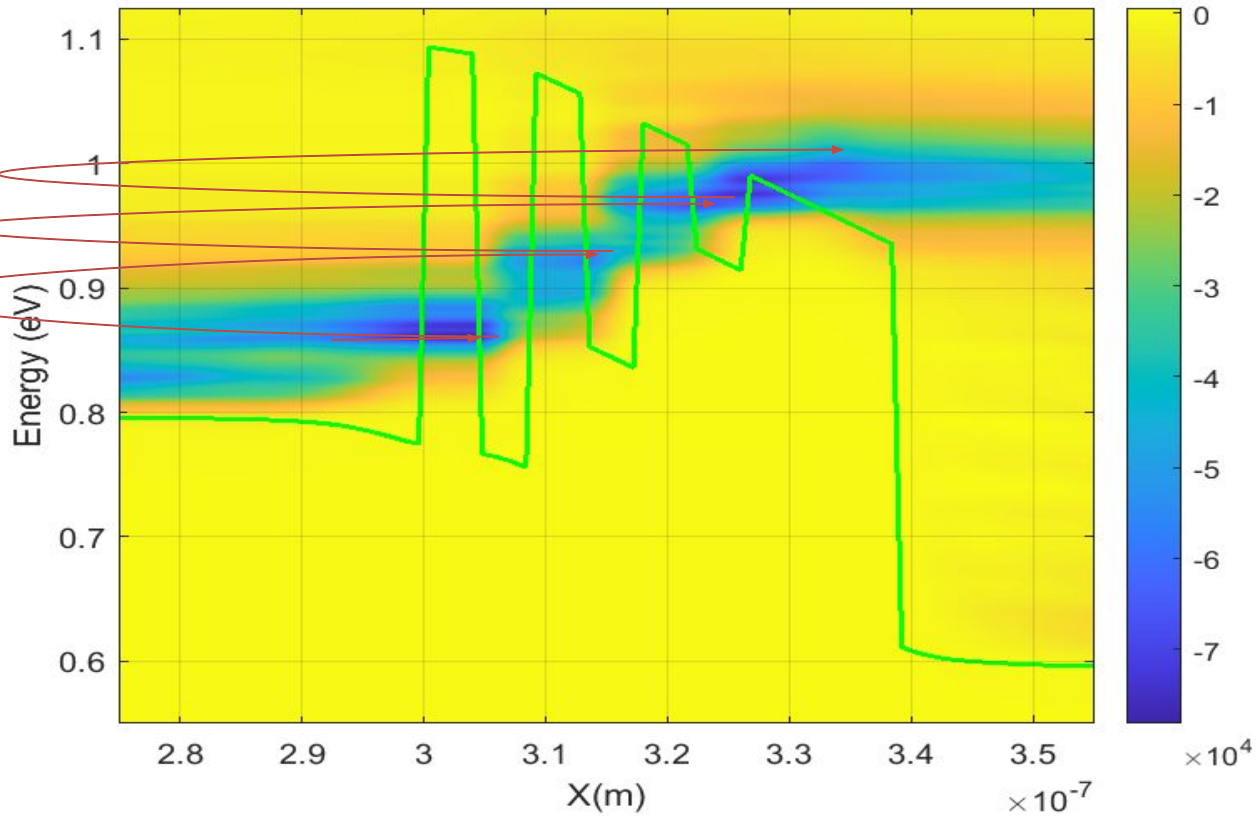
$I_p^{(1)}$: Energy current

[3] C. A. Stafford, Phys. Rev. B 93, 245403 (2016).

Proof of concept

Electron current spectrum:

V = 0.2 V

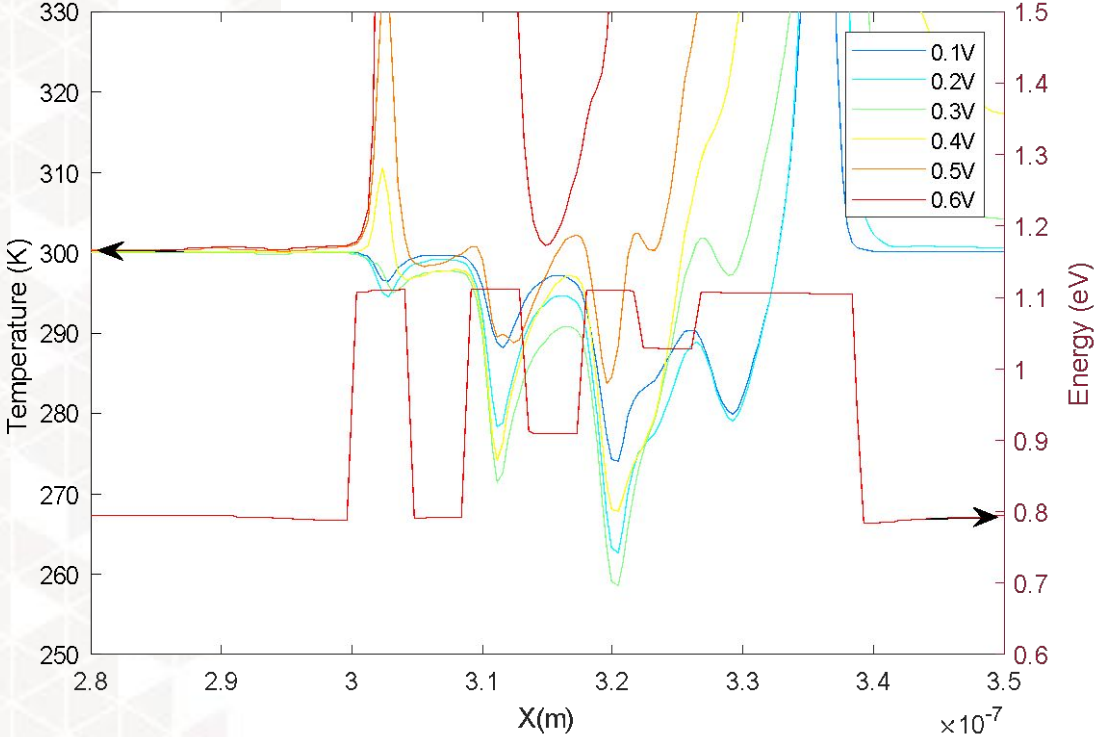


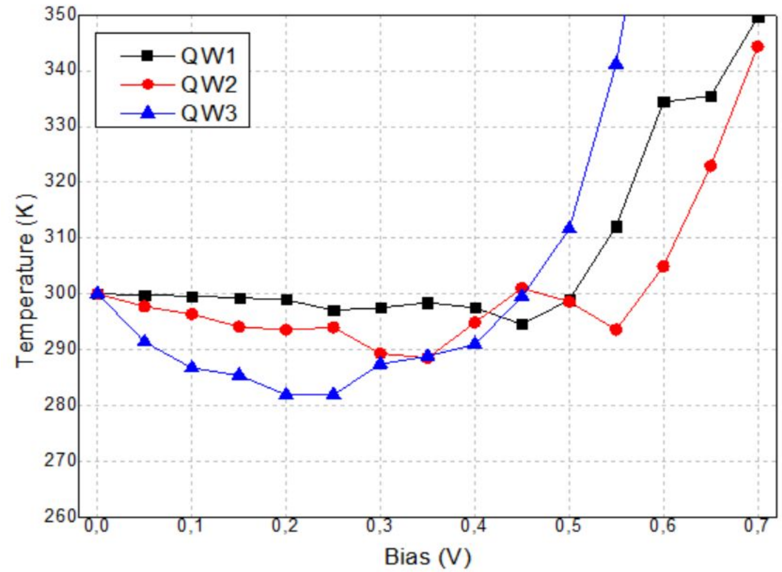
Key message:

- Electrons follow the quantum well states' increase in energy

Proof of concept

Electron temperatures:



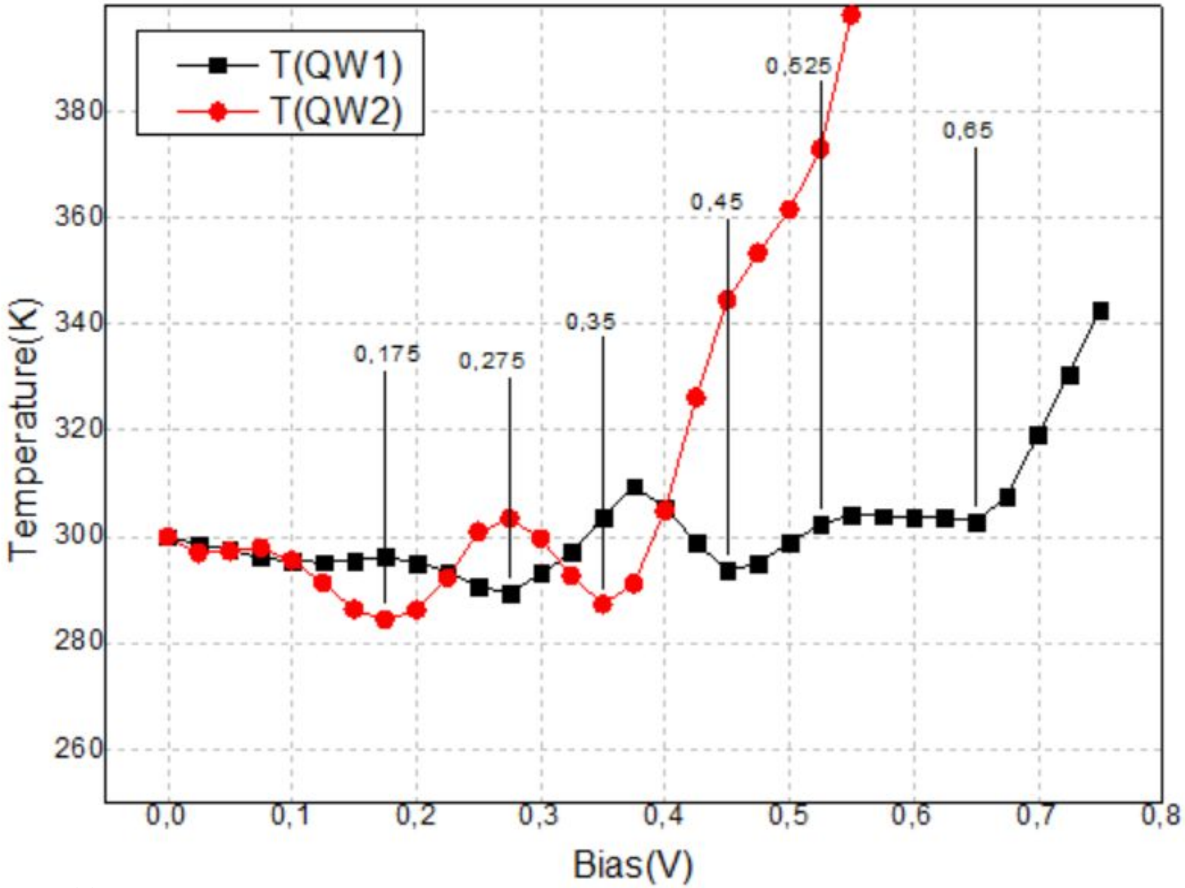


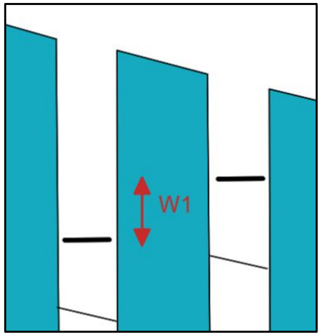
Key message:

- Electrons are cooled, up to 20K inside the QWs
- Simplification of the structure may lead to a better understanding

Temperature oscillations

Electron temperatures: 2QW structure



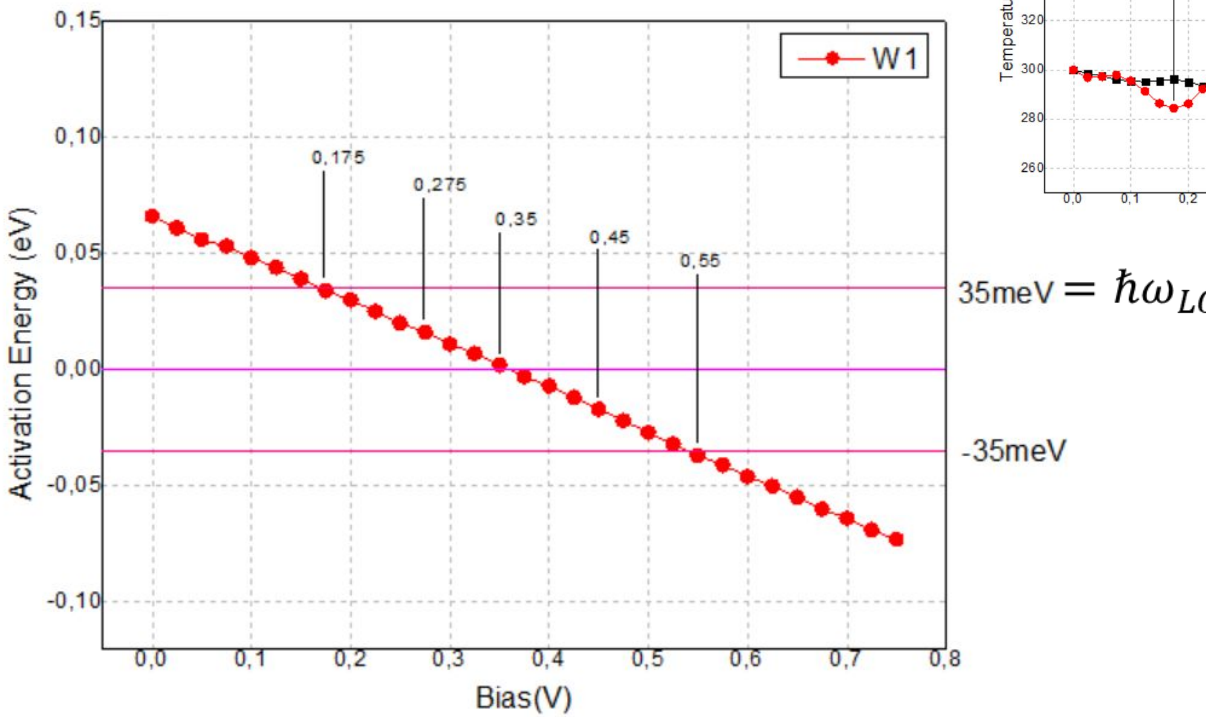


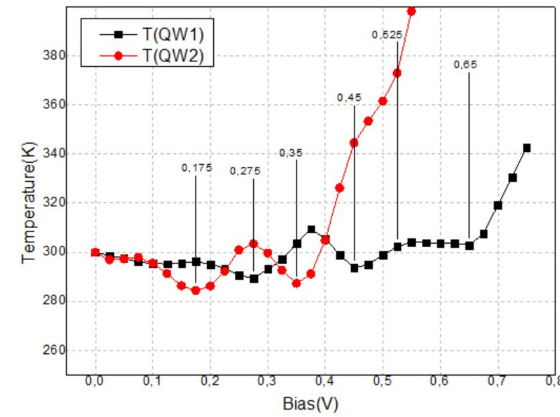
Key message:

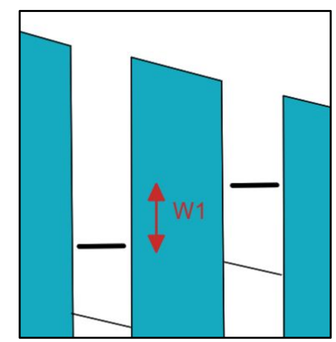
- Anticorrelation between the electron temperatures
- Impact of activation energy (W1)?

Temperature oscillations

Activation energy:







Key message:

- Maxima and minima of electron temperature occur when $W1 = \frac{n}{2}(\hbar\omega_{LO})$

Conclusion

- Proof of concept for the Quantum Cascade Cooler, a new type of cooling nano-device
- Determination of the importance of the optical phonon energy in multiple quantum well heterostructure

Next step:

- Confirmation by experimental data

References

[1] M.Bescond et al. “Thermionic cooling devices based on resonant-tunneling AlGaAs/GaAs heterostructure”

- DOI: 10.1088/1361-648X/aaa4cf

[2] M.Moussavou, et. al. “Physically based diagonal treatment of polar optical phonon self-energy: performance assessment of III-V double-gate transistors,”

- DOI: 10.1103/PhysRevApplied.10.064023

[3] C. A. Stafford, “Local temperature of an interacting quantum system far from equilibrium”

- DOI: 10.1103/PhysRevB.93.245403

[4] A. Shastry and C. A. Stafford, “Temperature and voltage measurement in quantum systems far from equilibrium”

- DOI: 10.1103/PhysRevB.94.155433

Acknowledgement : ANR Project GELATO
https://gelato-nanocoolers.im2np.fr