



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:

Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Our World
in Data

Transistor count

50,000,000,000

10,000,000,000

5,000,000,000

1,000,000,000

500,000,000

100,000,000

50,000,000

10,000,000

5,000,000

1,000,000

500,000

100,000

50,000

10,000

5,000

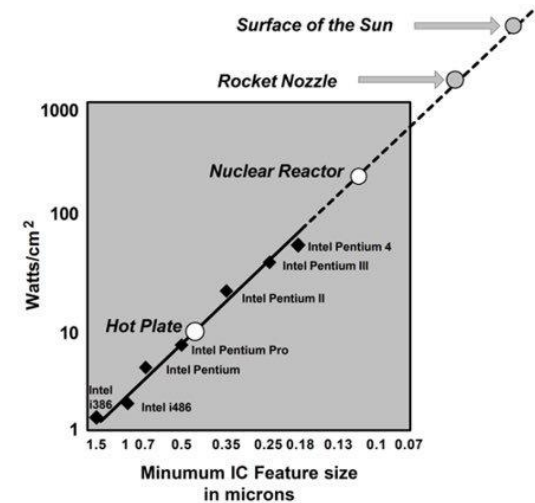
1,000

Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

OurWorldinData.org – Research and data to make progress against the world's largest problems.

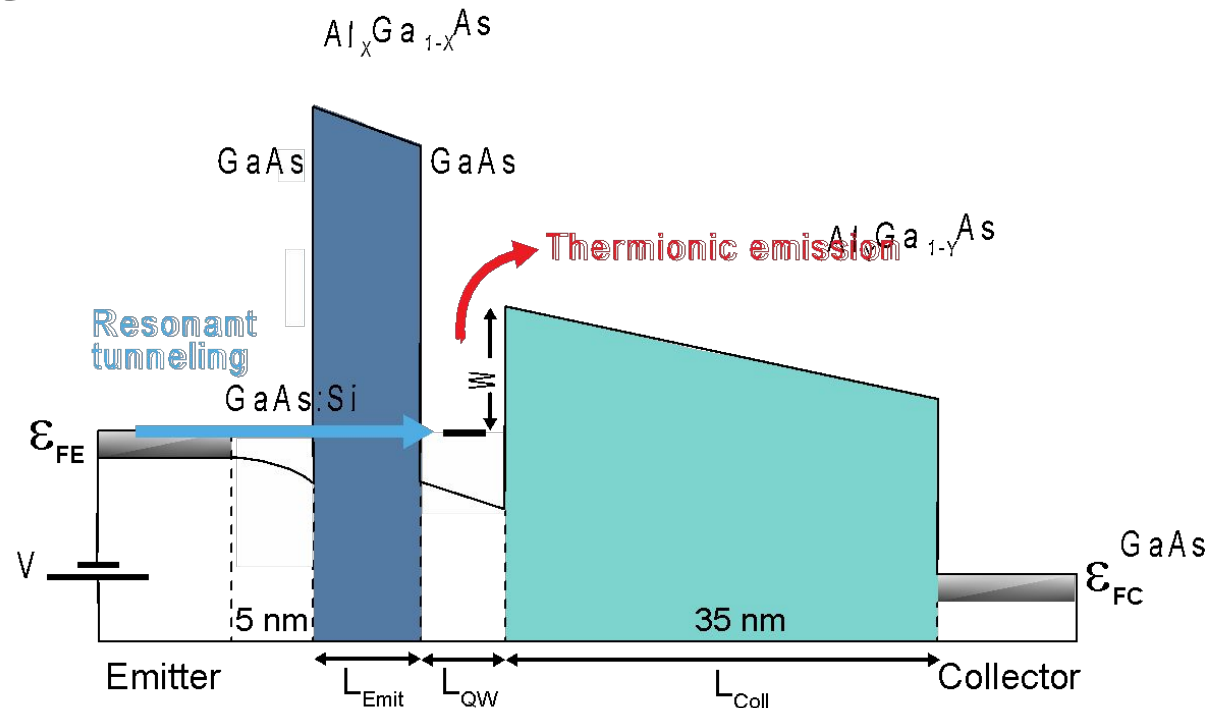
Year in which the microchip was first introduced

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Context:

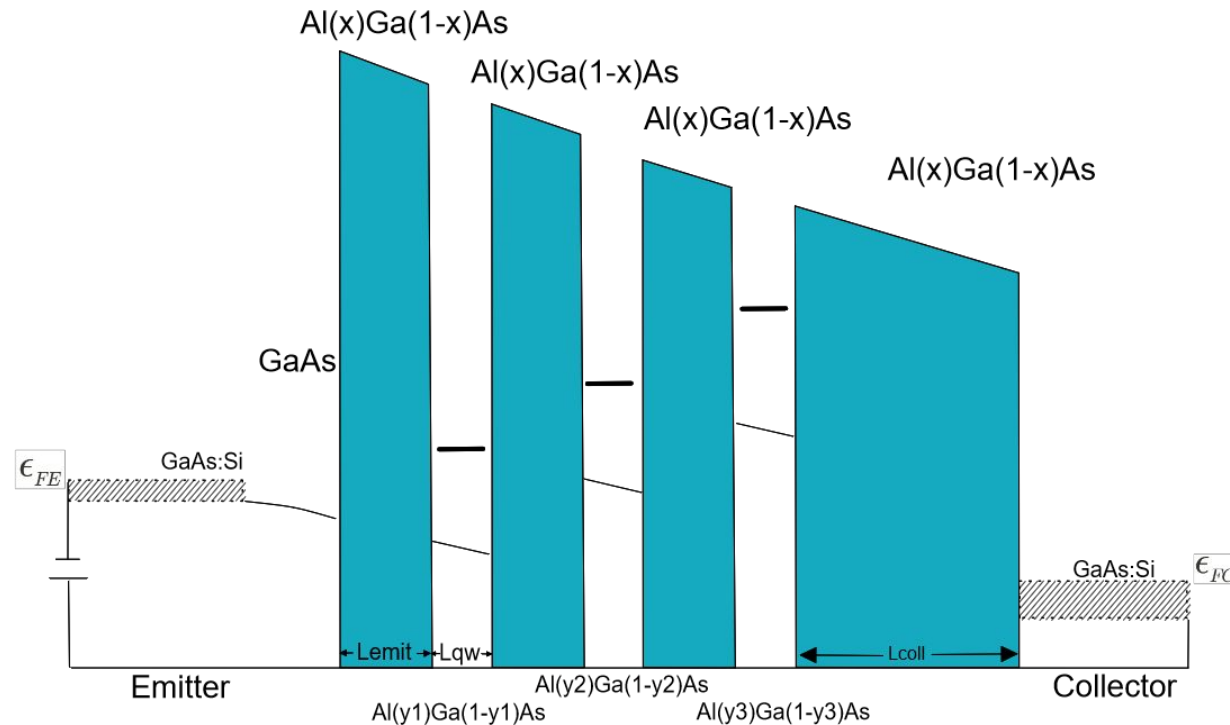
Cooling nano-device based on thermionic emission:



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

Injecting cold electrons by resonant tunnelling and extracting hot electrons \Rightarrow Thermionic cooling

Quantum Cascade Cooler



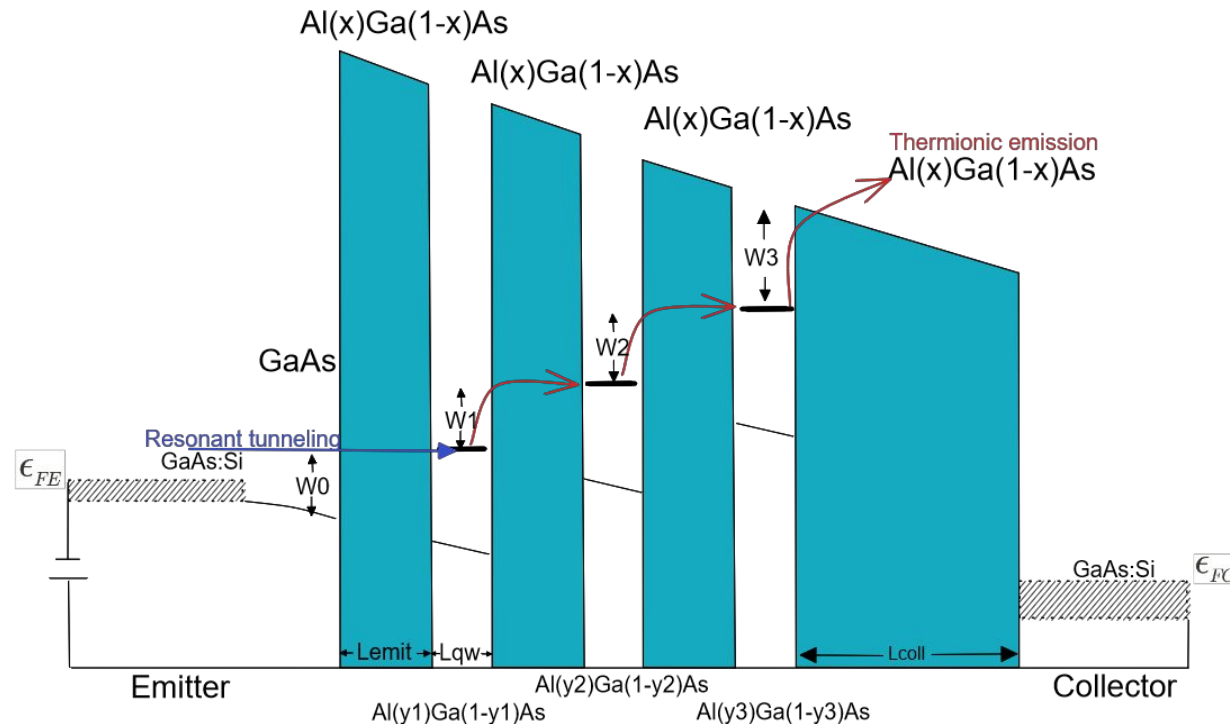
Typical layer length:

L_{emit} : 4nm

L_{qw} : 4nm

L_{coll} : 12nm

Quantum Cascade Cooler



Typical layer length:

L_{emit} : 4nm

L_{qw} : 4nm

L_{coll} : 12nm

Self-consistent method

Green's functions coupled to Heat and Poisson equations:

NEGF equations for electrons

$$[EI - H - \Sigma_c - \Sigma_{ph}] G = I$$

Heat equation

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

Poisson equation

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

Including interactions with:

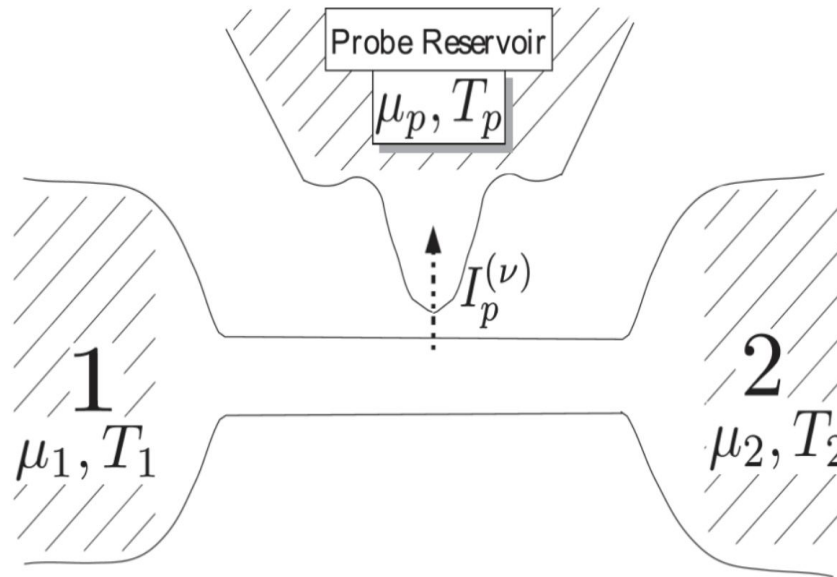
- Acoustic Phonons (AP) - elastic
- Polar optical phonons (POP) – inelastic [2]

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:

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

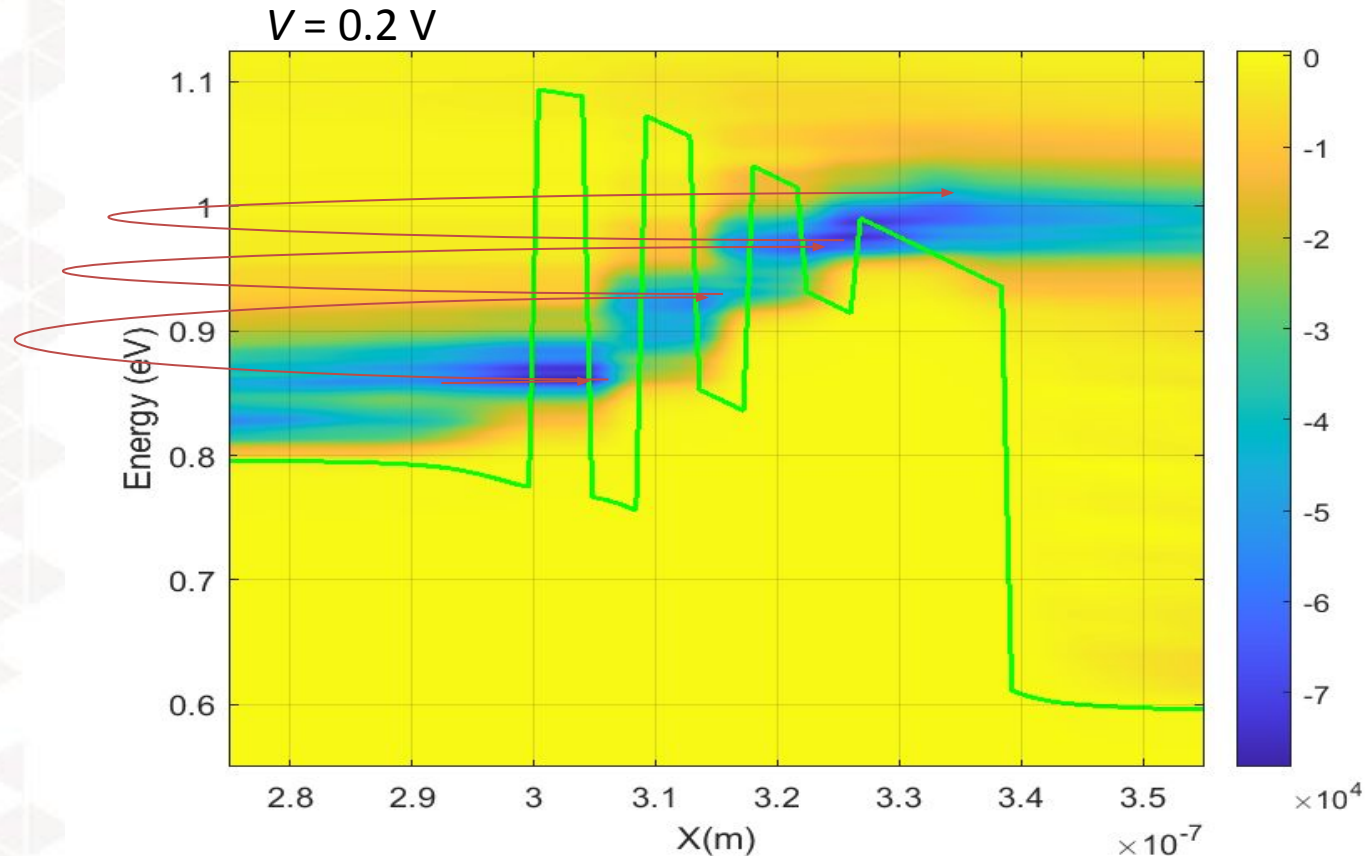
Probe in local equilibrium with the system:

$$\begin{cases} I_p^{(0)} \leftarrow \text{Charge current} \\ I_p^{(1)} \leftarrow \text{Energy current} \end{cases} = 0 \Rightarrow \begin{cases} T_{\text{probe}} = T_{\text{device}} \\ \mu_{\text{probe}} = \mu_{\text{device}} \end{cases}$$

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

Proof of concept

Electron current spectrum:

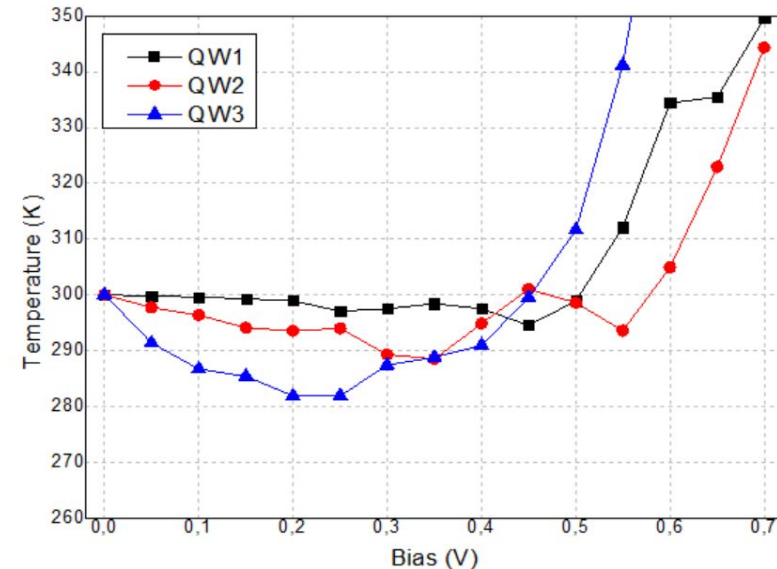
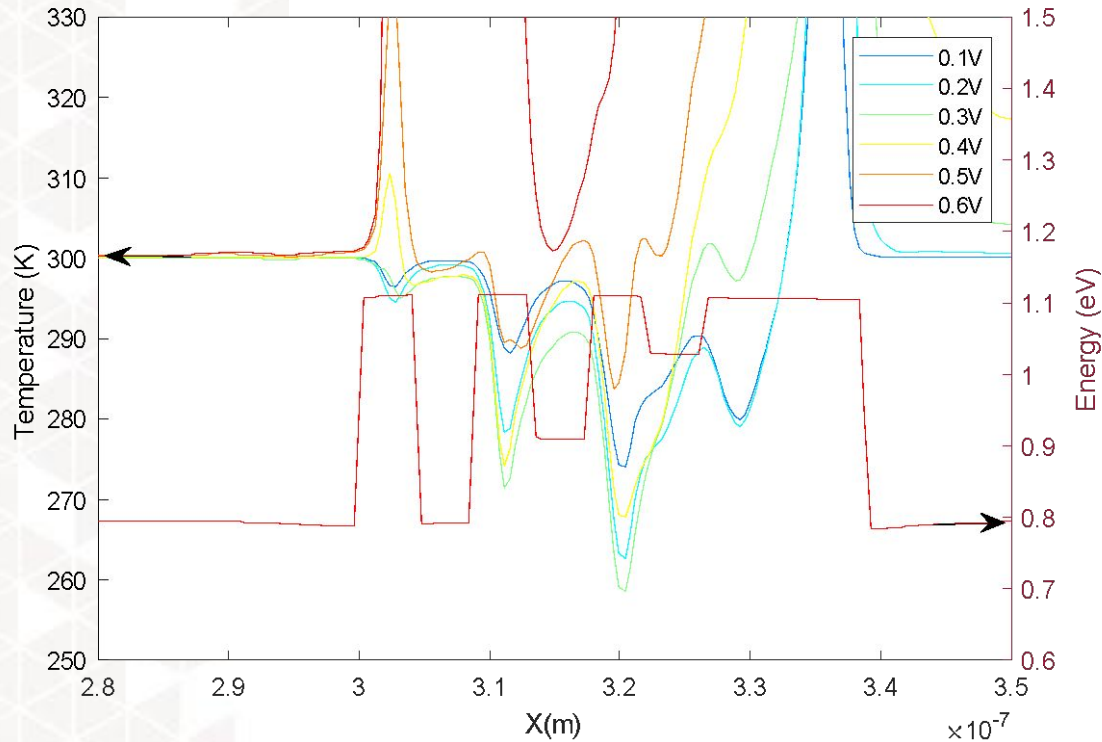


Key message:

- Electrons follow the quantum well states' increase in energy

Proof of concept

Electron temperatures:

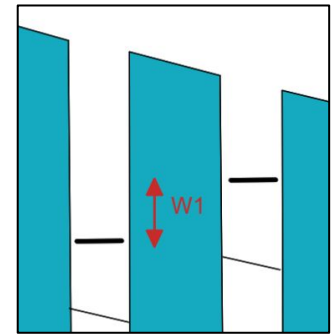
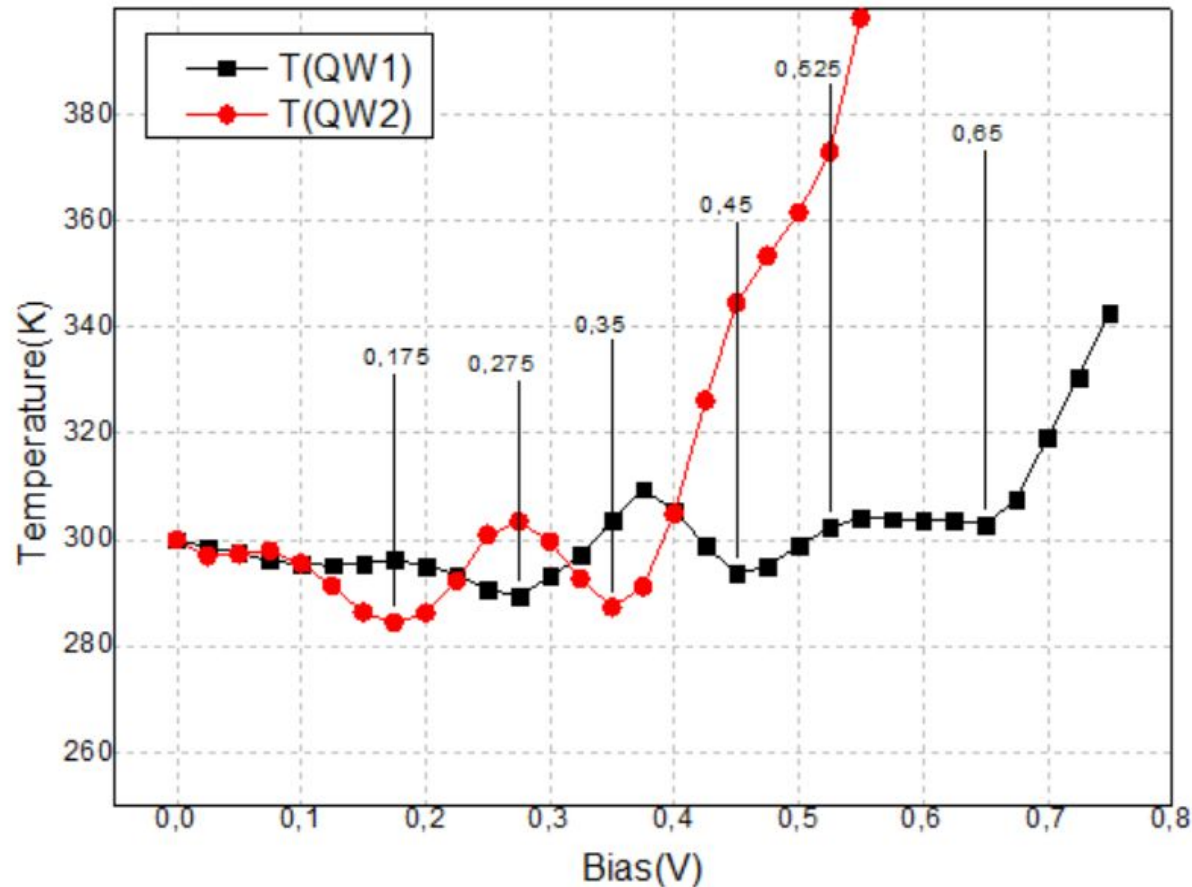


Key message:

- 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

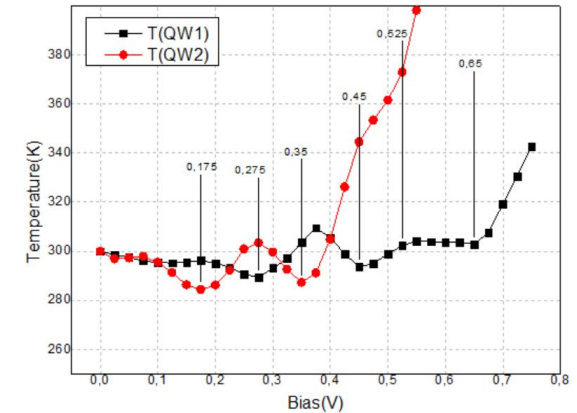
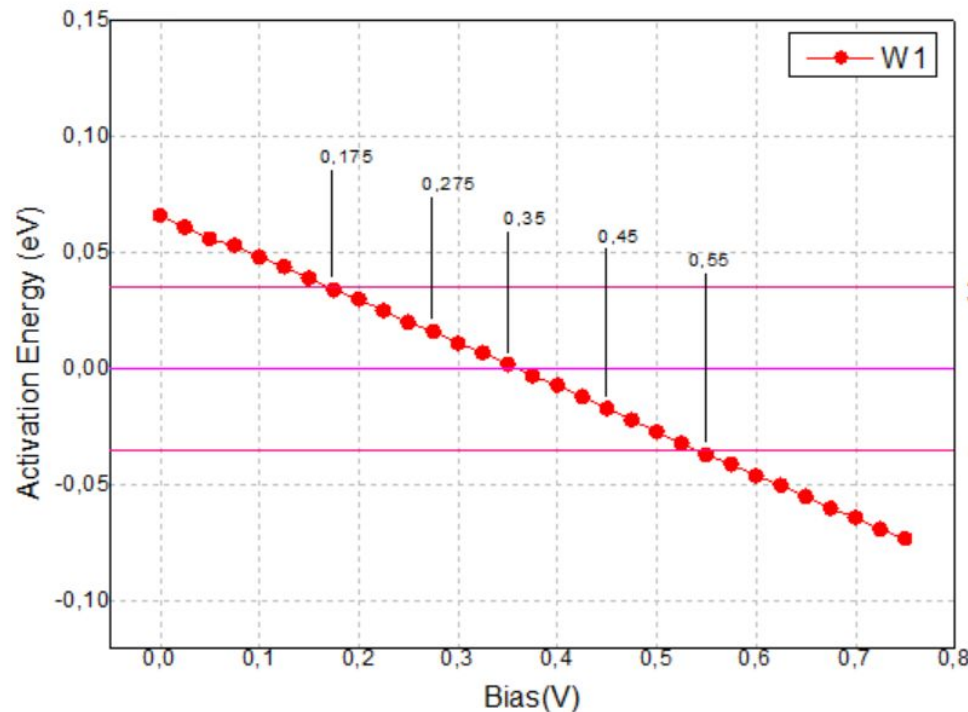


Key message:

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

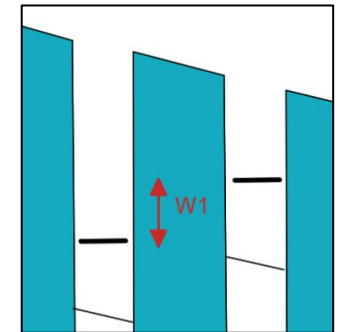
Temperature oscillations

Activation energy:



$$35\text{meV} = \hbar\omega_{LC}$$

$$-35\text{meV}$$



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

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<https://gelato-nanocoolers.im2np.fr>