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

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INTRODUCTION

We propose and study an innovative heterostructure as a cooling nanodevice based on tunneling filtering and thermionic emission. The structure, whose layers are made of AlGaAs (Fig.1) with varying Al concentration, is designed to exhibit progressively higher quantized states within two consecutive quantum wells (QWs). By applying a bias voltage between the two contacts, we induce a net current, and we “force” electrons to absorb phonons during successive transmissions before being extracted from the last well. Derived from a previously investigated structure [1], the “Quantum Cascade Cooler” is expected to yield increased efficiencies when compared to single quantum well structures as each electron now have to absorb multiple phonons on their way to the collector.

MODEL AND DISCUSSIONS

In order to investigate the properties of such structure, we use an in-house code which couples self-consistently non-equilibrium Green’s function formalism for electron, heat equation and Poisson equation [1]. We include the interactions between the electrons and both acoustic phonons (elastic) and polar optical phonons (inelastic) [2] through the use of self-energies. This self-consistent approach yields important electronic properties to understand the underlying physics in such device. For instance, we can see that the designed resonant tunnelling way across the QW states that can be observed in figure 2-a) shapes the electron flow represented in figure 2-b).

We subsequently determine the temperature of electrons (usually different from the lattice one in out-of-equilibrium regimes) by using the virtual Büttiker probes [3]. The principle of the latter is to weakly couple a probe to the active region of the structure of interest. We then cancel both the carrier and heat current between the probe and the system by modifying the electron temperature and electrochemical potential of the probe. The probe will be in local equilibrium with the structure, even though the device operates far from equilibrium.

With this method we calculate, in each quantum well, the average electron temperature (Fig.3-a) for which we observe anticorrelated oscillations. We relate the latter to the energy difference W between the ground state of successive QWs (Fig.3-b) and notice that the period of the oscillations corresponds to the energy of an optical phonon ($\hbar\omega_{LO}$ =35 meV). We propose that these oscillations are the result of the competition between the phonon assisted transmitted and reflected electron flow in the second QW. This point will be discussed in detail during the workshop.

CONCLUSION

By numerically investigating the cooling properties of an AlGaAs based heterostructure, we manage to provide a proof of concept for the Quantum Cascade Cooler and propose an interpretation of the polar optical phonon energy dependency on the cooling behaviour.

REFERENCES

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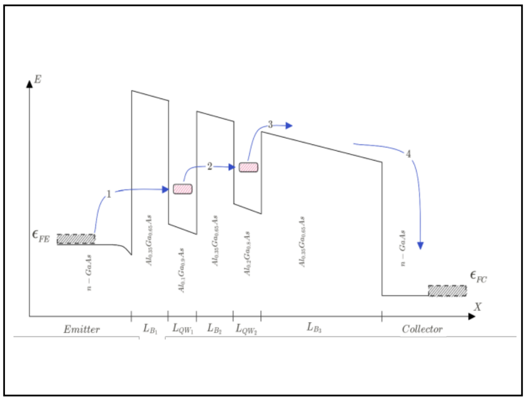

Fig. **1**. Sketch of the considered Quantum Cascade Cooler heterostructure under potential bias. The red dashed rectangles represent the QW states, while E_{FE} and E_{FC} are the Fermi levels of the emitter and collector respectively. For all the considered devices, doping in the emitter and the collector is 10^{18} cm^{-3}. $L_{B1} = L_{B2} = 6$ nm, $L_{QW1} = L_{QW2} = 5$ nm, $L_{B3} = 30$nm. Blue arrows highlight intended pathway for the electron flow.

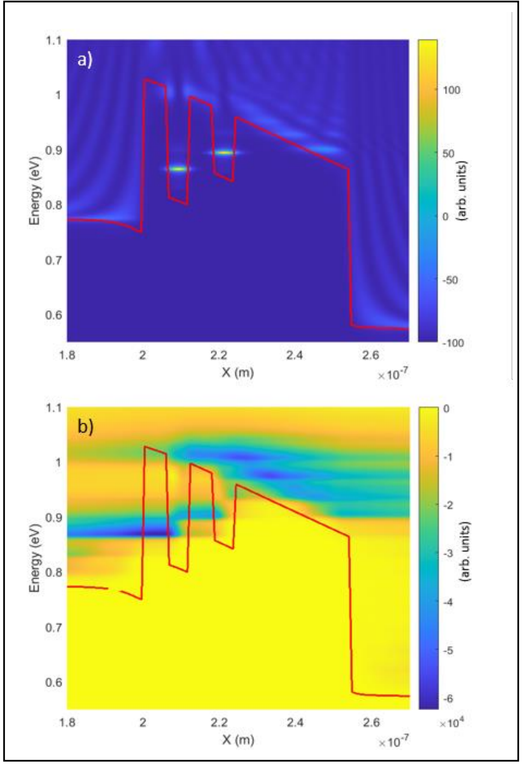

Fig. 2. a) Local density of states of the device. b) Electron current spectrum going from the left to the right. In both figures, the red solid red lines represent the potential profile of the structure ($V = 0.2$ V). $E_{FE} = 0.8$ eV and $E_{FC} = 0.6$ eV

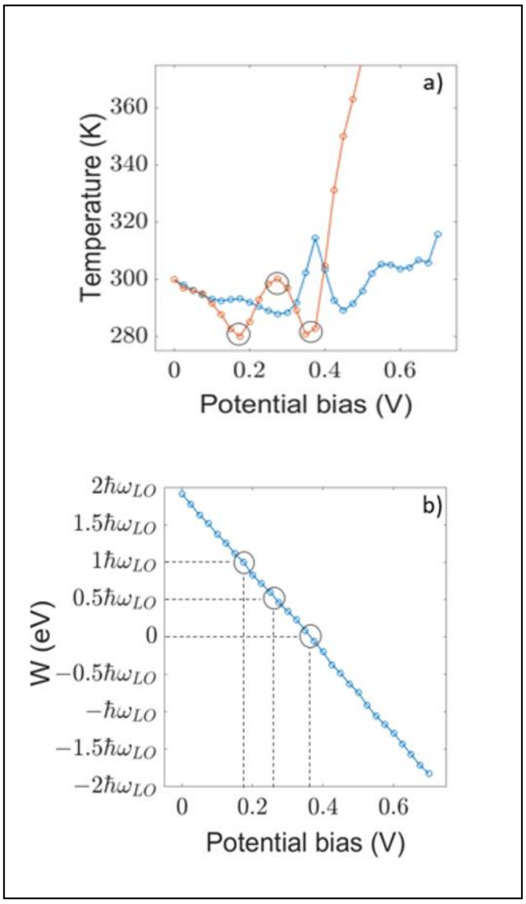

Fig. 3. a) Average temperature in the first (blue) and second (orange) QW as a function of bias. b) Energy difference W between the ground states of the first and second quantum wells as a function of bias (>0 when QW$_2$'s ground state is above QW$_1$'s). Black circles and black dotted lines highlight biases and energy differences corresponding to extrema of temperature respectively.

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