高効率半導体熱電子放出冷却デバイス:量子カスケードクーラー

Highly efficient thermionic cooling semiconductor device: the Quantum Cascade Cooler

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The understanding and control of cooling properties at the nanoscale represent major scientific and industrial issues. In that context, thermoelectricity appears to be a relevant solution as a "green" approach operating at small scales. However, since its cooling efficiency is limited near thermodynamic equilibrium, we propose to investigate nanostructures whose working principle applies far from it. This is the field of thermionic cooling. We recently demonstrated both experimentally [1] and theoretically [1,2] that an asymmetric AlGaAs/GaAs double barrier heterostructure (Figure 1-a)) can efficiently act on the electronic and phononic bath's refrigeration. In this structure, "cold" electrons are injected from the emitter into the GaAs quantum well (QW) *via* a resonant tunneling effect through a potential barrier. "Hot" electrons are extracted from the QW through a thermionic process above the thick AlGaAs alloy barrier.

In this work, we propose a cooling device which consists of sequentially stacked thermionic emission structures. Thanks to appropriate band engineering, it is possible to progressively increase the energy level in each GaAs QW (Figure 1-b)). In this case, an electron absorbing a phonon in the first period can tunnel into the next period of the structure, where another phonon can be absorbed. This process is similar the one occurring in quantum cascade laser [3] between electron and photon emission, which leads us to identify this structure as "quantum cascade cooler" (QCC). To assess the performances, we used an "in-house" code based on the non-equilibrium Green's Function formalism, in which the electrical and thermal transport equations are self-consistently solved [2,4].

The cooling power density shown in Figure 3-c) demonstrates that the cooling effect occurs in each QW, extending the refrigeration over the entire structure. Simulations also indicate that best cooling performances are obtained when the energy interval between two consecutive QW states equals the polar optical phonon frequency $\hbar\omega_{pop}$ (≈35 meV in GaAs). This is the key parameter. In such a configuration, QCC can achieve a cooling power several times larger than that of the single-stage QW structure (Fig. 1-a)), while providing a similar coefficient of performances. Therefore, we believe that the present quantum cascade cooler, based on sequential "tunneling/thermionic emission" processes, is very promising for nano-scale refrigeration.

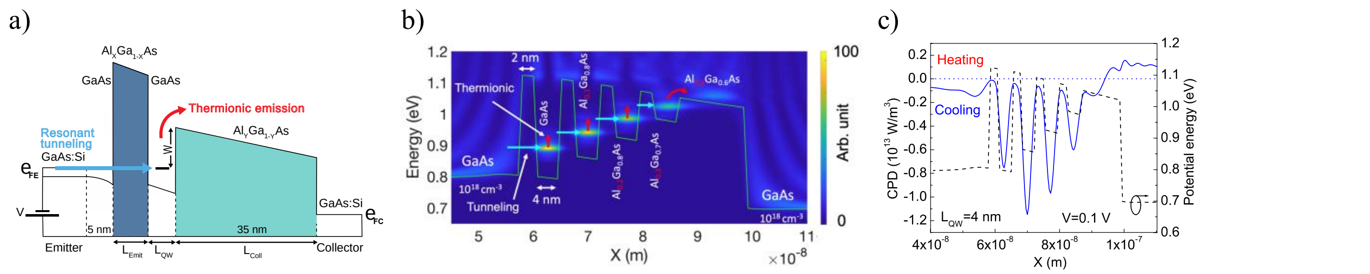

Figure 1: a) Schematic representation of the asymmetric double barrier heterostructure [1,2]. b) LDOS (arb. unit) of the quantum cascade cooler (QCC). Horizontal and vertical arrows show the resonant tunneling and thermionic effects respectively. The green solid line represents the potential energy profile; c) Calculated cooling power density (CPD) along the QCC. Negative value corresponding to a cooling phenomenon, the entire QCC is now efficiently refrigerated.

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