Highly Efficient Thermionic Cooling Semiconductor Devices based on Tilted-Barrier Heterostructures

Marc Bescond[1,2*], Kazuhiko Hirakawa[1,2]

[1] *LIMMS-CNRS, UMI 2820, Tokyo, Japan*
[2] *Institute of Industrial Science and INQIE, University of Tokyo, Tokyo, Japan*
**bescond@iis.u-tokyo.ac.jp*

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. Moreover, at the nanoscale, transport properties allow to develop highly efficient thermoelectric devices operating in a non-equilibrium regime: this is the field of thermionic cooling. We recently demonstrated both experimentally and theoretically [1] that an asymmetric AlGaAs/GaAs double barrier thermionic cooling heterostructure (Fig. 1) can 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 the thin potential emitter barrier. "Hot" electrons are then removed from the QW through a thermionic process above the thick AlGaAs alloy collector barrier, extracting the activation energy W from the lattice *via* phonon absorption. As a result, the QW cools and the collector heats.

In this work, we assess the cooling performances of this structure, using an "in-house" non-equilibrium Green's Function formalism, in which the electrical and thermal transport equations are self-consistently solved [2]. We first report an extensive study of the impact of W by varying the QW thickness (L_{QW}) on the electrical and cooling properties (Fig. 2). We demonstrate that the best cooling characteristics are obtained for W close to the polar optical phonon energy of the material, $\hbar\omega_{LO}$ (≈35 meV in GaAs) (Fig.3). This is the key parameter. Although promising, the performances are found to degrade at high bias due to the tunneling of electrons across the collector barrier (Fig. 4-a) and Fig. 5). We therefore propose an original structure with a tilted potential in the collector barrier that is able to reduce this parasitic tunnel escape of electrons in the QW (Fig. 4-b)). Simulations indicate that such a structure leads to an improvement of the coefficient of performance over the entire applied bias range by at least 60 %, while maintaining a similar cooling power (Fig. 6) [3]. Therefore, we believe that the present low-energy-injection/high-energy-extraction structure coupled with a tilted potential barrier may lead to the conception of thermionic cooling nanodevices of crucial technological interest.

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[2] M. Bescond, D. Logoteta, F. Michelini, N. Cavassilas, T. Yan, A. Yangui, M. Lannoo, K. Hirakawa, J. Phys.: Condens. Matter **30**, 064005 (2018).
[3] M. Bescond and K. Hirakawa, Phys. Rev. Appl. **14**, 064022 (2020).

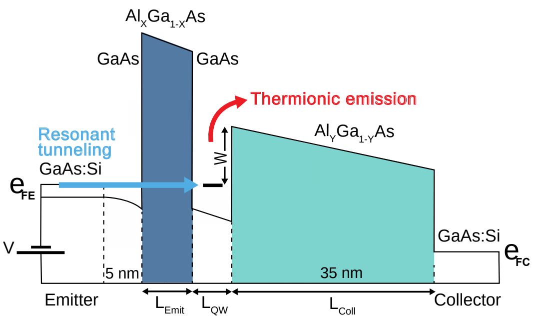

Fig.1: Considered asymmetric double-barrier heterostructure. For all the considered devices, doping in the emitter and the collector is 10^{18} cm^{-3}. Here L_{QW} denotes the quantum well thickness and W denotes the activation energy. L_{Emit} = 2 nm and L_{Coll} = 35 nm, with X = 0.4 and Y = 0.15, their respective aluminum concentrations.

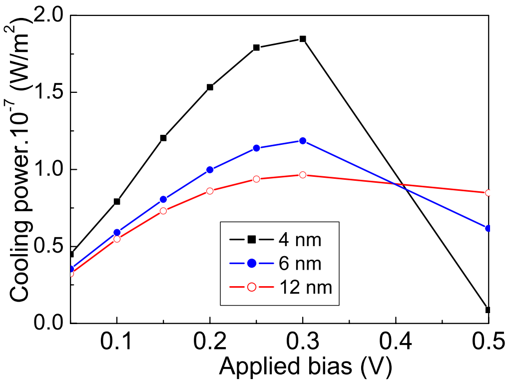

Fig.2: Cooling power for three L_{QW}: 4 nm (filled squares), 6 nm (filled circles), and 12 nm (open circles). The best cooling is reached for L_{QW}=4 nm.

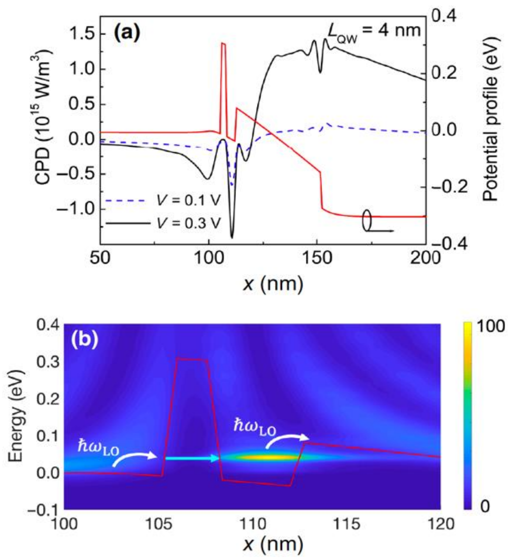

Fig.3: (a) Cooling power density (CPD) for V = 0.1 V (dashed line) and V = 0.3 V (solid line); (b) LDOS in the QW region at V = 0.3 V. In both panels, the solid red line represents the energy potential profile. Here L_{QW} = 4 nm.

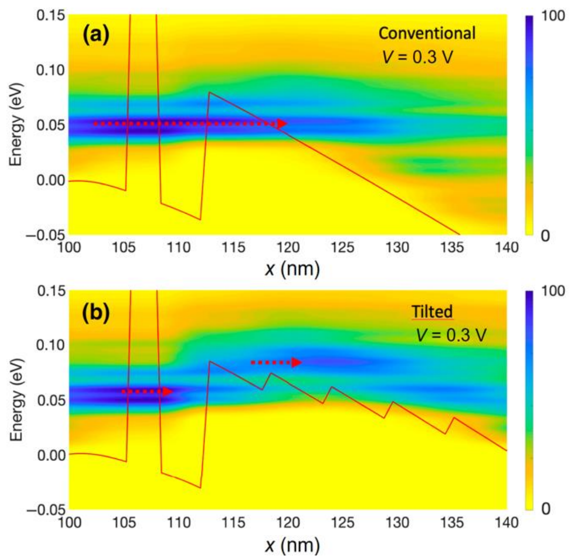

Fig.4: Current spectra for (a) the conventional structure with Y = 0.15 and (b) the tilted structure with Y varying from 0.15 to 0.3 in steps of 5 nm. The red arrows indicate the electron flux through and above the collector barrier. Here L_{QW} = 4 nm and the applied bias is V = 0.3 V.

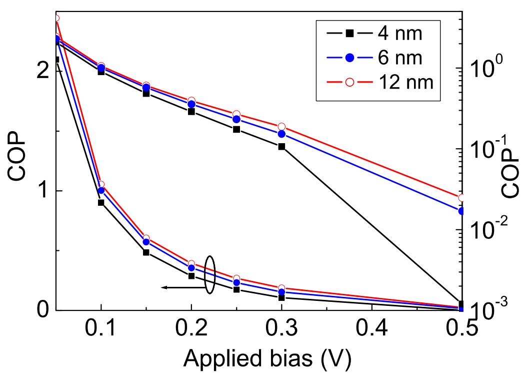

Fig.5: Coefficient of performance (COP) for three L_{QW}: 4 nm (filled squares), 6 nm (filled circles), and 12 nm (open circles). The COP is degraded at high bias, in particular, due to tunneling effect across the collector barrier.

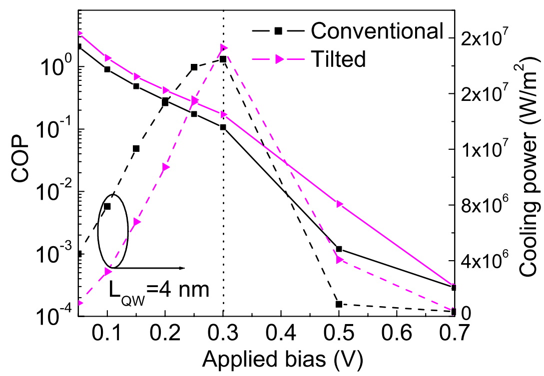

Fig.6: Comparison of COP and cooling power of the conventional and tilted devices. The tilted device clearly provides enhanced performances at high bias, where the thermionic cooling structures are the most relevant.