# Temperature-induced boomerang effect of electron flow in semiconductor heterostructures

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## ABSTRACT SUBMISSION

We theoretically report a remarkable boomerang effect of electron flow when applying a lattice temperature gradient across an asymmetric double-barrier heterostructure.

## INTRODUCTION

Thermoelectric devices consist in converting heat into electricity or vice versa. Those devices are based on the diffusive phonon and electron transport, and operate in close to equilibrium regime, where their produced power is obviously limited. The scenario is significantly different in nanostructures where carrier transport can be assumed as strongly ballistic. In this non-equilibrium regime, electron temperature may significantly differ from the lattice one, raising the opportunity to obtain devices with better performances than conventional thermoelectric structures. We recently demonstrated that an asymmetric double-barrier heterostructure can efficiently act on both the electronic and phononic bath's refrigeration when applied a bias between the emitter and collector contacts [1].

## MODEL AND DISCUSSIONS

Here, we focus on the opposite effect, *i.e.* when a temperature gradient is applied between the collector and the emitter, and we study the induced electrical current properties (Fig. 1). We demonstrate that electrons are subject to an unexpected boomerang effect. Depending on the lattice temperature increase/decrease, electrons respectively absorb/emit a phonon and subsequently go back to the reservoir from which they have been injected (Fig. 2).

Our simulation code, which self-consistently solves the non-equilibrium Green's function framework and the heat equation, is capable to calculate the electron temperature and electrochemical potential inside the device. By investigating those non-equilibrium thermodynamic quantities (Fig.3), we show that the boomerang effect is due to the sign inversion of the local electron distribution (Fig. 4). In particular, simulation results evidenced a variation of the electrochemical potential inside the device to compensate the temperature gradient, and to maintain the electrostatic neutrality in the access regions [2].

## CONCLUSION

We report an original temperature gradient induced boomerang effect, able to control the direction flow of electrons in a given energy interval. Such a boomerang effect, while it does not (almost) transport electrons, transfers a high energy flux from a hot area to a colder one. Finally, our study demonstrates an additional validation of the virtual probe approach to determine thermodynamic properties in strongly non-equilibrium regime.

## REFERENCES

[1] M. Bescond, G. Dangoisse, X. Zhu, C. Salhani and K. Hirakawa, *Comprehensive analysis of electron evaporative cooling in double-barrier semiconductor heterostructures*, Phys. Rev. Appl. **17,** 014001 (2022).

[2] C. Belabbas, A. Crépieux, N. Cavassilas, F. Michelini, X. Zhu, C. Salhani, G. Etesse, K. Hirakawa, and M. Bescond, *Temperature-induced boomerang effect of electronic flow in asymmetric double-barrier semiconductor heterostructures*, submitted (2023).

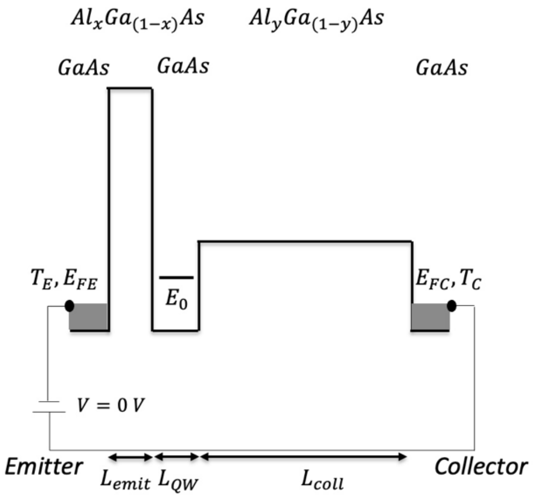

Fig. 1. Sketch of the considered asymmetric double-barrier heterostructure. $L_{emit}$, $L_{QW}$ and $L_{coll}$ refer to the thicknesses of the emitter barrier, the quantum well and the collector barrier respectively. $E_0$ is the quantum well state, while $E_{FE}$ ($T_E$) and $E_{FC}$ ($T_C$) are the Fermi levels (temperatures) of the emitter and collector respectively. For all the considered devices, doping in the emitter and the collector is $10^{18}$ cm$^{-3}$, $L_{emit}$=$L_{QW}$=5 nm and $L_{coll}$=100 nm.

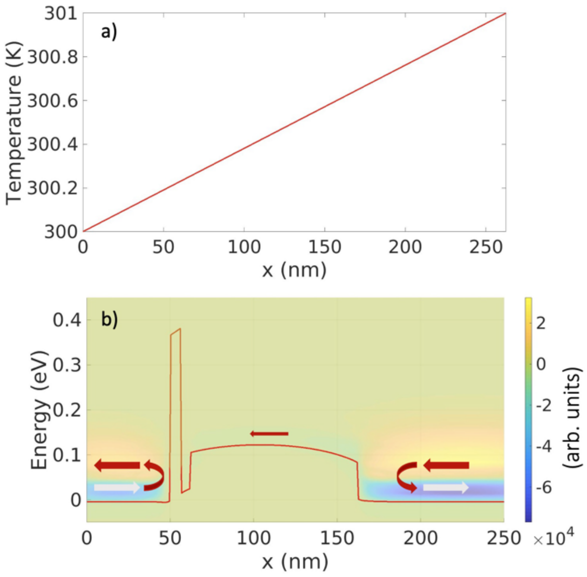

Fig. 2. a) Lattice temperature gradient along the device shown in Fig. 1. A temperature gradient of 1 K is applied between the emitter ($T_{emit}$=300 K) and collector ($T_{coll}$=301 K) reservoirs; b) Corresponding electron current spectrum. The solid red line represents the energy potential profile, while red and white arrows indicate the electron flow and reflection on the potential barrier. The smaller red arrow in the central region represents the total electron flow, going from right to left. No potential bias is applied ($V$=0 V).

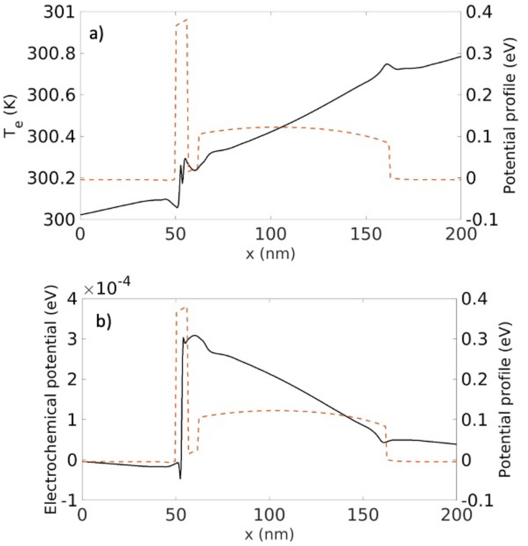

Fig. 3. a) Non-equilibrium electron temperature along the device and b) corresponding electrochemical potential when applying lattice temperature gradient of 1 K and no potential bias ($V$=0 V).

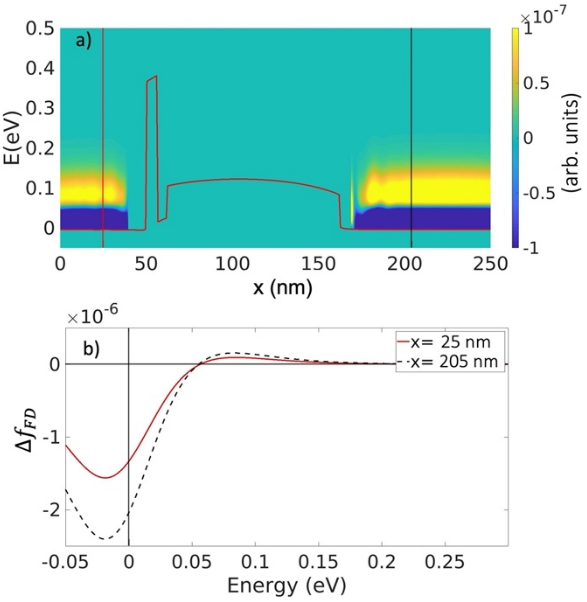

Fig. 4. a) Difference between two consecutive plans of the Fermi-Dirac distributions calculated with the electron temperature and chemical potential shown on Fig. 3-a) and -b) respectively; b) Vertical cuts of Fig. 4-a) at x=25 nm (red solid line) and x=205 nm (dashed line). The vertical black solid line defines the Fermi-levels of the emitter and collector (equal to each other since there is no applied bias).

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