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LETTER TO THE EDITOR

Thermionic current reversal

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Abstract
We have analysed the thermionic current over a potential barrier between a hot and a cold metallic wire, in the absence of an externally applied electric field. Because of the quantum nature of the transmission probability and the temperature behaviour of the Fermi distribution function, under proper conditions the thermionic electric current reverses its direction. However, the heat current remains in the same direction although its magnitude is suppressed.

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In 1838, Heinrich Lenz observed the freezing of water into ice on a bismuth–antimony junction when an electric current passed through the junction in one direction, and the melting of the ice into water when the current was reversed. Consequently, a thermoelectric power generator also works as a refrigerator. Because of the low efficiency of the diffusive thermoelectric process, recently much attention has been paid to the more efficient thermionic process [1–5].

The fundamental quantum-mechanical process of an electron moving across a potential barrier plays the central role in thermionic power generation and refrigeration. An important phenomenon relevant to the current over a potential barrier has been much studied. In a simple set-up where the barrier is due to a vacuum gap between two parallel metal electrodes, the space charge in the vacuum region [6] enhances the barrier strength and so suppresses the thermionic current. To remove the accumulated space charge, metal–semiconductor multilayer structure was first suggested [7], and modulation-doped semiconductor superlattices were more commonly used later. However, it has been proved recently [8] that such charge accumulation still exists in the barrier material.

While the classical phenomenon of charge accumulation only affects the magnitude of the thermionic current, here we will present a novel quantum mechanism which even reverses the direction of the thermionic current. We will demonstrate this effect with a simple system

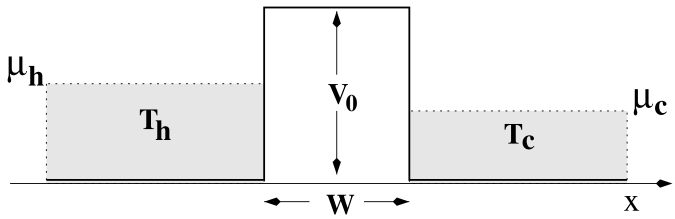

Figure 1. The potential profile along two identical metallic wires separated by an insulating barrier material. The two wires are connected to two thermal reservoirs of temperatures T_h and T_c, and hence have two different chemical potentials μ_h and μ_c.

of two identical metallic conducting wires separated by a layer of insulating material. There is no bias applied across the wires, and the two wires are connected to two thermal reservoirs with a higher temperature T_h and a lower temperature T_c. The potential profile along the wires, which is defined as the x-axis, is sketched in figure 1. Here the difference in chemical potentials μ_h and μ_c is entirely due to the two different temperatures. Such a system can be easily realized with the fabrication technology of semiconductor heterostructures.

The electrons are confined in the yz-plane. To simplify the analysis, let us assume that both wires have the same rectangular cross section of widths a and b. The dispersion relation of electrons in the wires is then simply

$$E_{l_y,l_z}(k) = E_{l_y,l_z} + \frac{\hbar^2 k^2}{2m} \qquad E_{l_y,l_z} = \left[(l_y/a)^2 + (l_z/b)^2\right]\frac{\hbar^2\pi^2}{2m} \tag{1}$$

where l_y and l_z are integers and label the channels of the one-dimensional (1D) electron motion along the wires. If the wires are heavily-doped semiconductors, m should be the effective mass.

We will first consider a pure 1D transport with only the lowest 1D band ($l_y = l_z = 0$) occupied by electrons. This can be achieved by reducing the widths a and b to increase the separation of the discrete energy levels. For this single channel case, to simplify the writing we will remove the channel indices. Namely, the energy $E_{l_y,l_z}(k)$ is simply expressed as $E(k)$. The chemical potentials depend on their respective temperatures as

$$\mu_\gamma = \left[1 + \frac{\pi^2}{12}\left(\frac{k_B T_\gamma}{\epsilon_F}\right)^2\right] E_F \tag{2}$$

with γ for h and c. The electric current density along the x-axis is calculated with the Landauer formula

$$j = \frac{e}{\pi\hbar}\int_0^\infty \mathrm{d}E\, \mathcal{T}(E)\,[f_h(E, T_h, \mu_h) - f_c(E, T_c, \mu_c)] \tag{3}$$

where $f_h(E, T_h, \mu_h)$ and $f_c(E, T_c, \mu_c)$ are Fermi distribution functions in the hot and cold wires, respectively. If the metallic wires are heavily-doped semiconductors, the Fermi energy E_F can be controlled by adjusting the impurity concentration.

In the classical picture the energy-dependent transmission probability $\mathcal{T}(E)$ through the potential barrier given in figure 1 is one if $E > V_0$, and is zero if $E < V_0$. The current density j is then simply the Richardson thermionic current and is always positive, because the number of high energy electrons increases with temperature. In the quantum-mechanical picture, however, it is well known that the transmission probability is an oscillating function

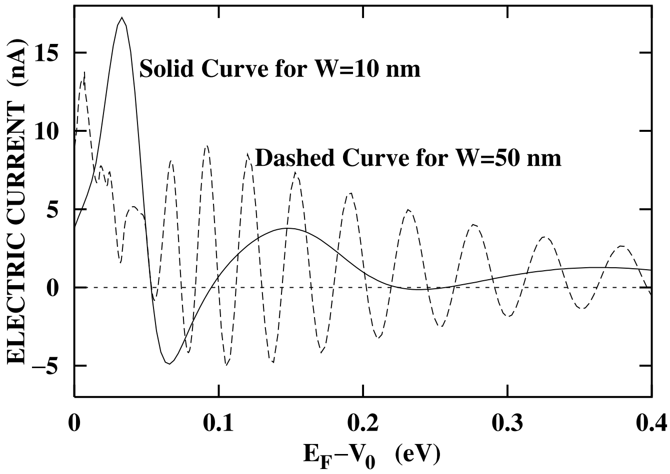

Figure 2. Calculated current along two doped GaAs quantum wires separated by an AlGaAs barrier material with barrier height 0.3 eV. The Fermi energy E_F is a varying material parameter.

of the energy:

$$\mathcal{T}(E) = \left[1 + \frac{V_0^2}{4E(E - V_0)} \sin^2(\kappa W)\right]^{-1} \tag{4}$$

where $\kappa = [2m(E - V_0)/\hbar^2]^{1/2}$. The transmission probability is one when $\kappa W/\pi$ is an integer. Around such an energy region, if $f_h(E, T_h, \mu_h)$ is less than $f_c(E, T_c, \mu_c)$, then the current j may become negative. If the barrier width W is wide, the negative current may appear repeatedly when the chemical potentials μ_h and μ_c in equation (3) vary.

We have performed numerical calculations to demonstrate the phenomenon of thermionic current reversal. We choose doped GaAs material for the two identical quantum wires, and AlGaAs alloy for the barrier. Many other choices of materials will serve the purpose equally well. The carrier density in each wire is represented by the Fermi energy E_F, which is a varying parameter in our calculation. For a potential barrier height $V_0 = 0.3$ eV and the temperatures $T_c = 60$ K and $T_h = 70$ K, the calculated current is plotted in figure 2 for two barrier widths $W = 10$ nm and $W = 50$ nm. Around suitable values of the Fermi energy (or the carrier density in the wires), the reversed current can be as large as 5 nA. When the barrier width is increased (from solid curve to dashed curve) several regions of current reversal appear as expected from the theory. Besides the current reversal, we see that the current can also be turned off completely.

Our extensive numerical calculation indicates that the electric current is rather sensitive to the temperatures T_h and T_c. Hence, it is one origin of the thermal noise of the electric current.

Since there is no external bias applied to our system, the heat current should remain in the same direction when the electric current reverses its direction. In a recent work [9], the heat current and its relation to the Joule heat were analysed. If we replace in equation (3) the electric charge e by the energy E measured from the chemical potential, we obtain the formula for the heat current [9]. The calculated heat current for $W = 10$ nm, $V_0 = 0.3$ eV, $T_h = 70$ K and $T_c = 60$ K is plotted as the solid curve in figure 3. As a reference, the corresponding electric current (solid curve in figure 2) is also shown as the dashed curve in units of $100\times$ nA. When the electric current reverses it direction, the heat current is suppressed but remains in

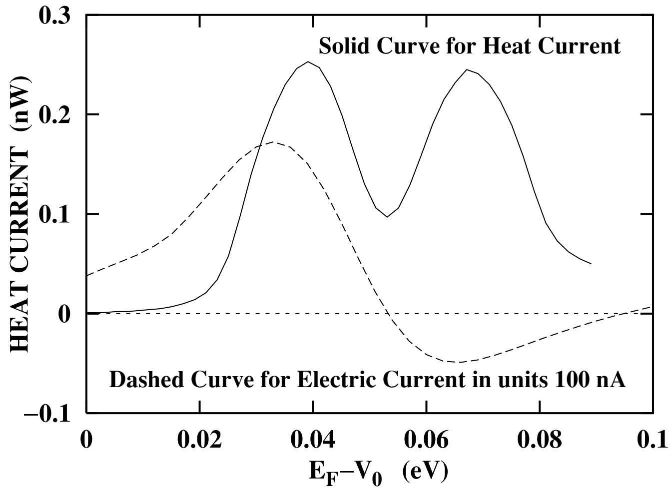

Figure 3. Calculated heat current (solid curve) for the barrier width $W = 10$ nm, under the same condition as that for figure 2. The dashed curve is the reference electric current in units of 100× nW.

the same direction. Hence, when the electric currents flowing in opposite directions cancel completely, the corresponding heat flows cancel only partially.

We have formulated our theory of thermionic current reversal in a single conducting channel. The mathematical analysis and the numerical computation can be easily extended to multi-channel cases, although the actual work will be more complicated. Nevertheless, the mechanism of thermionic current reversal will remain the same, that is, the energy dependence of the quantum-mechanical transmission probability.

To close this letter, we would like to emphasize that we have provided a fundamental physical picture, together with an adequate mathematical analysis, to demonstrate the novel phenomenon of thermionic current reversal in the absence of an externally applied electric field. At the same time the thermal current obeys the fundamental thermodynamic laws. Although we have presented numerical results using simple semiconductor heterostructures, the observation of our predicted phenomenon may require another type of sample design.

Acknowledgments

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References

[1] Mahan G D, Sofo J O and Bartkowiak M 1994 *J. Appl. Phys.* **83** 4683
[2] Shakouri A and Bowers J E 1997 *Appl. Phys. Lett.* **71** 1234
[3] Shakouri A, LaBounty C, Piprek J, Abraham P and Bowers J E 1998 *Appl. Phys. Lett.* **74** 88
[4] Mahan G D and Woods L M 1998 *Phys. Rev. Lett.* **80** 4016
[5] Venkatasubramanian R, Silvola E, Colpitts T and O'Quinn B 2001 *Nature* **413** 597
[6] Langmuir I 1923 *Phys. Rev.* **21** 419
[7] Mahan G D 1994 *J. Appl. Phys.* **76** 4362
[8] Mal'shukov A G, Ma Z, Antonyuk V B and Chao K A 2001 *Solid State Commun.* **119** 563
[9] Humphrey T E, Newbury R, Taylor R P and Linde H 2002 *Preprint* cond-mat0201087