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Electro-Thermal Transport in Quantum Point Contact Nanodevice

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Abstract The Peltier effect was discovered several decades ago. The Peltier effect has been combined with modern low-dimensional quantum system materials, e.g., the quantum point contact (QPC), to open up a new research field. The Peltier coefficient and thermal transport in a QPC, under the influence of photon-assisted and different temperatures are investigated. Numerical calculations of the Peltier coefficient have been performed at different applied voltages, amplitudes, and temperatures. The obtained results are consistent with experimental results in the literature.

Keywords Peltier coefficient · Quantum point contact · Thermal transport

1 Introduction

The Peltier effect describes heat exchange that takes place at the junction of two different materials when electrical current flows between them. It is caused by the fact that the average energy that electrons transport can vary from material to material; when crossing between two such regions, charged carriers compensate for this energy difference by exchanging heat energy with the surrounding lattice. It was in 1834 that Peltier described the thermal effects at the junctions of dissimilar conductors when an electrical current flows between the materials.

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Suppose that a voltage difference ΔV and/or a temperature difference ΔT exist across the conductor, the electric current I and the thermal current P through the conductor can be expressed as [1]

$$I = -(\Delta V + S\Delta T)/R \tag{1}$$

$$P = \Pi I - \kappa \Delta T \tag{2}$$

where R is the resistance, S is the thermoelectric power, Π is the Peltier coefficient, and κ is the thermal conductance. The thermoelectric power and the Peltier coefficient are related by the Kelvin Onsager relation, $\Pi = ST$. Now if an electric current is run through a thermocouple, consisting of two distinct conductors, under isothermal conditions, then the junction acts as either a heat sink or a heat source depending on the current direction. The heat current P caused by this Peltier effect is directly proportional to I.

Ballistic constrictions (PC) connecting bulk reservoirs exhibit new properties when their sizes become comparable to the Fermi wavelength of the electrons. In particular, electronic transport in such systems of quantum (discrete) character, is portrayed by conductance quantization (varying in steps of $2e^2/h$, or multiples of the conductance quantum as a function of the gate voltage, or equivalently the width of the constriction) [2–5] and by the appearance of the peak-like (oscillating) structure of the thermopower coefficient [6–8].

Thermal transport in nanostructures is a key factor for device performance since the thermoelectric figure of merit is inversely proportional to thermal conductivity. Therefore, an understanding of thermal transport in nanostructure materials is crucial for physics (and engineering) high performance devices. Thermal transport in semiconductors is dominated by lattice vibrations called phonons, and phonon transport is often markedly different in nanostructures than it is in bulk materials for a number of reasons. First, as the size of a structure decreases, its surface-area-to-volume ratio increases, thereby increasing the importance of boundaries and interfaces. This paper deals with the thermal properties of a quantum point contact (QPC) under the influence of photon-assisted and different parameters. Also, we investigate the oscillations of the Peltier coefficient and the thermal transport in a QPC with respect to applications in solid-state devices [9].

2 Theoretical Treatment

We consider ballistic electric and thermal transport through a two-dimensional QPC connecting two bulk reservoirs, and the distance between the right and left reservoirs is L. A two-dimensional electron gas (2DEG) is formed on the interface between InAs and AlAs/InAs [10]. InAs does not form a Schottky barrier when brought into contact with a metal, thus allowing the realization of highly transparent contacts between the metal and the 2DEG. This is due to the fact that InAs, unlike GaAs, which forms a Schottky barrier when brought in contact to a metal, forms a surface accumulation layer, therefore pinning the Fermi level in the conduction band [10]. Two gate electrodes are deposited on the sample, and we apply voltage V_G on them relative to 2DEG. If V_G is negative, a narrow channel is formed on 2DEG underneath the gap between the two electrodes because of a valley of the electrostatic potential due to the charge on the electrodes. This narrow channel is called the quantum point contact.

A bias voltage V is applied between the reservoirs which are kept at different temperatures T_1 and T_2. The existence of electrons with different temperatures in the system prevents the establishment of thermal equilibrium. The thermal transport through the point contact may be described in the entropy current formalism [11] as modified in [12] for the Landauer scheme [13]. The electronic contributions to the entropy and heat flows which are dominant in conductors are taken into consideration, and photon assisted transport is observed in QPC with an enhanced current density where the photon energy is $\hbar\omega$. In this description the electric current, I, and the entropy flow, I_S, are expressed in terms of the equilibrium Fermi functions, f_0, of the bulk reservoirs [14] and they are given by,

$$I = \frac{2e}{h} \int \mathrm{d}E \left[f_\mathrm{o} \left(\frac{E-eV+m\hbar\omega-\mu_1}{k_\mathrm{B}T_1} \right) - f_\mathrm{o} \left(\frac{E+eV+m\hbar\omega-\mu_2}{k_\mathrm{B}T_2} \right) \right] \sum \Gamma_{n'n}(E) \tag{3}$$

and

$$I_s = \frac{2}{h} \int \mathrm{d}E \left[v_o \left(\frac{E-eV+m\hbar\omega-\mu_1}{k_\mathrm{B}T_1} \right) - v_o \left(\frac{E+eV+m\hbar\omega-\mu_2}{k_\mathrm{B}T_2} \right) \right] \sum \Gamma_{n'n}(E) \tag{4}$$

where the chemical potentials $\mu_i = \mu(T_i), i = 1, 2$, are determined by the temperatures of the reservoirs T_i, k_B is the Boltzmann constant, $\Gamma_{n'n}$ is the transmission probability for the incident channel into the conducting channel, and the function ν_0 in Eq. 4 is the entropy density [14] given by

$$v_\mathrm{o}(x) = f_\mathrm{o}(x)\log[f_\mathrm{o}(x)] + (1 - f_\mathrm{o}(x))\log[1 - f_\mathrm{o}(x)] \tag{5}$$

The transmission probabilities $\Gamma_{n'n}$ for the incident $n'n$ channel have a form,

$$\Gamma_{n'n} = \sum_{-\infty}^{\infty} j_n^2 \left(\frac{1}{\hbar\omega} \right) eV_\mathrm{max} \left[1 + \left(n'/2 \right) (VL/\hbar)^2 \right]^{-1} \tag{6}$$

The time varying potential is $V = V_\mathrm{max} \sin(\omega t) + V_G$ under the effect of the external field, where ω is the frequency of the external field, V_max is the amplitude, J_n is the nth-order Bessel function of the 1st kind, and $V$is the varying potential. The differential Peltier coefficient of the quantum contact, Π, is given by [14]

$$\Pi/T = (\partial I_s/\partial I)|_{T_1=T_2=T} \tag{7}$$

To get an explicit expression for the Peltier coefficient, Π, we have to integrate Eqs. 3 and 4 after substituting the transmission probability $\Gamma_{n'n}$ (Eq. 4).

3 Discussion and Conclusion

The model studied in the present paper confirms that electron transport through a point contact is ballistic since the mean free path is much larger than the size of the constriction. The above analysis shows that the Peltier effect in a two-dimensional QPC (2DQPC) may be influenced and controlled by external parameters such as an applied voltage and external field.

The capacitance of nanodevice systems at a high frequency is the critical point because the ac current may go through the strait capacitor instead of the device. So one must consider that the cut-off frequency should be much smaller than THz. The

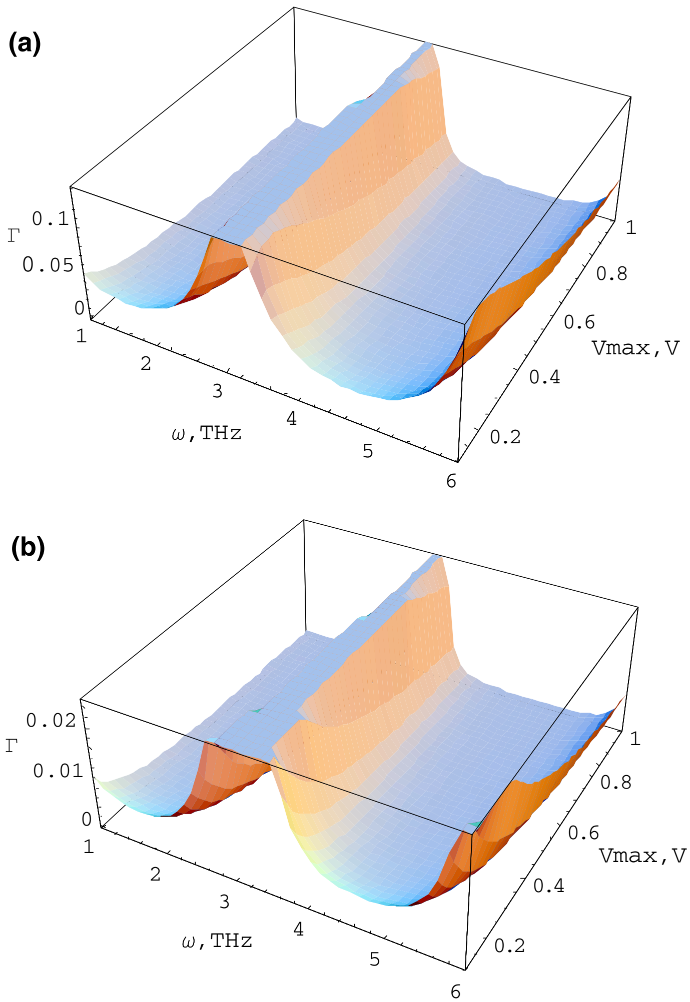

Fig. 1 Transmission probability, Γas a function of the frequency, ω (in THz) of the external field, at different magnitudes to $V_{\max}$(in V): (a) $L = 20\,\text{nm}$ and (b) $L = 50\,\text{nm}$

electronic transmission probability is sensitive to the external fields as we show in Figs. 1 and 2. It is very easy to see the significance of the frequency on the behavior and the magnitude of the transmission. The value of the existing capacity, V_{max}, has a clear significance on Fig. 1a ($L = 20$ nm) and Fig. 1b ($L = 50$ nm). Also, these results show the high transmission around 3 THz in the infrared region and this may be useful to set optical devices. Figure 2 shows the resonance with sharp peaks at different frequencies and tunneling times. At the distance between the left and right sides, $L = 20$ nm, the magnitude of transmission is 0.1 as shown in Figs. 1a and 2a. When $L = 50$ nm, the magnitude of transmission is significantly decreased to 0.02

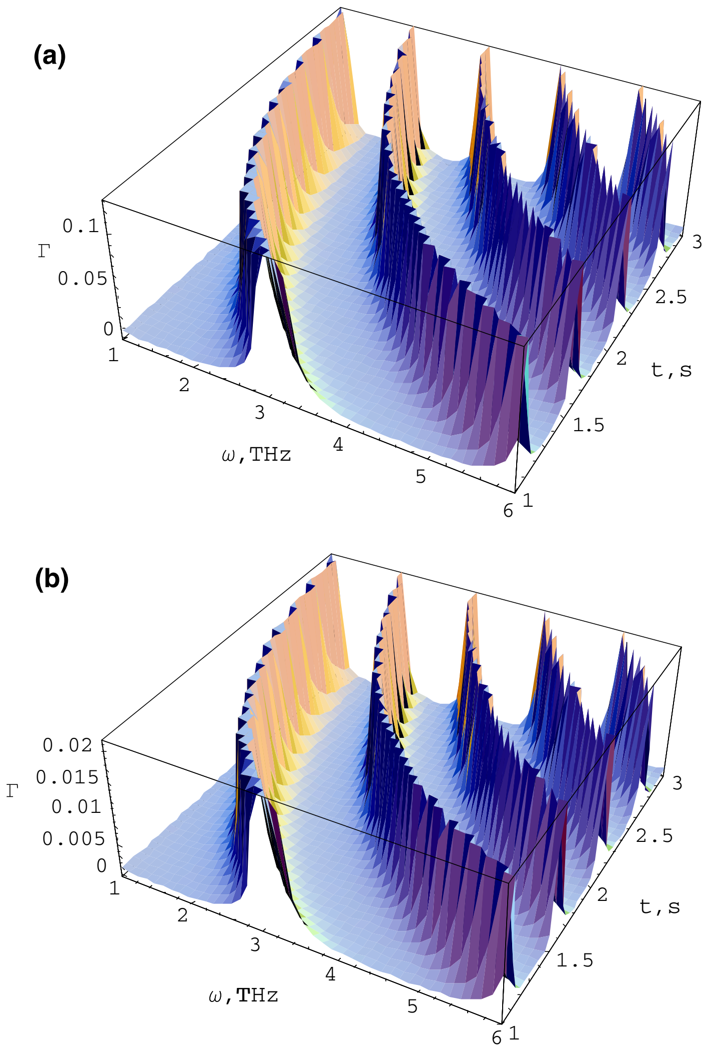

Fig. 2 Transmission probability, Γ, as a function of frequency, ω (in THz) of the external field, at different relaxation times, t(in s): (a) $L = 20$ nm and (b) $L = 50$ nm

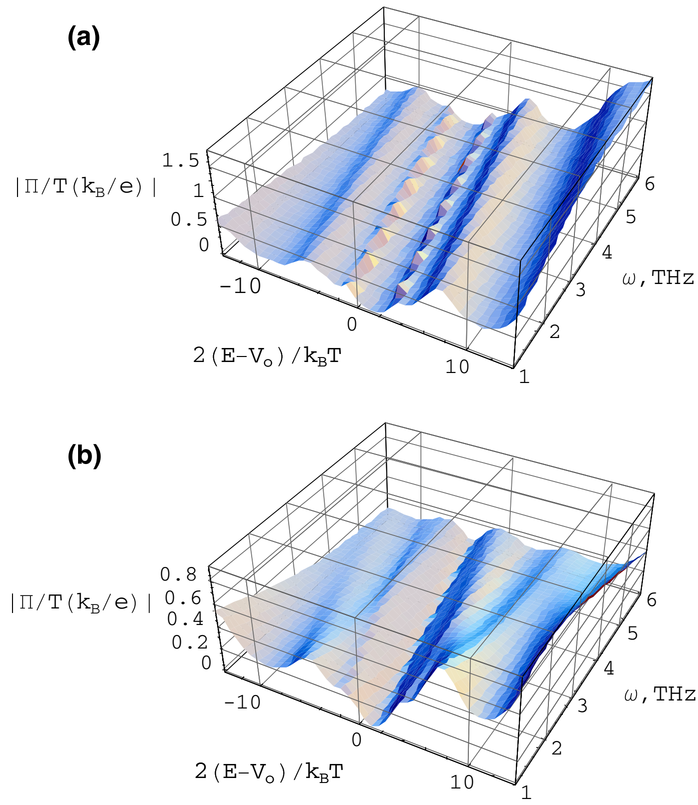

Fig. 3 Absolute value of the Peltier coefficient (Π, in units of $k_B T/e$) of a contact plotted versus the dimensionless parameter $[2(E - V_o)/k_B T]$ for different frequencies: (a) $V_{max} = 0.2V$ and (b) $V_{max} = 4V$

as shown in Figs. 1b and 2b. This result shows excellent agreement with previous data.

Given the importance of the Peltier coefficient in applications of thermal transport systems, we have demonstrated a Peltier effect in quantum contacts exhibited by the appearance of new peaks at finite voltages (see Fig. 3). Such behavior of the Peltier coefficient, Π, in QPCs is due to the influence of the external fields on the spectrum of electronic states in the micro-constrictions, allowing one to change and control the number of conducting channels. As shown in Fig. 3, we calculated the Peltier coefficient dependence on the dimensionless parameter, $[2(E - V_o)/k_B T]$, with different frequencies. There are some differences in the peak behavior in Fig. 3a and b. The magnitude of the Peltier coefficient is around 1.5 (Fig. 2a) with $V_{max} = 0.2$, which decreases to 0.8 (Fig. 3b) when $V_{max} = 4$. That means that the applied voltage is an important parameter to achieve the desired Peltier coefficient in different applications. Also, we can explain the new peaks by the positive effect of photon-assisted transport in our system. The transmission probability can be affected by photon emission and absorption. The magnitude of these effects strongly depends on L and the bound-state character of the electrons.

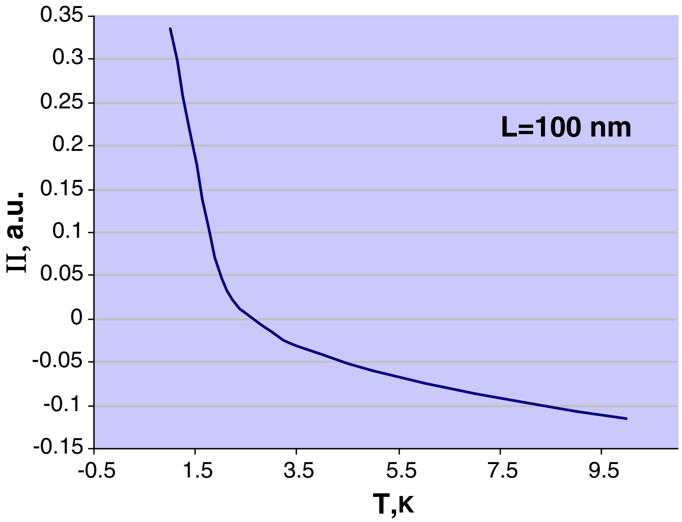

Fig. 4 Peltier coefficient (Π) plotted versus the temperature

The value of the existing capacity, $V_{\max}$, in the equation for the applied voltage, $V = V_{\max} \sin(\omega t)$, has a clear significance on the peak areas formed by the effect of external fields as well as the energy system. In Fig. 3a, we find more sharp peaks at large magnitude ($\sim$1.5) to the Peltier coefficient. The sharpest peaks decreased with the capacity value as shown in Fig. 3b. This is due to the impact of the value of the applied voltage as well as the capacity factor in the magnitude of the Peltier coefficient. Also, the appearance of new peaks confirmed the Peltier coefficient in the nonlinear voltage regime, resulting in violation of Onsager's principle of the coefficients. Figure 4 shows the Peltier coefficient as a function of temperature with the assumption, $T_1 = T_2 = T$. The value of the Peltier coefficient decreases with an increase in temperature. The behavior of the Peltier coefficient with temperature is almost the same as for current density-temperature characteristics in 2DQPC [15,16].

In recent years the Peltier effect has been employed widely in measuring devices for performing thermophysical tests and is used to correct the errors of temperature-measuring instruments and a series of thermophysical quantities. Also I hope in the future I can study the treatment of electro-opto-thermal effects based on the temperatures and size because it will be very useful in medical devices and therapy.

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