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Ballistic thermal transport in multi-terminal graphene junctions

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ABSTRACT

Ballistic thermal transport properties in Y-branch three-terminal and H-branch four-terminal graphene junctions are systematically investigated by using nonequilibrium Green's function method. A comparative analysis for the Y-branch and H-branch quantum structure models is made. The results show that the increased junction in H-branch four-terminal graphene junctions can obviously reduce the thermal conductance of the adjacent quantum channel and slightly influence the thermal conductance of the farside quantum channel. The total thermal conductance displays almost the same thermal conductance property in both Y-branch and H-branch quantum structures.

1. Introduction

Quantum devices, due to unique physical properties and potential application in extensive domains, have attracted increasing attention in recent years [1–13]. However, overheating in ever-smaller integrated circuits and nanodevices needs efficient heat removal from these low-dimensional structures. Surprisingly, graphene not only possesses excellent electrical properties [14], but also possesses extremely high thermal conductivity [15] and presents the promising base material for future quantum devices. Due to its enormous potential applications, graphene has been attracting particular attention and many interesting physical effects are found such as thermal rectification effects [16,17], thermal conductance modulator [18], negative differential conductivity [19], defect-induced circulating thermal current [20], nonlinear phonon transport [21], and so on. The thermal-conductance properties have also been reported in various geometries in graphene and show close relation with structural characteristics and geometry details [22–28]. Especially, the multi-terminal ballistic junctions have drawn increasing attention because of revealing some interesting magnetic [29], electronic [30,31], and thermal properties [21]. Interestingly, it is natural to consider whether the total thermal conductance is of proportion to the junction channels in quantum devices. In this work, we compare the thermal transport properties in Y-branch three-terminal ballistic junctions (YTBJS) and H-branch four-terminal ballistic junctions (HFBJS). Our studies show that although there are more quantum channels in four-terminal graphene ballistic junctions, the total thermal conductance has little increased, as will be shown below.

2. Model and method

We model the YTBJS and HFBJS as illustrated in Fig. 1a and b. The system can be divided into five regions for HFBJS (four regions for YTBJS): four semi-infinite thermal terminals, which are assumed to be in thermal equilibrium (the top-left terminal (region I), the top-right terminal (region II), the bottom-left terminal (region IV, note that this region does not exist in YTBJS), and the bottom-right terminal (region III)), and a finite central connected region. Since all sub-10-nm graphene nanoribbons are semiconducting and the thermal conductance of GNRs narrower than 10 nm is mostly dominated by phonons in recent experiment [32], in this work, the thermal conductance contributed by electrons is not considered. Among the four thermal terminals (three thermal terminals for YTBJS), only the left terminal with temperature T_1 is the energy-input terminal and the others with temperature T_2 are the energy output terminals ($T_1 > T_2$). The widths of the four terminals are labeled by N_{TL} (The top-left terminal), N_{TR} (The top-right terminal), N_{BL} (The bottom-left terminal), N_{BR} (The bottom-right terminal), and the width and length of the central connected region are $N_{TL} + N_M + N_{BL}$ and N_L, respectively. There are two in-plane modes and one out-of-plane mode in GNRs, and the Hamiltonian between the in-plane and the out-of-plane modes is completely decomposed. In this paper, we mainly focus on the thermal transport related to the out-of-plane mode. Being the phonon mean free path for graphene is 775 nm [34], which is much longer than the sizes of HFBJS and YTBJS, the phonon–phonon

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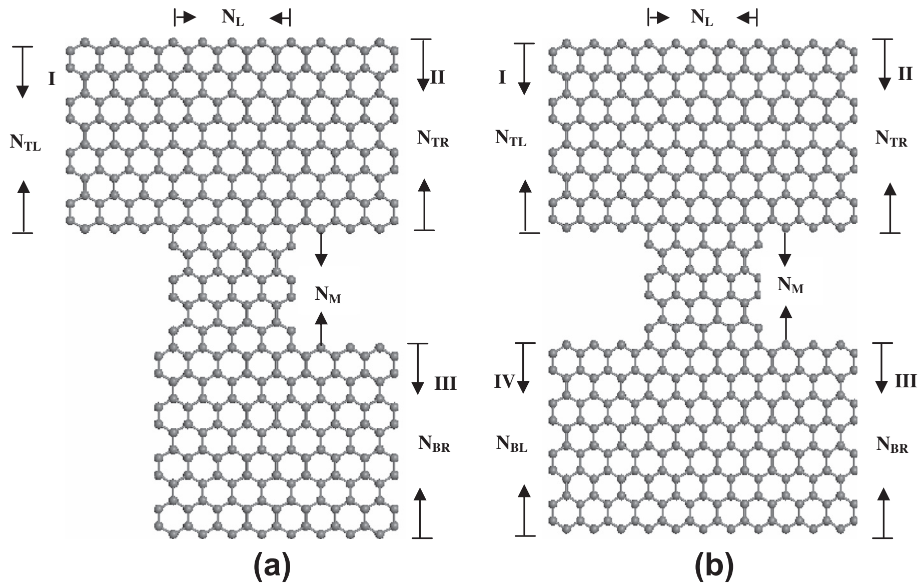

Fig. 1. (a and b) Schematics of Y-branch three-terminal ballistic junctions without the bottom-left terminal (YTBJS) and H-branch four-terminal graphene ballistic junctions with the bottom-left terminal (HFBJS), respectively.

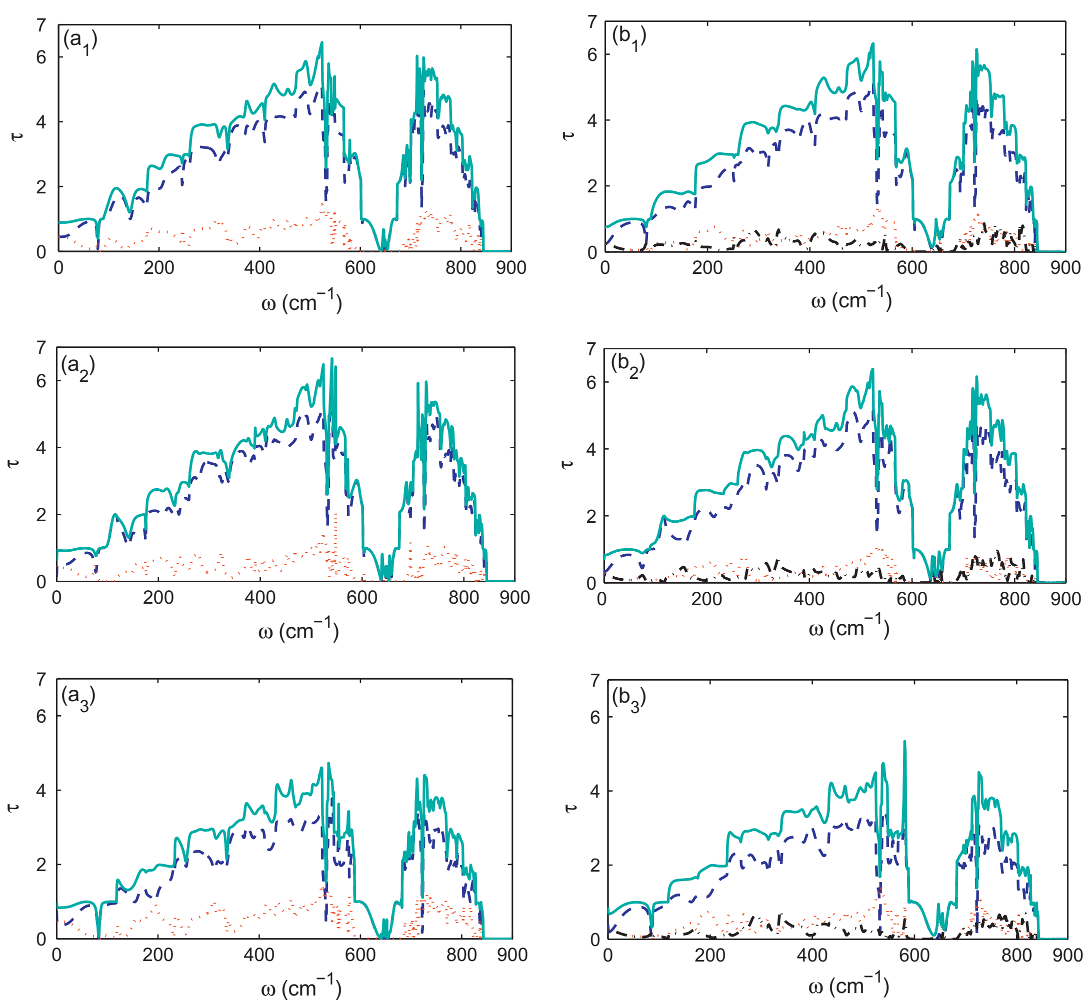

Fig. 2. (a and b) describe the phonon transmission function using nonequilibrium Green's function (NEGF) method in YTBJS and HFBJS, respectively. solid, dashed, dotted, and dash-dotted curves correspond to the total transmission rate, the transmission rate in the top-right terminal, the transmission rate in the bottom-right terminal, and the transmission rate in the bottom-left terminal, respectively. (a_1) and (b_1) correspond to $N_{TL} = N_{TR} = N_{BL} = N_{BR} = 8\alpha$, $N_M = 4\alpha$ ($\alpha = 0.145$ nm)); (a_2) and (b_2) correspond to $N_{TL} = N_{TR} = 8\alpha$, $N_{BL} = N_{BR} = 6\alpha$, and $N_M = 6\alpha$; and (a_3) and (b_3) correspond to $N_{TL} = N_{TR} = 6\alpha$, $N_{BL} = N_{BR} = 8\alpha$, and $N_M = 4\alpha$; respectively. Here, we always take $N_L = 4\sqrt{3}\alpha$.