Direct calculation of nonequilibrium current in a magnetic field

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Abstract

We calculate nonlinear $I-V$ characteristics in the system comprising a tunnel junction and a rectangle barrier to study quantum interference effects using the lattice Green's function method based on Keldysh's theory. © 2000 Elsevier Science B.V. All rights reserved.

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With advanced technology of the nano-fabrication, it becomes possible to make various structures on mesoscopic scale and the nonlinear transport in these systems becomes one of the current topics. For instance, the measurements of quantum interference of electrons in metal rings interrupted by two small junctions are reported [1].

We have been studying the nonlinear $I-V$ characteristics and the spatial distribution of current through a biased region [2,3]. The method employed is based on Keldysh's theory, and is an extension of the recursive Green function method for a lattice model. In this work, we investigate the $I-V$ characteristics in a system comprising a tunnel junction and a single rectangle barrier at the center as depicted in the inset of Fig. 1. To this system, we apply the bias voltage $eV$ taking the chemical potential of the left and right sides of the hatched rectangles in Fig. 1, $\mu_L$ and $\mu_R$, to be $\mu_L = \mu_R + eV$. The on-site energy in the closed rectangle is much higher than that in the hatched regions. Especially, we examine the Aharonov–Bohm (AB)-type interference effect on the tunnel current under a finite voltage. We use a model on a square lattice which is finite $M$ in the $y$-direction [2,3], and take the transfer integral $t$ as a unit of the energy. Also, we introduce a magnetic field $B$ through the Peierls phase and take $\phi_0/a^2$ as a unit, where $\phi_0$ is the flux quantum and $a$ is the lattice constant.

In Fig. 1(a), the total current in the case of $\mu_R = -3.6$ is shown as a function of $B$ for several bias voltages $eV$. In the linear response case at $eV = 0.001$, we can see narrow dips appearing quasi-periodically. These dips are due to the resonant reflection occurring between two edge states through the local states surrounding the rectangle barrier [4,5], and take place with a period $\Delta B = 0.004$ which corresponds to the inverse of the area of the local state surrounding the barrier. As the bias voltage increases, this oscillatory behavior due to the AB-type effect becomes weak [see Fig. 1(a) at $eV = 0.5$]. This is because many resonant states exist in the energy spectrum between $\mu_R$ and $\mu_R + eV$, and thus, the current becomes less sensitive to the change of $\mu_R$. We note that a similar tendency is also seen in the $\mu_R$ dependence of the tunneling current through a double barrier [2,3,6].

We also examined the effects of the randomness by introducing impurities around the rectangle barrier: we add the potential energy by 0.5 for 10% of the sites chosen randomly from $10 \times 20$ sites at the center [see Fig. 1]. Fig. 1(b) gives typical examples of the $B$ dependence of the current for an average of 50 different impurity configurations. By the averaging, the sharp dips disappear and the curve structure begins to resemble that in Fig. 1(a) at $eV = 0.1$.

Next, we discuss the bias voltage dependence of the current. Fig. 2 shows the currents as a function of $eV$ for the average of the 50 different impurity configurations. The currents show oscillatory behaviors, and the interval

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Fig. 1. $B$ dependence of the current (a) without impurity and (b) with impurities. The inset shows the schematic figure of the system (width $M = 20$). The on-site energy is taken to be 100 in the closed rectangle (10 × 10 sites) and 2 in the hatched rectangles (2 × 5 sites in each). The additional static potential due to the bias voltage is also applied to each site.

of the maximum is about $\Delta eV = 0.22$. The oscillatory behaviors are well explained by the obtained energy dependence of the transmission probability (not shown). These behaviors are attributable to the periodic change of the quantized local level around the barrier [7].

In summary, we have calculated the nonlinear $I$–$V$ characteristics in the system comprising the tunnel junction and the rectangle barrier, and examined the AB-type interference effects on the tunnel current under the finite bias voltage. We also investigated the spatial distributions of the current, and the results will be presented in future.

Fig. 2. $eV$ dependence of the currents for several values of $B$.

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References