Numerical study of the sideband quenching in driven mesoscopic systems

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Abstract

Coherent electron transport through a system driven by a time-varying potential is theoretically studied by employing a transfer-matrix method which enables us to investigate not only dc but also ac transport of dynamical mesoscopic systems. It has been found that ac currents in a driven double-barrier system become minimum at certain values α^* of the strength of the time-varying potential, as in the case of the sideband quenching of dc transport. The nature of the ac quenching is, however, different from the dc one.

Key words: photon-assisted tunneling; ballistic transport; sideband quenching

In a system driven by a time-varying potential with frequency ω, an electron wavefunction possesses sideband components with energies $E + n\hbar\omega\,(n = 0, \pm 1, \pm 2 \cdots)$, where E is the incident electron energy. It is well known that the spectral weight of the nth sideband component is proportional to $|J_n(V_{\rm ac}/\hbar\omega)|^2$ if the time-varying potential has a homogeneous spatial profile, where J_n is the nth-order Bessel function. Thus, the spectral weight vanishes at zeros of the Bessel function. This is called the "sideband quenching" phenomenon[1,2]. While most of previous works on the sideband quenching have been focused on dc transport, the sideband quenching exerts an influence on the ac current induced by the time-varying potential. It is quite interesting to study the quenching behavior of ac currents in actual experiments with both static and time-varying potentials having inhomogeneous profiles.

In this paper, we investigate the quenching effect of ac transport through a driven double-barrier system. In order to analyze transport properties of driven mesoscopic systems, we employed a transfer-matrix method which enables us to compute transmission coefficients of a dynamical mesoscopic system with arbitrary potential profiles. Our results show that additional quenching points appear in the ac current in contrast to the dc quenching. This is because ac currents are a consequence of quantum interference between different sideband states.

We consider, for simplicity, a one-dimensional mesoscopic system with a static potential $V_{\rm dc}(x)$ and a harmonically oscillating potential $V_{\rm ac}(x)\cos\omega t$. An electron in the system can be described by the Schrödinger equation,

$$i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2} + V_{\rm dc}\,(x) + V_{\rm ac}\,(x)\cos\omega t\right]\psi. \quad (1)$$

In the transfer-matrix method, the system is divided into N segments. The width of these segments Δx is so small that the potentials $V_{\rm dc}(x)$ and $V_{\rm ac}(x)$ can be regarded as constants in each segment. The wavefunction ψ^l in the lth segment is given by

$$\psi^l = \sum_{n=-\infty}^{\infty}\left(A_n^l e^{ik_n^l x} + B_n^l e^{-ik_n^l x}\right)$$

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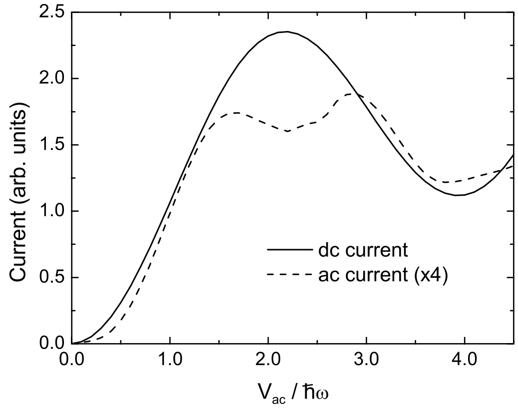

Fig. 1. dc and ac currents as a function of the strength of the time-varying potential.

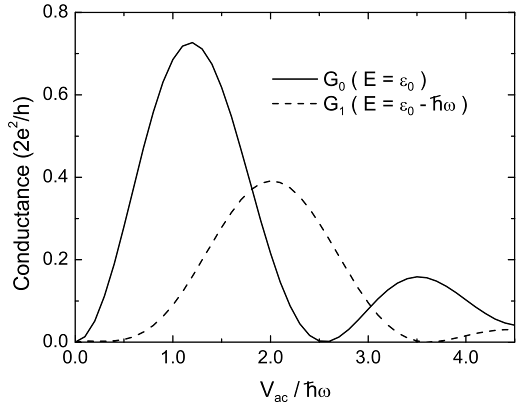

Fig. 2. dc conductances through the main and sideband resonant levels as a function of the strength of the time-varying potential. The incident energy is fixed to be $\varepsilon_0 - \hbar\omega$.

$$\times \sum_{m=-\infty}^{\infty} J_m\left(\frac{V_{\rm ac}^l}{\hbar\omega}\right) e^{-i(E+n\hbar\omega+m\hbar\omega)t/\hbar}, \quad (2)$$

where $k_n^l = \sqrt{2m^*(E - V_{\rm dc}^l + n\hbar\omega)}/\hbar$, and $V_{\rm dc}^l$ and $V_{\rm ac}^l$ are representative values of $V_{\rm dc}(x)$ and $V_{\rm ac}(x)$ in the lth segment, respectively. Suffixes m and n denote sideband indices. From matching conditions between adjacent segments, one can construct the transfer matrix and calculate the transmitted wavefunction. If we write the transmitted wave as

$$\psi_{\rm T} = \sum_{n=-\infty}^{\infty} C_n e^{ik_n x} e^{-i(E+n\hbar\omega)t/\hbar}, \quad (3)$$

the coefficient C_n includes $J_m(V_{\rm ac}^l/\hbar\omega)$ ($m = 0, \pm1, \ldots$; $l = 1, 2, \ldots$) in a complex manner for an inhomogeneous potential profile. Therefore, the sideband quenching is not so simple in contrast to the homogeneous one.

Figure 1 shows the dc and ac currents as a function of the strength of a time-varying potential. The static and time-varying potentials are given by

$$V_{\rm dc}(x) = V_{\rm dc}\left[e^{-(x-x_{\rm dc})^2/\xi_{\rm dc}^2} + e^{-(x+x_{\rm dc})^2/\xi_{\rm dc}^2}\right], \quad (4)$$

and

$$V_{\rm ac}(x) = V_{\rm ac} e^{-x^2/\xi_{\rm ac}^2}, \quad (5)$$

where $V_{\rm dc} = 20\,\rm meV$, $x_{\rm dc} = 50\,\rm nm$, $\xi_{\rm dc} = 50\,\rm nm$, and $\xi_{\rm ac} = 70\,\rm nm$. We fix the frequency of the time-varying potential as $\hbar\omega = 1.0\,\rm meV$. The incident electron energy is chosen to be $E = \varepsilon_0 - \hbar\omega$, where ε_0 is a resonant energy of the double-barrier potential ($\varepsilon_0 = 19.3\,\rm meV$). The dc current becomes minimum at $V_{\rm ac}/\hbar\omega \simeq 3.8$. This value is close to the first zero of $J_1(x)$. This means that the coefficient C_0 in Eq. (3) is dominated by a single Bessel function $J_1(V_{\rm ac}^*/\hbar\omega)$ even for inhomogeneous potential profiles, where $V_{\rm ac}^*$ is an effective strength of the time-varying potential. For the system treated here, $V_{\rm ac}^*$ is nearly equal to $V_{\rm ac}$. Another minimum at $V_{\rm ac}/\hbar\omega \simeq 2.4$ can be found in the ac current shown in Fig. 1. This may correspond to the first zero of $J_0(x)$. The reason of this additional quenching is that the ac current is a consequence of quantum interference between the 0th and first sideband states. In order to confirm this interpretation, we calculated dc conductances G_0 and G_1 through the main and sideband resonant levels, respectively. Results shown in Fig. 2 give a clear evidence that G_0 and G_1 take their minimum values at $V_{\rm ac}/\hbar\omega = 2.4$ and 3.8, respectively. The ac quenching phenomenon predicted here can be efficiently observed in a driven mesoscopic ring.

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