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Transport suppression in heterostructures driven by an ac gate voltage

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Abstract

We explore the possibility of inducing in heterostructures driven by an ac gate voltage the coherent current suppression recently found for nanoscale conductors in oscillating fields. The destruction of current is fairly independent of the transport voltage, but can be controlled by the driving amplitude and frequency. Within a tight-binding approximation, we obtain analytical results for the average current in the presence of driving. These results are compared against an exact numerical treatment based on a transfer-matrix approach.
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1. Introduction and modelling

The study of electron transfer comprises a rich variety of systems in many different areas such as chemistry, biology, and life sciences [1,2]. Although electron transfer processes are mainly attributed to electrochemical applications, they are conceptually related to molecular electronics [3–5] and electron transport in low dimensional materials in solid-state physics. In that context, semiconductor heterostructures represent a popular physical system for the investigation of mesoscopic transport [6–8] and tunnelling phenomena [9–13]. The main reason for this is the high mobility and the rather long mean free path of the charge carriers populating them. Standard beam epitaxy techniques make the accurate growth of alloys of such materials on substrates possible, and the nearly identical lattice parameters, together with the possibility of controlling the band gap, turn the combination $GaAs/Al_xGa_{1-x}As$ into an ideal candidate for building complex low dimensional structures with quantum wells and tunnel barriers. Moreover, these setups open various ways to study tunnelling in time-dependent systems [14–16]. A straightforward possibility for introducing a time-dependence is the application of an ac transport voltage which only modulates the energies of the electrons in the leads while the potential inside the mesoscopic region remains time-independent. This kind of driving allows for a description within Tien–Gordon theory [17] which expresses the dc current in terms of the static transmission and an effective distribution function for the lead electrons. If the time-dependence enters via an external microwave field or an ac gate voltage, however, such an approach is generally insufficient [18].

A remarkable difference with respect to the static situation is the emergence of inelastic transport channels

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stemming from the emission or absorption of quanta of the driving field. For a periodically time-dependent transport situation, however, we expect the transmission probabilities and, consequently, the resulting current to be time-dependent as well. This follows indeed from a recently presented Floquet theory for the transport through driven tight-binding systems [16,18]. For the computation of the dc current, this approach justifies the applicability of a Landauer-like current formula where the static transmission is replaced by the time-averaged transmission of the time-dependent system.

The transmission of both the elastic and the inelastic transport channels can depend sensitively on the driving parameters; the contribution of certain channels can even vanish. For the transport across two barriers which enclose an oscillating potential well, Wagner [19] showed that it is possible to suppress the contribution of individual inelastic scattering channels. The total current, however, is given by the sum over all channels, and thus it is not possible to isolate the contribution of a single channel in a current measurement. By contrast, in the case of transport through a two-level system with attached leads, it has been found that driving with a dipole field has directly observable consequences. There, the driving not only affects the contribution of individual transport channels, but the dc current can be suppressed almost entirely [20,21]. Therefore, for the appearance of this *coherent current suppression*, it is essential that the central region consists of at least two weakly coupled wells which oscillate relative to each other [18].

In this work, we explore the possibility of coherent current suppression in double-well heterostructures. Thereby, we compare two theoretical approaches to describe coherent transport in quantum-well structures: The transfer-matrix method and a tight-binding approach. As a model we consider the triple-barrier structure sketched in Fig. 1 where the driving enters via an oscillating gate voltage which modulates the bottom of the left well. The applied transport voltage is assumed to shift the Fermi energy of the left lead by $-eV$ with

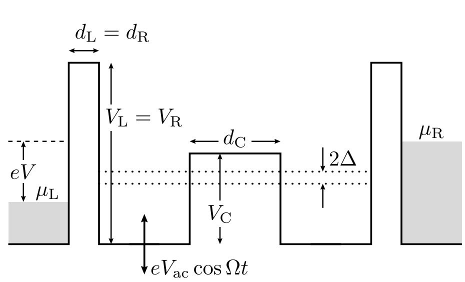

Fig. 1. Model potential for the double-well heterostructure. In the numerical calculations, we employ barriers with the heights $V_L = V_R = 90$ meV, $V_C = 40$ meV and the widths $d_L = d_R = 5$ nm, $d_C = 15$ nm. The dotted lines mark the energy of a metastable tunnel doublet with splitting energy 2Δ. The left well is subject to an electric dipole field generated by an alternating gate voltage with amplitude V_{ac}.

$-e$ being the electron charge. We note that since the time-dependent gate voltage affects only one well, the structure depicted in Fig. 1 is sufficiently asymmetric to also act as an electron pump, i.e., to induce a non-zero current for $eV = 0$ [16]. In this work, however, we focus on the transport properties in the presence of a finite bias voltage.

For the exact numerical computation of the transmission probabilities, we employ the transfer-matrix method developed by Wagner [22], which is reviewed in Section 2. In Section 3, we introduce the related tight-binding system for which the transport properties can be calculated analytically within a high-frequency approximation scheme [21]. The predictions from the perturbative approach are compared to the exact solution in Section 4.

2. Transfer-matrix method

Following Landauer [23], we consider the coherent mesoscopic transport as a quantum mechanical scattering process. The central idea of this approach is the assumption that sufficiently far from the scattering region, the electronic single-particle states are plane waves and that their occupation probability is given by the Fermi function with the chemical potential depending on the applied voltage. The unitarity of evolution under coherent ac driving allows us to write the resulting currents as [24]

$$I = \frac{e}{h} \int \mathrm{d}E[T_{RL}(E)f_L(E) - T_{LR}(E)f_R(E)], \tag{1}$$

where $T_{RL}(E)$ denotes the total transmission probability – i.e., summed over transverse modes and outgoing inelastic channels – of an electron with energy E from the left lead to the right lead while $T_{LR}(E)$ describes the respective scattering from the right to the left lead. For time-independent conductors, the time-reversal symmetry of the quantum mechanical scattering process together with the energy conservation ensures $T_{RL}(E) = T_{LR}(E)$ such that, in the absence of a transport voltage, the current vanishes. This is not the case for a general time-dependent structure [16].

When the total Hamiltonian is time-periodic due to an external driving field, $H(x,t) = H(x, t + \mathscr{T})$, one can apply Floquet theory [25,26,14]. It states that the corresponding time-dependent Schrödinger equation has a complete set of solutions of the form

$$\psi_\alpha(x,t) = \exp(-\mathrm{i}\epsilon_\alpha t/\hbar)u_\alpha(x,t), \tag{2}$$

where $u_\alpha(x,t) = u_\alpha(x, t + \mathscr{T})$ denotes the so-called Floquet states, and ϵ_α the so-called quasienergies in analogy to the quasimomenta of Bloch theory.

Owing to their time-periodicity, we can decompose the Floquet states into a Fourier series

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