



杭州电子科技大学
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Quantum Transport

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Time-dependent transport in interacting and noninteracting resonant-tunneling systems

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We consider a mesoscopic region coupled to two leads under the influence of external time-dependent voltages. The time dependence is coupled to source and drain contacts, the gates controlling the tunnel-barrier heights, or to the gates that define the mesoscopic region. We derive, with the Keldysh nonequilibrium-Green-function technique, a formal expression for the fully nonlinear, time-dependent current through the system. The analysis admits arbitrary interactions in the mesoscopic region, but the leads are treated as noninteracting. For proportionate coupling to the leads, the time-averaged current is simply the integral between the chemical potentials of the time-averaged density of states, weighted by the coupling to the leads, in close analogy to the time-independent result of Meir and Wingreen [Phys. Rev. Lett. **68**, 2512 (1992)]. Analytical and numerical results for the exactly solvable noninteracting resonant-tunneling system are presented. Due to the coherence between the leads and the resonant site, the current does not follow the driving signal adiabatically: a "ringing" current is found as a response to a voltage pulse, and a complex time dependence results in the case of harmonic driving voltages. We also establish a connection to recent linear-response calculations, and to earlier studies of electron-phonon scattering effects in resonant tunneling.

I. INTRODUCTION

The hallmark of mesoscopic phenomena is the phase coherence of the charge carriers, which is maintained over a significant part of the transport process. The interference effects resulting from this phase coherence are reflected in a number of experimentally measurable properties. For example, phase coherence is central to the Aharonov-Bohm effect,¹ universal conductance fluctuations,¹ and weak localization,² and can be affected by external controls such as temperature or magnetic field. The study of stationary mesoscopic physics is now a mature field, and in this work we focus on an alternative way of affecting the phase coherence: external *time-dependent* perturbations. The interplay of external time dependence and phase coherence can be phenomenologically understood as follows. If the single-particle energies acquire a time dependence, then the wave functions have an extra phase factor, $\psi \sim \exp[-i \int^t dt' \epsilon(t')]$. For a uniform system such an overall phase factor is of no consequence. However, if the external time dependence is different in different parts of the system, and the particles can move between these regions (without being "dephased" by inelastic collisions), the phase difference becomes important.

The interest in time-dependent mesoscopic phenom-

ena stems from recent progress in several experimental techniques.³ Time dependence is a central ingredient in many different experiments, of which we mention the following:

(i) *Single-electron pumps and turnstiles.* Here time-modified gate signals move electrons one by one through a quantum dot, leading to a current which is proportional to the frequency of the external signal. These structures have considerable importance as current standards. The Coulombic repulsion of the carriers in the central region is crucial to the operational principle of these devices, and underlines the fact that extra care must be paid to interactions when considering time-dependent transport in mesoscopic systems.

(ii) *ac response and transients in resonant-tunneling devices.* Resonant-tunneling devices have a number of applications as high-frequency amplifiers or detectors. For the device engineer a natural approach would be to model these circuit elements with resistors, capacitances, and inductors. The question then arises as to what, if any, are the appropriate "quantum" capacitances and inductances one should ascribe to these devices. Answering this question requires the use of time-dependent quantum-transport theory.

(iii) *Interaction with laser fields.* Ultrashort laser pulses allow the study of short-time dynamics of charge carriers. Here again, coherence and time dependence






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- Change of Basis
- Position, Momentum, and Translation
- The density matrix

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Recommend Readings

Text Book:

J. J. Sakurai, *Modern Quantum Mechanics*, Cambridge University Press (3rd edition, 2020).

Additional reading materials:

1. P. A. M. Dirac, *Principles of Quantum Mechanics*.
2. Guang-Jong Ni and Su-Qing Chen, *Advanced Quantum Mechanics*, Fudan University Press. (In Chinese)
3. R. Shankar, *Principles of Quantum Mechanics*, Plenum Press.
4. Li Zhang and Molin Ge, *Frontier Problems in Quantum Mechanics*.

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2023

1. 半导体物理基础 运输

丁华霖 理学院物理系

第一章 半导体物理基础

思考：什么是半导体材料？

固体材料的分类（宏观）——导电性能

分类	电阻率 ρ ($\Omega \cdot \text{cm}$)
导体	$< 10^{-4}$
半导体	$10^{-4} \sim 10^9$
绝缘体	$> 10^9$

