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Miniband landscape of disordered dimer superlattices

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Abstract

We investigate numerically the universal quantum fluctuations of the resistance and conductance in disordered dimer semiconductor superlattices. These systems exhibit sets of extended states (in spite of being disordered) due to the resonance induced by the dimer structure. We show that the transmission amplitude $\tau(E)$ is a function of the energy of injected electrons and that its main characteristic is a "center" where $\tau(E) \approx 1$. This region of energy can be considered as consisting of weakly localized states proper of mesoscopic systems. On the other hand, the landscape of the allowed energies is a complex one, because close to the band edges, where $\tau(E) \ll 1$, states are strongly localized. We attempt to understand these two regions by investigating the universal fluctuation properties of the resistance and conductance in both of them. We also hope that this study will contribute to the knowledge about universal fluctuations in mesoscopic systems.

Keywords: Disordered dimer superlattice; Resonance; Quantum fluctuations

1. Introduction

One of the main reasons for the interest in mesoscopic systems is connected with the fabrication of future electronic nano-devices [1,2]. In this context, there exist a lot of problems that must be solved before wide applications of such devices are possible. In particular, when the density of these devices grows (up to $10^9\,\mathrm{dev/cm}^2$ in the future memory chips), collective quantum effects become significant. These effects include device–device interaction, cooperative quantum effects, and others [3,4]. These quantum collective interactions lead to additional instabilities, in comparison with the classical ones.

The pure quantum instability, in which we are mainly interested in this paper, is connected with the so-called "quantum conductance fluctuations" in mesoscopic devices [5–17]. These fluctuations are universal and appear because under the condition $l \leq l_{\mathrm{ph}}$ quantum interference effects play a significant role, even in the presence of disorder. Here l is the linear size of the mesoscopic sample and l_{ph} is the length of the phase coherence of the electronic wave function. Actually, when $l \leq l_{\mathrm{ph}}$, a unique quantum wave function exists for the whole mesoscopic sample.

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This wave function significantly depends on the specific realization of the positions of defects (even at given concentration of defects). Usually this situation is realized at low enough temperatures when inelastic scattering can be neglected. These quantum universal fluctuations lead to the "universal problem" of non-reproduction of the results of measurements in different mesoscopic devices.

2. Previous results on universal fluctuations

As was shown by Melnikov [5,6] and Abrikosov [7] (see also references cited in [5–7] the distribution function $W(\rho, L)$ of the resistance ρ for a 1D disordered system of length L (measured in the units of the mean free path length) does not become narrow as $L \to \infty$, and has a flat tail at large ρ. To compute the distribution function $W(\rho, L)$ Melnikov [6] used a recurrence relation for the S-matrix which describes the elastic scattering processes of an electron by isolated impurities.

The main results of [5–7] can be summarized in the following way. Let τ be the transmission probability, $\rho = 1/\tau$ the resistance, and $\sigma = \tau$ be the conductance of the system (all these functions are taken dimensionless). Then, for a disordered system with disorder in the form of Gaussian white noise, the distribution function $W(\rho, L)$ is found to be generally non-Gaussian. For large L and $\ln \rho$ (strong localized limit), the asymptotics of the distribution function has the form [5–7],

$$W(\ln \rho, L) = \frac{1}{\sqrt{4\pi L}} \mathrm{e}^{-(L-\ln \rho)^2/4L}, \quad L \gg 1,\ \ln \rho \gg 1. \tag{1}$$

It then follows from (1) that in the strong localized limit, the quantity $\ln \rho$ has a Gaussian distribution (logarithmically normal in ρ) with a variance $(2L)^{1/2}$.

Already the first calculations performed in [6] showed that the main reason for the anomalous (logarithmically normal) behavior of the distribution function $W(\rho, L)$ in the strong localized regime ($\rho \gg 1$) is connected with strong quantum interference effects. These results were further significantly developed in [10–17], for 2D and 3D mesoscopic systems, and can be summarized briefly as follows [15]. The one-parameter scaling $g \sim \hbar G/\mathrm{e}^2$ (where G is the dimensional conductance) describes only the main structure of the distribution function of conductance in a weakly localized ("metallic") region [18]. In this case, the distribution function can be considered close to a Gaussian. In the localized regime all moments of fluctuations become of the same order as the average conductance, and the Gaussian distribution function vanishes. Moreover, even in the case of weak localization the tails of the distribution function which define the high-order moments of fluctuations are shown to be logarithmically normal [15].

3. Results in random dimer superlattices

The main idea of this work, which we present below, is the following. We have investigated numerically the universal quantum fluctuations of the conductance σ in a random dimer semiconductor superlattice (DSL) [19]. In this model of disordered superlattice (SL), we consider that the width of the quantum wells takes at random only two values, a and a'. The thickness of the barriers separating neighbor quantum wells is assumed to be the same in the whole SL, b. A DSL is constructed by imposing the additional constraint that quantum wells of thickness a' appear only in pairs, hereafter called dimer quantum well (DQW), as shown in Fig. 1. It is not difficult to show that there exist a resonant energy, that depends only on the physical parameters of the SL, for which perfect transparency is attained at a single DQW. What is most important, this resonant phenomenon survives when several DQWs are placed at random in a SL (DSL) [20]. This means that the main characteristic of the DSL, as compared to random SLs, is the occurrence of a set of states for which $\tau(E) \approx 1$, close to the resonant energy, provided that the SL parameters are chosen so that the resonant energy lies in an allowed miniband. This region of energy can be considered as a weakly localized regime. On the other hand, in the vicinity of the edges of a miniband $\tau(E) \ll 1$, and these regions of energy

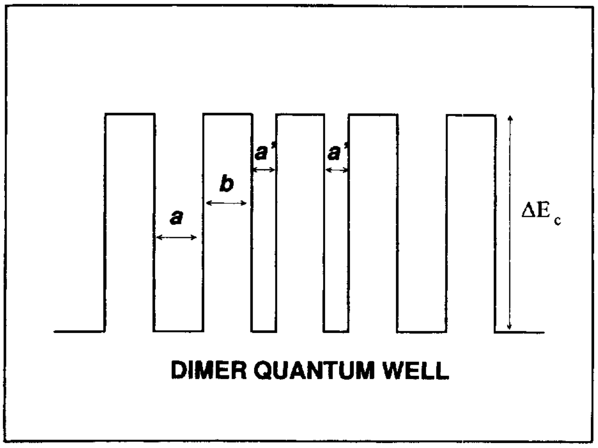


Fig. 1. Schematic diagram of a SL containing a DQW.

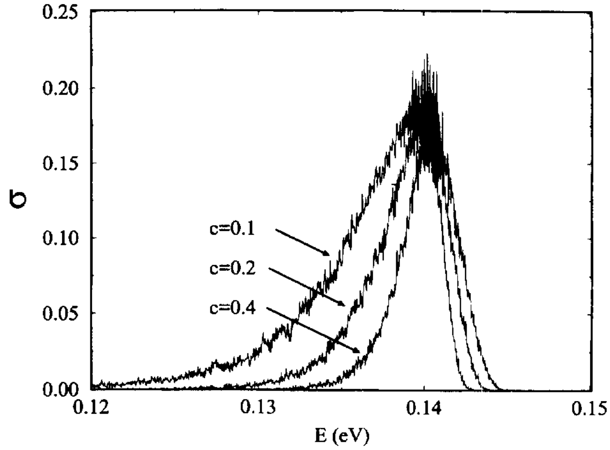


Fig. 2. Conductance vs. energy for different fractions c of the DQWs. Results correspond to ensemble averages of 1000 DSLs with $N = 200$ barriers. Notice the strong enhancement of the conductance close to the resonant energy $E_r = 0.141$ eV.

can be considered in the regime of strong localization. Therefore, we hope that investigating the fluctuation properties of the resistance $\rho(E) = 1/\tau(E)$ and the conductance $\sigma(E) = \tau(E)$ in these two regions by varying the energy E inside a chosen miniband, we can obtain a better understanding of the role of universal fluctuations in this mesoscopic system.

As a particular example, we have chosen a GaAs-$Ga_{0.65}Al_{0.35}As$ structure, where the conduction-band offset is $\Delta E_c = 0.25$ eV (see Fig. 1). Energies are measured relative to the bottom of the quantum wells. The effective masses are $m^* = 0.067m$ in GaAs and $m^* = 0.096m$ in $Ga_{0.65}Al_{0.35}As$, m being the free electron mass. In our computations we have taken $a = b = 32$ Å and $a' = 26$ Å. Thus, the resonant energy is found to be $E_r = 0.141$ eV and lies within the only allowed miniband below the barrier [20]. Fig. 2 shows the conductance $\sigma(E)$ as function of the electron energy E for different fractions c of DQWs. Results correspond to 1000 ensemble averages, but we should mention here that for a single realization the pattern of the conductance presents several narrow peaks displaying a very high value of transmittance, the number of these peaks being related to the number of the wells in the DSL (see [20, Fig. 3] for more details). It is apparent the noticeable enhancement of $\sigma(E)$ close to the resonant energy E_r, the maximum value being independent of the fraction c of DQWs. Fig. 3 shows the relative fluctuation of the conductance for the same DSL, defined as $\Delta\sigma/\sigma \equiv \sqrt{\langle\sigma^2\rangle/\langle\sigma\rangle^2 - 1}$ and $\langle\cdots\rangle$ stands for ensemble average. It is worth mentioning the strong decrease of the fluctuation level close to the resonant energy E_r and that this value is independent of the fraction of DQWs. Finally, in Fig. 4 we plot the distribution function W for $\ln\rho$ in the strong localization regime, namely away the resonant energy (Fig. 4(a)), and in the weak

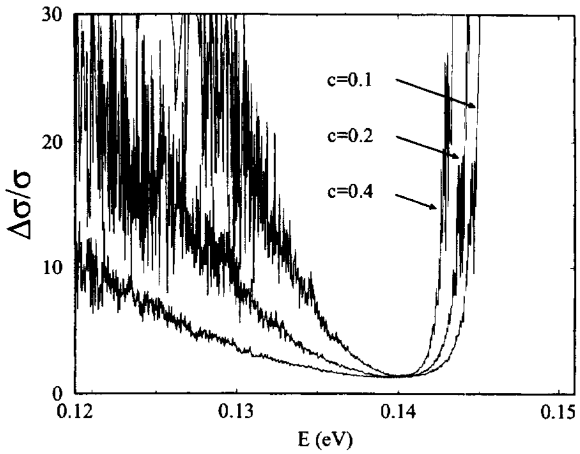
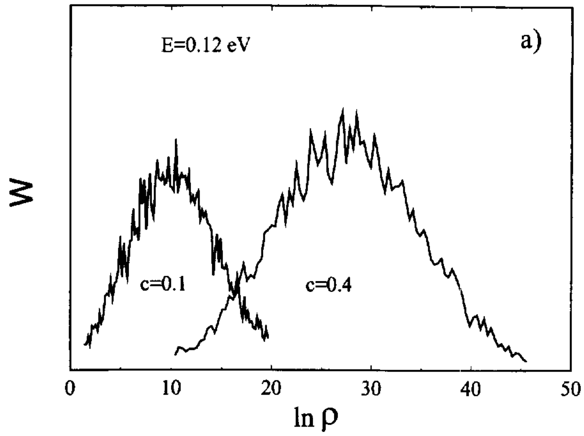


Fig. 3. Relative fluctuations of the conductance as a function of the electron energy. Parameters are the same as in Fig. 2. Notice the marked reduction around the resonant energy $E_r = 0.141$ eV.



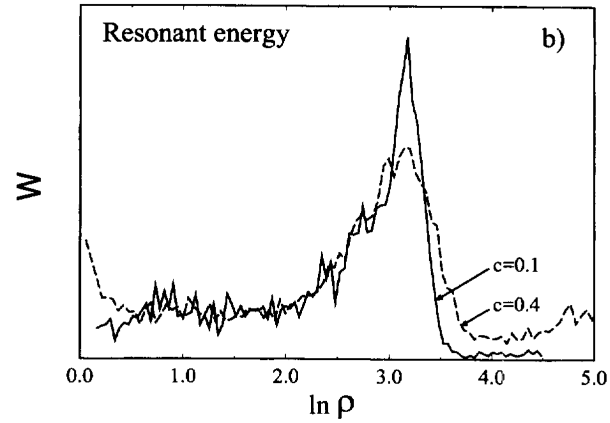


Fig. 4. Distribution function W of $\ln\rho$ for two different fractions of DQWs: (a) at $E = 0.12$ eV, away from the resonant energy and (b) at the resonant energy $E_r = 0.141$ eV.

localization regime, namely at the resonant energy (Fig. 4(b)). In the former case the distribution function is close to the Gaussian distribution in $\ln\rho$ (logarithmically normal distribution), whereas in the later case the distribution function is significantly different from the logarithmically normal distribution, and presents a long tail in the low resistance region and clearly becomes non-symmetric.

4. Discussions and conclusions

From the above scenario we can draw the following conclusions. First, universal fluctuations are severely reduced in the weak localization regime (see, Fig. 3). This means that the good transport properties of DSLs are quite independent of the particular realization of the system. This conclusion agrees with our previous claim that the DSL presents high values of the conductance, no matter how the particular arrangement of the DQWs is in each realization of the system [19,20]. On the contrary, in the opposite case, when localization effects are strong, the fluctuations are very significant. This is expected to occur because the spread of electronic wave functions is small and, therefore, the electronic state is very sensitive to the local enviroment, which vary from sample to sample or even from one region to another within the same sample. In addition, we have found that the value of the fluctuations in the weak localization regime is also independent of the number of DQWs placed in the DSL, which gives additional support about the generality of the delocalization phenomena in DSLs. Second, we have confirmed numerically that in the case of strong localization, the distribution function $W(\ln\rho, L)$ is close to Gaussian (logarithmically normal distribution) for DSLs, as it is the case in one-dimensional lattices with Gaussian white noise, given in (1). However, this is not the situation in the weak localization regime, where this distribution function is asymmetric and presents a long tail in the low resistance region. This implies that the probability of finding DSLs with high conductance is actually significant. However, a complete theory of this asymmetric distribution is still lacking, which points out the need for more work in this direction.

Acknowledgements

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