Effect of Electron Interaction on Statistics of Conductance Oscillations in Open Quantum Dots: Does the Dephasing Time Saturate?

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We perform self-consistent quantum transport calculations in open quantum dots taking into account the effect of electron interaction. We demonstrate that, in the regime of the ultralow temperatures $2\pi k_B T \lesssim \Delta$ (Δ being the mean-level spacing), the electron interaction strongly smears the conductance oscillations and thus significantly affects their statistics. Our calculations are in good quantitative agreement with the observed ultralow temperature statistics of Huibers *et al.* [Phys. Rev. Lett. **81**, 1917 (1998)]. Our findings question a conventional interpretation of the ultralow temperature saturation of the coherence time in open dots which is based on the noninteracting theories, where the agreement with the experiment is achieved by introducing additional phenomenological channels of dephasing.

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Introduction.—Decoherence of quantum states due to interaction with the environment represents one of the fundamental phenomena in quantum physics. In low-dimensional semiconductor structures such as quantum dots, wires, and antidots, the decoherence processes are central to electronic transport and spin or charge manipulation. A temperature dependence of the phase coherence time in open quantum dots τ_φ has been a focus of significant experimental activity during the past decade [1–8]. The experiments indicate that several mechanisms might be simultaneously responsible for the electron decoherence, including a large [9] and a small (Nyquist) [10] energy-transfer scattering. Surprisingly, practically all experiments report a remarkable effect of a saturation of the phase coherence time at ultralow temperatures $T \lesssim 100$ mK. The origin of this effect is not understood, and at present no theory is available to address the electron decoherence in confined ballistic systems. It should be noted that a similar effect of the saturation of the phase coherence time is also found in nanoscaled metallic wires, and the origin of this saturation also remains open and highly debated [11].

Experimental determination of the dephasing time τ_φ is typically based on predictions of the random matrix theory (RMT) [12] for the statistics for quantum transport such as the mean and variance of conductance oscillations, the weak localization corrections, the probability distribution of conductance, and others [12–14]. The RMT is essentially a noninteracting theory relying on a one-electron description of quantum transport. In order to fit the experimental data, the dephasing time τ_φ is included as a phenomenological parameter of the theory typically within a Büttiker's fictitious voltage probe or as an imaginary potential in the Hamiltonian [12,14]. A deviation of the experimental data from the predictions of a purely coherent model of noninteracting electrons is then attributed to inelastic scattering due to dephasing which is extracted using τ_φ as a fitting parameter.

How does the electron interaction affect the conductance oscillations in the open dots? This question was posed in several theoretical studies with somewhat conflicting conclusions [15–18]. For example, Brouwer and Aleiner [15] argued that the Coulomb interactions enhance the weak localization and increase conductance fluctuations, whereas Brouwer, Lamacraft, and Flensberg [16] questioned these conclusions. None of the above studies, however, addressed the problem of the low-temperature saturation of the coherence time. In the present Letter, we, based on the first-principles self-consistent quantum transport calculations, study the effect of the electron interaction on the probability distribution of the conductance $P(G)$ in open dots. We demonstrate that, for ultralow temperatures $2\pi k_B T \lesssim \Delta$ (Δ being the mean-level spacing), the distributions of $P(G)$ are strikingly different for noninteracting and interacting electrons. We compare our calculated statistics for interacting electrons with the corresponding experimental results of Huibers *et al.* [5] and find a good quantitative agreement. Our results therefore strongly indicate that a deviation of the experimental data from the RMT predictions in the regime of ultralow temperatures can be accounted for by the electron interaction alone without introducing additional channels of the inelastic scattering. Our findings thus question the conclusion concerning the saturation of the τ_φ in open dots which is obtained by neglecting electron interaction and under the assumption that the above deviation is due to the inelastic scattering only.

Model.—We consider an open quantum dot defined by split gates in a GaAs heterostructure; see Fig. 1. The Hamiltonian of the whole system (the dot plus the semi-infinite leads) can be written in the form $H = H_0 + V(\mathbf{r})$, where $H_0 = -(\hbar^2/2m^*)\{(\frac{\partial}{\partial x} - \frac{eiBy}{\hbar})^2 + (\partial^2/\partial y^2)\}$ is the kinetic energy in the Landau gauge, and the total confining potential $V(\mathbf{r}) = V_{\text{conf}}(\mathbf{r}) + V_H(\mathbf{r})$ is the sum of the electrostatic confinement (including contributions from the top gates, the donor layer, and the Schottky barrier) and the

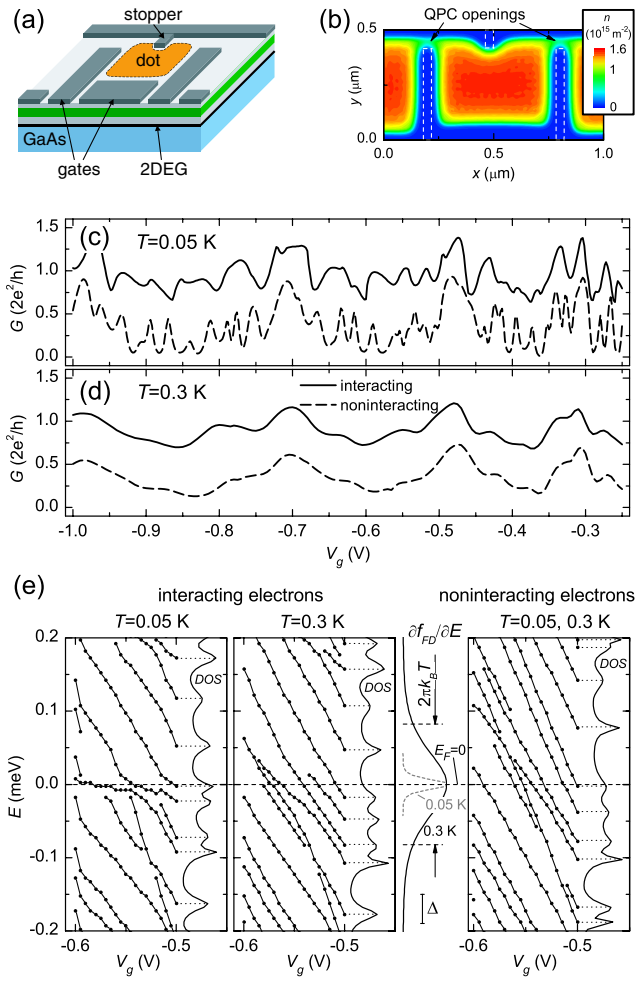

FIG. 1 (color online). (a) A schematic layout of a split-gate open quantum dot defined in a GaAs heterostructure. The geometrical size of the dot is 660×520 nm; the width of the leads is 540 nm. The width of the QPC openings is 100 nm (which corresponds to one propagating mode). The widths of the cap, donor, and spacer layers are 14, 36, and 10 nm, respectively); the donor concentration is 0.6×10^{24} m^{-3}. (b) A representative self-consistent electron density in the dot [note that the densities for the interacting (Hartree) and noninteracting (TF) electrons are not distinguishable on the scale of the figure]. White dashed lines indicate a geometry of the metallic gates. (c),(d) The calculated conductance of the dot for interacting (Hartree) and noninteracting (TF) electrons as a function of the gate voltage V_g for (a) $T = 50$ mK and (b) $T = 300$ mK; $B = 20$ mT. [The conductance curves for interacting electrons are shifted by e^2/h.] (e) Resonant energy structure (i.e., positions of the peaks in the DOS as a function of the V_g) for different temperatures; a calculated DOS is shown for $V_g = -0.5$ V; the Fermi energy is set $E_F = 0$. [Note that the resonant energy structure for noninteracting electrons is practically undistinguishable for the given temperatures]. The inset shows the derivative of the Fermi-Dirac distribution function for $T = 0.05$ and 0.3 K and the transport window $2\pi k_B T$. The bar indicates the mean-level spacing separation $\Delta = 0.041$ meV corresponding to the actual dot size $\sim 460 \times 370$ nm^2.

Hartree potential (see [18,19] for details):

$$V_H(\mathbf{r}) = \frac{e^2}{4\pi\varepsilon_0\varepsilon_r}\int d\mathbf{r}' n(\mathbf{r}')\left(\frac{1}{|\mathbf{r}-\mathbf{r}'|} - \frac{1}{\sqrt{|\mathbf{r}-\mathbf{r}'|^2 + 4b^2}}\right), \quad (1)$$

where $n(\mathbf{r})$ is the electron density, the second term corresponds to the mirror charges situated at the distance b from the surface, and $\varepsilon_r = 12.9$ is the dielectric constant of GaAs. The dot and the leads are treated on the same footing; e.g., the Coulomb interaction and the magnetic field are included both in the lead and in the dot regions. We consider the spinless electrons because in relatively large dots as those studied here the electrons are spin degenerate [20,21]. We also neglect the exchange and correlation effects, which have been shown to affect the calculated conductance only marginally [18]. Note that the role of the electron interaction in the resonant-tunneling heterostructures (described within the Hartree approximation) was discussed in Ref. [22].

To outline the role of the electron interaction, we also calculate the conductance of the open dot in the Thomas-Fermi (TF) approximation, where the self-consistent electron density is given by the standard TF equation. This approximation does not capture the quantum-mechanical quantization of the electron motion and hence corresponds to a noninteracting one-electron approach, where, however, the total confinement is given by a smooth realistic potential; see [18] for details.

The magnetoconductance through the quantum dot in the linear response regime is given by the Landauer formula $G = -(2e^2/h)\int dE T(E)[\partial f_{\rm FD}(E - E_F)/\partial E]$. A detailed description of the self-consistent conductance calculation (as well as the validity and applicability of the method and the Hamiltonian) are given in our previous publications [18,19]. Note that the present approach corresponds to the "first-principles" magnetoconductance calculation (within the effective mass approximation) that starts from a geometrical layout of the device, is free from phenomenological parameters, and does not rely on model Hamiltonians whose validity is poorly controlled.

Results and discussions.—Figure 1(c) shows the conductance of an open quantum dot calculated in the Hartree and TF approximations (interacting and noninteracting electrons, respectively) for $T = 50$ mK. The parameters of the dot are indicated in Fig. 1 and are chosen close to those studied experimentally by Huibers *et al.* [5]. All of the results discussed in this Letter correspond to one propagating mode in the quantum point contact (QPC) openings. The striking difference between the conductance curves is clearly manifested in a strong suppression of the high-frequency components of the oscillations for the interacting electrons in comparison to the noninteracting case. Thus, the electron interaction causes an apparent smearing of the conductance oscillations, which is similar

to the effect of the temperature or inelastic scattering. This smearing of oscillations is caused by the pinning of resonant levels to the Fermi energy in the vicinity of resonances [18]. This is illustrated in Fig. 1(e), which shows an evolution of the peak position of the resonant energy levels. In the vicinity of the resonances, the density of states (DOS) of the dot is enhanced such that electrons with the energies close to E_F can easily screen the external potential. This leads to the ''metallic'' behavior of the system when the electron density in the dot can be easily redistributed to keep the potential constant. As a result, in the vicinity of a resonance, the system only weakly responds to the external perturbation (change of a gate voltage, magnetic field, etc.); i.e., the resonant levels becomes pinned to the Fermi energy (see Ref. [18] for a detailed discussion of the pinning effect). For noninteracting electrons, the nonlinear screening and hence the pinning effect are absent, such that the successive dot states sweep past the Fermi level in a linear fashion; see Fig. 1(e).

The pinning of resonant levels drastically affects the conductance probability distribution $P(G)$. Figure 2(a) shows $P(G)$ calculated for interacting and noninteracting electrons for the cases of a time-reversal symmetry $\beta = 1$ ($B = 0$) and a broken time-reversal symmetry $\beta = 2$ ($B \neq 0$) for $T = 50$ mK. The time-reversal symmetry is broken by the application of a magnetic field $B \gtrsim \phi_0/A$, where $\phi_0 = h/e$ is the flux quantum and A is the dot area (typically, $B \sim 20$–40 mT). Figure 2(a) shows that the statistics of the conductance distribution $P(G)$ for the case of noninteracting electrons closely follow the corresponding RMT predictions for $\tau_\varphi = 0$ and $T = 0$ [12,13] for both $\beta = 1$ and $\beta = 2$. At the same time, the statistics for the interacting electrons are strikingly different from those for the noninteracting case. Thus, due to the effect of the electron interaction, the ultralow-temperature statistics of the conductance oscillations of quantum dots are not described by the RMT.

As the temperature increases, the difference between the conductances $G = G(V_g)$ as well as between the corresponding conductance distributions $P(G)$ for interacting and noninteracting electrons diminishes; see Fig. 2(b) ($T = 100$ mK). For a sufficiently high temperature, this difference disappears; see Figs. 1(d) and 2(c) ($T = 300$ mK). The reason for that is that the temperature strongly reduces the effect of resonant level pinning. Indeed, when the transport energy window $\sim 2\pi k_B T$ [determined by the condition when the derivative of the Fermi-Dirac distribution is distinct from zero; see Fig. 1(e)] exceeds the mean-level spacing $\Delta = 2\pi\hbar^2/m * A$ (A being the dot area), the conductance is mediated by several levels. As a result, several levels always contribute to screening at the same time, and hence the screening efficiency of the dot is affected very little when a gate voltage or magnetic field is varied. A quenching of the pinning for temperatures $2\pi k_B T \gtrsim \Delta$ due to suppression of the resonant level screening is illustrated in Fig. 1(e) ($T = 300$ mK). Note that, for the dot under consideration, the condition $2\pi k_B T = \Delta$ corresponds to $T \approx 100$ mK. Thus, for $2\pi k_B T \gtrsim \Delta$, the effect of electron interaction on the conductance is strongly suppressed such that the conductances and their probability distributions for interacting and noninteracting electrons are practically the same.

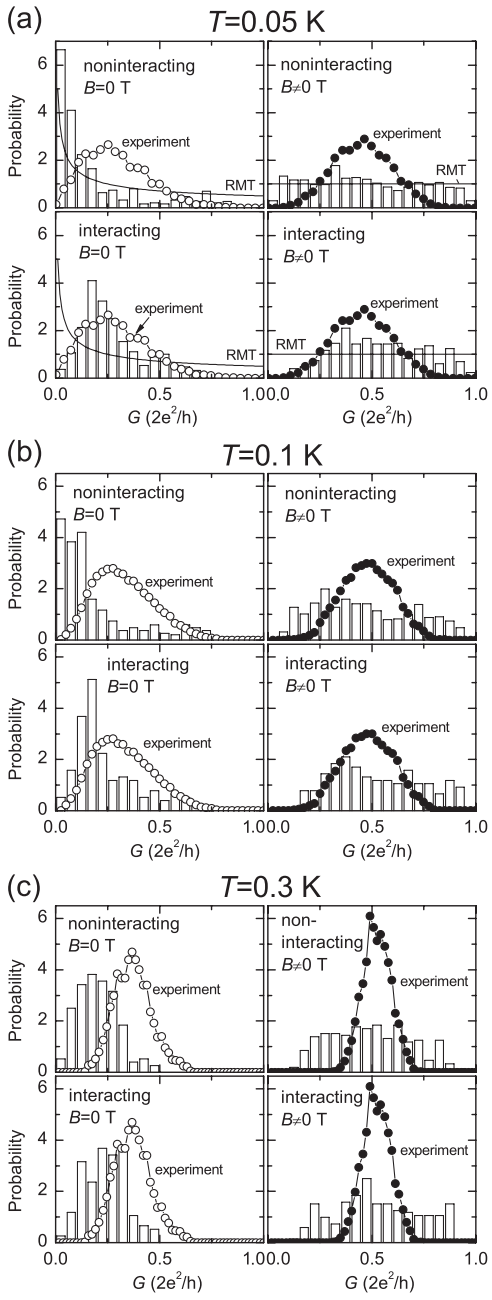

FIG. 2. Probability distribution of the conductance $P(G)$ for interacting and noninteracting electrons for different temperatures for the cases of the time-reversed symmetry ($\beta = 1$) and the broken time-reversed symmetry ($\beta = 2$). The experimental data are adapted from Ref. [5]. Solid lines in (a) correspond to the predictions of the RMT ($T = 0$, no dephasing).

The probability distribution $P(G)$ in open quantum dots with one propagating channel in the leads was studied by Huibers *et al.* [5]. Figure 2(a) shows that, in the regime of the ultralow temperatures $T = 50$ mK, the calculated conductance statistics for interacting electrons agree quite well with the corresponding experimental distribution $P(G)$ for both $\beta = 1$ and $\beta = 2$. The measured conductance distribution $P(G)$ in Ref. [5] was well described by the RMT predictions where the inelastic scattering was introduced using τ_φ as a fitting parameter. Our results, instead, demonstrate that, once the electron interaction is accounted for, the agreement with the experiment for $2\pi k_B T \lesssim \Delta$ is achieved without assuming additional inelastic scattering channels. We thus conclude that, for the regime of ultralow temperatures, the experimentally inferred value of τ_φ might be greatly underestimated, which implies that the dephasing time does not saturate. As the temperature increases, the calculated conductance distribution starts to deviate from the experimental statistics; see Fig. 2(b) and 2(c). As discussed above, for the temperature $2\pi k_B T \gtrsim \Delta$, the electron interaction practically does not affect the conductance oscillations and their statistics. Thus, for $2\pi k_B T \gtrsim \Delta$, the difference between the calculated and the experimental statistics can be attributed to the effect of dephasing. Our criterion for the transition temperature $2\pi k_B T \sim \Delta$ is consistent with the findings reported by Bird *et al.* [2,7] and Clarke *et al.* [3], who find a saturation behavior of τ_φ at transition temperatures T_{onset} near the mean-level spacing. A relation between T_{onset} and Δ was also discussed by Hackens *et al.* [8]. However, some experiments [6] do not show a clear relation between T_{onset} and Δ, such that more systematic studies are needed in order to prove the connection between T_{onset} and Δ.

We stress that our calculations are performed for purely coherent electrons. The dephasing effects can be easily included in our model phenomenologically through an imaginary potential in the Hamiltonian [12]. We do not provide a systematic fit of the experiment simply because of a computational burden related to this task: Each point on the conductance plot requires up to 1 h of processor time. We note, however, that such a fit is outside the scope of our study, where we focus on the role of the electron interaction in a regime of the ultralow temperatures $2\pi k_B T \lesssim \Delta$.

The findings reported in this Letter outline the importance of the first-principles self-consistent quantum transport calculations for open quantum dots. Indeed, accounting for both global electrostatics through the Hartree potential [Eq. (1)] and the quantum-mechanical quantization in a self-consistent way is essential for revealing of the pinning effect that causes a drastic difference in the conductance of the interacting and noninteracting electrons. Note that this effect would not be captured in approaches utilizing model Hamiltonians (like those of Refs. [15,16], where the electron interaction is accounted for through the classical capacitance charging).

To conclude, we demonstrate that, for ultralow temperatures $2\pi k_B T \lesssim \Delta$, the electron interaction drastically changes the statistics of the conductance oscillations in open dots, leading to a significant departure from the conventional RMT description of noninteracting electrons. Our results demonstrate that the deviation of the observed statistics at ultralow temperatures from the RMT predictions can be accounted for by the electron interaction alone, such that a conclusion of the dephasing time saturation based on the noninteracting electron picture should be revised.

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