Saturation of Phase Breaking in an Open Ballistic Quantum Dot

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A variation in the saturated phase-breaking time in a ballistic quantum dot is found to occur as the size is varied. This variation differs from that observed earlier, in which a transition from quasi-two-dimensional to zero-dimensional behavior was thought to occur. Instead, these results suggest that the saturated phase-breaking rate is governed by a change in the *total number of electrons* within the dot. At higher temperatures, the phase breaking is governed by coupling to the quantum wire leads, and τ_ϕ may show the $T^{-2/3}$ variation expected for a one-dimensional wire due to the electron-electron interaction. [S0031-9007(99)09335-7]

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One of the key parameters for the observation of quantum interference effects in mesoscopic systems is the phase-breaking time τ_ϕ. In addition to internal processes, the coupling of a quantum system to its environment causes phase randomization of the electron wave function. There have been many measurements of this important phase-breaking time in diffusive mesoscopic structures, such as quasi-two-dimensional systems and quantum wires. The accepted theories of phase breaking in one- and two-dimensional diffusive systems at low temperature have been confirmed by numerous experiments [1]. However, there have been relatively few reported studies of phase breaking in zero-dimensional structures. Futhermore, there is no accepted theory for phase breaking in these systems. A troublesome characteristic of nearly all experimental studies of phase breaking in mesoscopic systems is the saturation of the phase-breaking time as $T \to 0$. The origin of this saturation is the subject of debate, and many different theories have been proposed in an attempt to explain the experimental observation [2–4].

Recently, the phase-breaking time has been measured in ballistic quantum dots which were coupled to their environment through open, or nearly open, quantum point contacts that opened abruptly to a two-dimensional electron gas (2DEG) [5–8]. In these experiments, a saturation of the phase-breaking time at low temperatures was found, with a decay at higher temperatures generally of the form of T^{-1}. The transition temperature between the low temperature saturation and the decay at higher temperatures was related to the mean-level separation, with saturation arising for

$$k_B T < \Delta = \frac{\pi \hbar^2}{m^* A}, \tag{1}$$

where A is the area of the dot. This behavior was predicated upon the phase-breaking processes occurring solely *within* the dot with a transition from quasi-two-dimensional to zero-dimensional behavior at low temperatures, as the discrete level spacing in the dot is resolved [7,8]. We return to this point below, but a completely different behavior is observed in our dot, where we find no evidence for a 0D to 2D transition, and propose a new property for the phase-breaking process.

Here, we discuss the observation of a saturation of τ_ϕ in an open quantum dot which is mediated by the point contact leads, and *coupled to quantum wires*. The saturated τ_ϕ is found to depend on the nature of the coupling between the dot and the wire, with the saturation extending to temperatures much greater than the estimated mean-level spacing of the dot from (1). At higher temperatures, τ_ϕ is found to exhibit an apparent $T^{-2/3}$ behavior, which is consistent with the coupling of the dot to a one-dimensional quantum wire [9].

The device studied here has a self-aligned gate, which masks a shallow etch of high mobility $Al_{0.3}Ga_{0.7}As/GaAs$ heterojunction material. The gated dot is defined by electron beam lithography to be 0.8 μm square with $\sim$150 nm quantum point contact leads positioned at either side. These leads open to quantum wires which gradually increase in width to 2 μm, over a distance of 10 μm, before reaching a two-dimensional electron gas patterned into a Hall bar structure [the device structure is shown in the inset in Fig. 1(a)]. The wires provide adiabatic coupling to the dot. The 2DEG had a carrier density of 3.8×10^{15} m^{-2} and a mobility of 30 m^2/V s, as determined by *in situ* Shubnikov–de Haas and Hall measurements. The device was mounted in good thermal contact to the sample post of a dilution refrigerator with a base temperature of 10 mK. Measurements were taken in a two-terminal configuration, using standard lock-in amplification techniques. The source-drain excitation was kept well below $k_B T$.

In this structure, the gate may have two effects. By applying negative voltages, the density may be decreased by standard vertical depletion of the 2DEG. At positive voltages, however, the measured density of the 2DEG saturates. With further increase of the (positive) gate voltage, the equilibrium dot size is increased as surface depletion at the sides of the dot (created by the etching) is decreased. In this way, the size of the dot and the

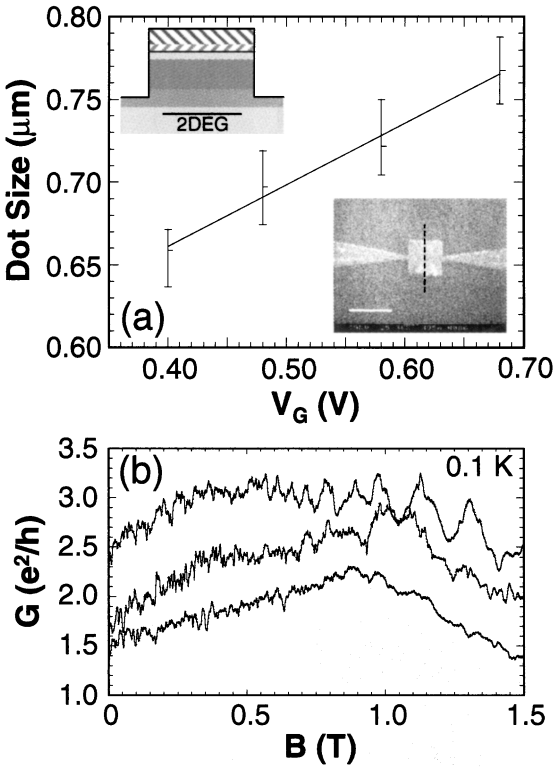

FIG. 1. Estimated dot size for varying gate voltage is shown in (a). The insets of (a) illustrate the device structure of a quantum dot coupled to quantum wires. The white bar in the lower right inset of (a) represents 1 μm. Magnetoconductance traces measured at (from top to bottom) $V_G = 0.64$, 0.53, and 0.42 V are shown in (b).

width of the quantum point contacts can be uniformly varied without a change in electron sheet density. The two-terminal magnetoresistance of the dot is measured as a function of the gate voltage, and thus the size of the dot and the width of the quantum point contact leads can be estimated. The dot size dependence on gate voltage is determined from the Aharonov-Bohm-like oscillations at high magnetic fields [10]. In Fig. 1(a), we plot the area of the dot over the range of gate voltages of interest in this work. In Fig. 1(b), we show the magnetoresistance measured for the three gate voltages at which the phase-breaking time is measured. The effective width of the leads may be inferred from the estimated dot size (assuming uniform depletion) and the observed linear change in conductance with gate voltage [11].

The measurement of the phase-breaking time is based on the magnetic field dependence of the magnetoconductance fluctuations in quantum dots [7,12]. As the magnetic field is increased, the cyclotron orbit becomes much smaller than the dot diameter, and a transition to edge-state transport occurs. Within the magnetic field range of this transition, the electron motion is increasingly confined to the boundaries in skipping orbits [13]. This reduces the effective area for coherent interference and in turn increases the correlation field of the fluctuations. The resulting magnetic field dependence of the correlation field is then

$$B_c(B) = 8\pi^2 m^* B/hk_F^2\tau_\phi\,, \tag{2}$$

where m^* is the electron effective mass and k_F is the Fermi wave vector. From the linear dependence of B_c on B, τ_ϕ can be estimated. Using this technique, Bird *et al.* [7,8] found phase-breaking times in split-gate ballistic quantum dots comparable to that obtained by the more complicated analysis of Marcus *et al.* [5,6] in similar experiments and to values found by Linke *et al.* [14], also using a different technique. All of these previous values are comparable to the values found in the present study and reveal a saturation in τ_ϕ at low temperature, with a transition temperature near the mean-level spacing.

The results of the phase-breaking time analysis for varying temperature and gate voltage are shown in Fig. 2(a). In Fig. 2(b), the amplitude of the conductance fluctuations at low magnetic field is plotted. The amplitude of the fluctuations continues to increase as the temperature is

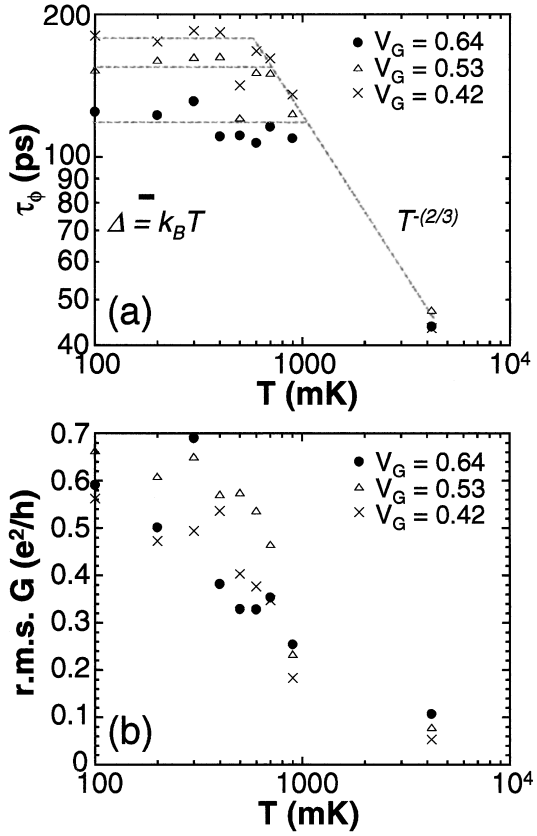

FIG. 2. Estimated phase-breaking time (a) and amplitude of the fluctuations (b) as a function of temperature. For the range of dot size estimated for all gate voltages, the equivalent range of mean-level spacing is represented by a bar labeled $\Delta = k_BT$ in (a). A higher gate voltage results in a larger effective dot size and stronger coupling to the wires.

lowered, which clearly shows that *the saturation in the phase-breaking time cannot be associated with a saturation in the sample temperature and instead is related to the intrinsic properties of the system.* With varying gate voltage, both the dot and leads may be affected, although the overall conductance does not change by more than e^2/h [Fig. 1(b)], which indicates that the lead-width variation is relatively small, in that the width of the wire at the contact is not varying nearly as much as the size of the dot. This is likely due to a much reduced effect of the gate metal coupling to the wire in these narrow regions. The estimated variation of the dot size for this range of gate voltage is substantial ($0.65-0.75$ μm). A lower saturated τ_ϕ is observed for a larger dot size, which is a result of a higher (positive) gate bias. Above about 1 K, the saturation is overcome by what appears to be a $T^{-2/3}$ dependence. The transition is clearly at a higher temperature than the effective mean-level spacing for this range of dot size, where the latter is indicated in Fig. 2(a) by the bar, which is well below 1 K.

The fact that we report the results for a single sample is a concern, particularly as the specific impurity distribution could be causing an effect. To address this, we have carried out three different illuminations of the sample. Each illumination does change the impurity distribution, and the ranges of dot size which can be probed by the gate voltage, but does not change the 2D density of carriers. In Fig. 3, we illustrate the manner in which these three sets of data adjoin one another to provide a relatively continuous variation with dot size. It is apparent that significant changes to the dot, caused by illumination, are not causing significant changes in the phase-breaking time. This suggests that we are measuring the intrinsic properties of the dot.

The lack of a dependence upon the mean-level separation is significant. It could be that the broadening of the discrete levels in the dot, Γ, is much larger than either k_BT or Δ. However, this would produce a relatively uniform density of states, and a temperature dependence would be expected from the thermal broadening of the Fermi-Dirac distribution. This is not supported by the constant value of the phase-breaking time. If a transition at $\Delta = k_BT$ were to occur, we would expect a larger transition temperature for smaller dots, according to (1). However, the data in Fig. 2(a) suggest the opposite, with the transition occurring at a lower temperature for smaller dots. Indeed, one can ask why, in the earlier measurements [7,8], there is a variation of the two-dimensional phase-breaking time with dot size. Such a behavior is not consistent with accepted theory for phase breaking in two dimensions. Rather, we suggest that it is likely that the two-dimensional phase-breaking behavior is not occurring *within* the dot, but in the 2DEG to which the dot is coupled by the quantum point contacts, and the transition is related to a variation in the coupling through the quantum point contacts.

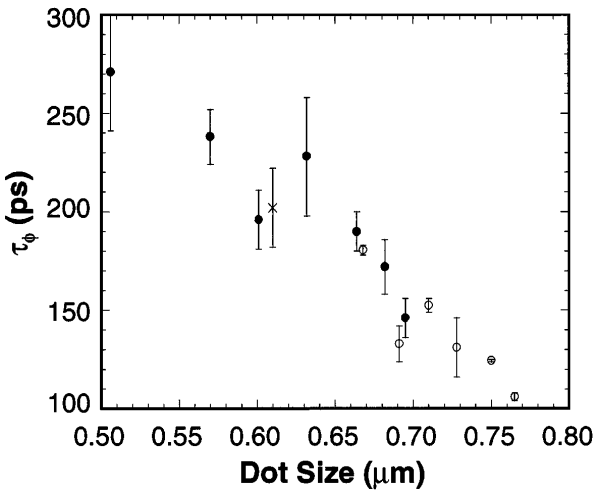

FIG. 3. Variation of the phase-breaking time with dot size at base temperature of the fridge (<50 mK) for three different illuminations of the dot (corresponding to the three symbols).

Recent experiments by Bird *et al.* [8] have shown that τ_ϕ may increase by more than an order of magnitude as the conductance is reduced below $2e^2/h$. It also has been shown that the quantum point contact leads of a quantum dot play an important role in selecting the available dot states for transport [15,16]. Basically, the leads restrict the momentum of the incoming electron and thus the coupling to the states in the dot. Here, we expect that the coupling of the leads also mediates the phase-breaking process in the system. If the coupling is weak (i.e., $G < 2e^2/h$), the phase-breaking process in the dot is effectively decoupled from the rest of the system. In the case of stronger coupling, the total phase-breaking rate is likely to be determined by contributions from the environment. We may express this behavior generally as

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_\phi}\bigg|_{\text{dot}} + \frac{1}{\tau_\phi}\bigg|_{\text{wire}}, \tag{3}$$

which is a simple addition of phase-breaking rates. The system involves coherent transport from one lead, through the dot, to the exit lead. In this situation, phase breaking can occur through a variety of channels both within and external to the dot. We presume in (3) that the various strengths of these channels are moderated by the temperature and by the coupling through the quantum point contacts. In the present study, the quantum point contacts are, in fact, the entire quantum wire to which the dot is coupled.

Saturation of the phase-breaking time has been commonly observed in quantum wires. Recently this has been attributed to *intrinsic* quantum fluctuations arising in either the electron-electron interaction [4] or the electromagnetic environment [3]. However, both theoretical and experimental estimates of this saturated level are well above those we find here. Moreover, the dependence

upon the gate voltage also suggests a mechanism internal to the dot itself. The scaling of the saturated τ_ϕ with dot area is further support for the introduction of (3). The results of the scaling in Fig. 2(a) suggest that the phase-breaking interaction is a function of the *total* number of electrons $N = nA$ within the dot, as the density n is fixed for these data and only the area A is changed. The electron-electron interaction actually is best viewed as the interaction with the collective modes of the *fixed* number of electrons within the dot, rather than just those few carriers within an isolated energy level of the quantized dot. In this view, there is no dependence upon Δ and that is consistent with the data in Fig. 2(a). This view is also consistent with the temperature decay of the phase-breaking time above the transition, which is that expected in a quasi-one-dimensional quantum wire [9], although a note of caution should be expressed here. The data in Fig. 2(a) suggest a $T^{-2/3}$ behavior, but there is not really sufficient data here to fully determine this fit. This is supported by one of the common theoretical treatments for phase breaking in a quantum wire [9], but the temperature and wire parameters are such that other mechanisms may be more important. More work is necessary to confirm this relationship. To be sure, there is no currently accepted theory for the phase-breaking process in zero-dimensional structures, and the results presented here, along with those of Refs. [5–8], provide important constraints on such a theory.

In conclusion, we observe a variation in the saturated phase-breaking time in a small ballistic quantum dot as the size is varied. This variation is different from that observed earlier, which was ascribed to a transition from quasi-two-dimensional behavior [7]. It is suggested that the behavior observed here is brought about by the leads of the ballistic quantum dot which mediate the interaction with the environment. The change in temperature dependence is ascribed to a transition from phase breaking solely within the dot to phase breaking in the coupled system. The saturation in this case is *not* attributed to broadening of the states in the dot, and the overall rate varies with the *total number of electrons* in the dot. At higher temperatures, the system is governed by the coupling of the quantum wire leads, which appears to show the τ_ϕ scaling of $T^{-2/3}$ expected for a high mobility one-dimensional structure due to the electron-electron interaction.

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