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LETTER TO THE EDITOR

Environmental coupling and phase breaking in open quantum dots

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Abstract. Studies of electron phase coherence in open quantum dots reveal a subtle interplay between geometry and materials-related considerations. Suppressing environmental coupling, by reducing the width of the quantum point contact leads, a strong suppression of dephasing is observed. The magnitude of the phase-breaking time in this high-resistance regime shows large variations from device to device, indicative of a sensitivity to the specific disorder configuration in the dot. In order to account for our observations, we suggest an interpretation of phase breaking which invokes the discrete nature of the level spectrum in the open dots and which emphasizes the role of the quantum point contacts in selectively exciting cavity eigenstates.

Recently, much interest has focused on the nature of electron transport in quantum dot devices, which are small semiconductor cavities connected to external reservoirs by means of quantum point contacts. An important characteristic of these devices is the strong quantization of electronic motion that their confining geometry generates. While it has been known for some time that coupling a quantum system to an external environment may modify, but not obscure, its discrete characteristics, this notion has recently been emphasized for the quantum dots of interest here [1]. In these devices, current flow is thought to occur via a highly selective process in which a small number of cavity eigenstates are excited by the collimating action of the input quantum point contact [2, 3]. At sufficiently low temperatures, phase coherence of the electrons is maintained over long distances and interference between the selectively excited eigenstates gives rise to the phenomenon of wavefunction scarring [2–7]. The scarring in turn implies that the current flow through the device is of a highly non-uniform nature, providing a remarkable manifestation of classical mechanics in the quantum transport behaviour. Since the scarring is strongly damped by scattering events which randomize electron phase coherence [4], an important parameter for assessing its importance in real devices is the phase-breaking time (τ_ϕ), the average timescale over which the wavelike nature of the electrons is maintained [8]. In quantum dot devices that generate a strong quantization of motion, it is expected that the magnitude of this parameter should reflect the details of the discrete level spectrum, and the manner in which this is modified by coupling to an external environment.

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Motivated by the above, in this letter we consider the influence of environmental coupling on the phase-coherent properties of *open* quantum dot devices, which are coupled to macroscopic reservoirs by means of quantum point contacts. Values for the phase-breaking time are deduced by studying the reproducible fluctuations, observed in the low-temperature magnetoconductance of the devices [8–10]. In order to address the issue of device-specific variations in behaviour, results are presented for seven different quantum dots that were fabricated in semiconductor material of varying quality, but which were measured under similar experimental conditions. Our investigations reveal that as the width of the point contacts is reduced to support no more than a few propagating modes, a significant increase, by as much as an order of magnitude, may be observed in the phase-breaking time. Further experiments reveal striking device-dependent variations in the magnitude of the phase-breaking time in this regime, indicative of a complex interplay between geometry and materials-related considerations. In order to account for these observations, we propose an interpretation of phase breaking which invokes the discrete nature of the level spectrum in the open dots, and which emphasizes the role of the quantum point contacts in selectively exciting cavity eigenstates.

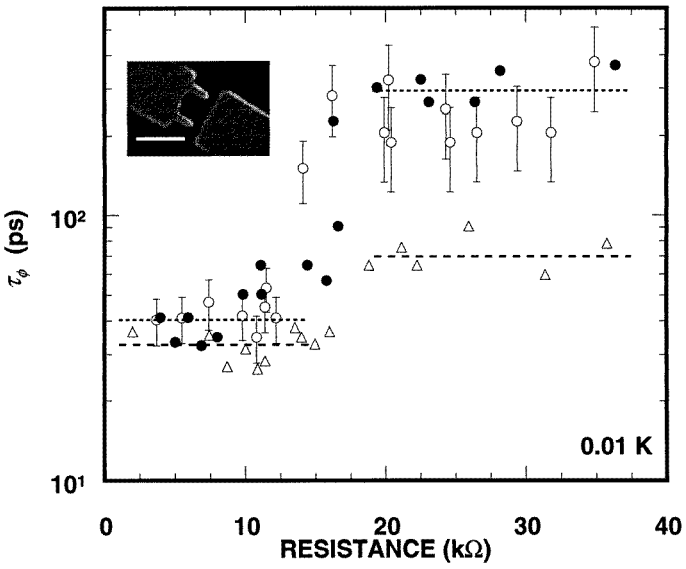

Figure 1. The variation of the phase-breaking time with the lead opening. Solid circles: 1 μm dot. Open circles: 0.4 μm dot. Open triangles: 0.6 μm dot. The lines are intended to guide the eye and additional error bars are omitted for clarity. All three dots were patterned on the same Hall bar ($n_s = 5 \times 10^{15}$ m^{-2} and $\mu = 70$ m^2 V^{-1} s^{-1}). Inset: an SEM micrograph of a 0.6 μm dot (spacer bar = 1 μm).

Split-gate quantum dots were realized by depositing Ti–Au gates on a GaAs/AlGaAs heterojunction substrate. The fine-line pattern of the gates was defined by electron beam lithography, allowing the realization of lithographically square dots whose sizes ranged from 0.4 to 1 μm (figure 1, inset). After illumination with a red LED at liquid helium temperatures, the Hall bars on which the gates were patterned were found to have carrier densities (n_s) of (4–5) $\times 10^{15}$ m^{-2} and mobilities (μ) of 20–70 m^2 V^{-1} s^{-1}. The samples were clamped to the mixing chamber of a dilution refrigerator and, unless stated otherwise, low-frequency magnetotransport measurements were made at a cryostat temperature of

10 mK. The four-terminal measurement configuration employed included negligible series contributions due to the two-dimensional source and drain regions and an excitation voltage of less than 3 μV was used for the current-biased measurements. By measuring the voltage drop across a 1 MΩ choke resistor connected in series with the gate voltage power supply, the possibility of leakage between the gates and the two-dimensional electron gas layer could be discounted, at least within our experimental resolution of 10 pA. From the observation of Aharonov–Bohm oscillations at high magnetic fields, an effective depletion of 50–100 nm around each gate edge was inferred. This in turn yields estimates for the average level spacing ($\Delta = h^2/2\pi m^* A$, where A is the dot area) which range from 920 to 130 mK, suggesting that the discrete level spectrum of the open dots should remain resolved under typical experimental conditions [6, 8].

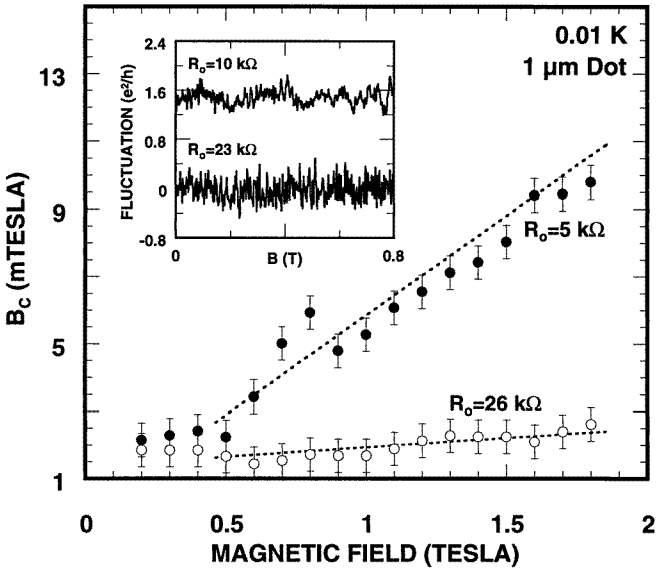

Figure 2. The magnetic field dependence of the correlation field in a 1 μm dot at two different lead settings. The dashed lines are least-squares fits to the data. Inset: conductance fluctuations, measured in the same dot for the indicated lead openings ($n_s = 5 \times 10^{15}$ m^{-2} and $\mu = 70$ m^2 V^{-1} s^{-1}).

In figure 1, we show the variation of the phase-breaking time with zero-field dot resistance (R_0), measured in three different quantum dots patterned in close proximity to one another. Estimates for the phase-breaking time were obtained from the high-field evolution of the reproducible fluctuations observed in the low-temperature magnetoconductance of the devices [6–10]. The basic idea is that, at high magnetic fields where current flow occurs by skipping orbits, the characteristic area for interference shrinks with increasing magnetic field. A straightforward analysis then predicts that the correlation field [6] of the fluctuations (B_c) should increase according [9] to

$$B_c = \frac{8\pi^2 m^*}{h k_F^2 \tau_\phi} B \tag{1}$$

where B is the applied magnetic field and k_F is the Fermi wavevector. Equation (1) indicates that when the phase-breaking time is independent of magnetic field then B_c should increase linearly with B, with a slope that is inversely proportional to the phase-breaking time. Such

behaviour is apparent in figure 2, where we show the magnetic-field-dependent variation of the correlation field obtained for two different settings of dot lead opening.

Turning to the results of figure 1, and focusing for now on the behaviour obtained in the 0.4 and 1 μm dots (open and solid circles), at relatively low resistances the phase-breaking time takes a constant value of approximately 40 ps. At higher resistances, however, a sudden and striking increase in the phase-breaking time is observed in both dots. Although we are unable to independently characterize the quantum point contacts of our devices, the transition to enhanced coherence appears to occur as the leads are narrowed to support only a few propagating modes ($R_0 = 13$–26 kΩ). Further increasing the dot resistance beyond this transition, no additional change in phase coherence is observed and the overall impression is instead one of a step-like transition. We emphasize that this variation in phase coherence is not simply an artifact of our numerical analysis, but is in fact reflected directly in the experimental data. In particular, the magnetoconductance fluctuations reveal a strong enhancement of their high-frequency content as the dot leads are narrowed (figure 2, inset), behaviour that is reminiscent of that seen in experiments in which phase coherence is enhanced by lowering the measurement temperature (see figure 1 of reference [8], for example).

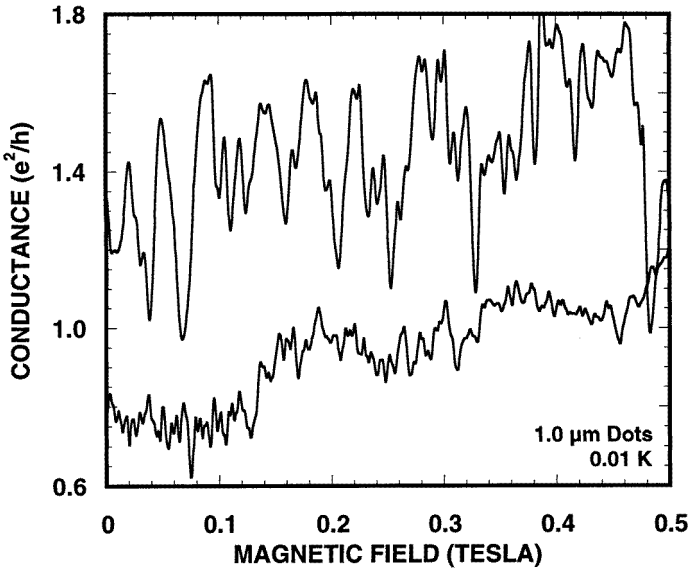

Figure 3. Conductance fluctuations in two 1 μm dots, patterned on nominally identical Hall bars ($R_0 = 20$ kΩ, $n_s = 4.4 \times 10^{15}$ m^{-2} and $\mu = 40$ m^2 V^{-1} s^{-1}). The lower curve ($\tau_\phi = 30$ ps) has been shifted downwards from the upper one ($\tau_\phi = 200$ ps) by $0.6e^2/h$.

In contrast to the behaviour in the 0.4 and 1 μm dots, a 0.6 μm device patterned on the same wafer showed only a factor of two increase when its leads were narrowed over the same range (figure 1, open triangles). This finding is consistent with our studies of other devices, which reveal considerable variations in the magnitude of the phase-breaking time in the high-resistance regime. Figure 3, for example, shows conductance fluctuations in two lithographically identical quantum dots, which were patterned on Hall bars with similar characteristics. While the zero-field resistance was adjusted to be roughly the same in the two devices (20 kΩ), a striking difference is nonetheless apparent in the amplitude of the

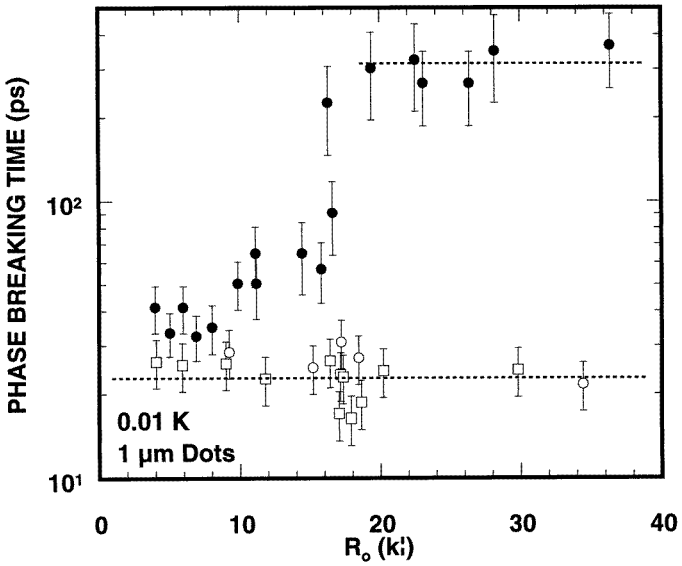

Figure 4. The variation of the phase-breaking time with lead opening in three 1 μm dots. Solid circles: $n_s = 5 \times 10^{15}$ m^{-2} and $\mu = 70$ m^2 V^{-1} s^{-1} (data of figure 1); open circles: $n_s = 4.4 \times 10^{15}$ m^{-2} and $\mu = 40$ m^2 V^{-1} s^{-1}; open squares: $n_s = 4.1 \times 10^{15}$ m^{-2} and $\mu = 20$ m^2 V^{-1} s^{-1}. The lines are intended to guide the eye.

resulting fluctuations, in turn implying very different values for the phase-breaking time. This poor correlation of phase coherence with the average properties of the bulk material is further illustrated in figure 4, which shows results for three lithographically identical dots that were patterned on wafers of varying mobility. Note how the two dots fabricated in the lower-quality material exhibit no noticeable variation in phase coherence with lead opening, while the higher-mobility one reveals an order of magnitude change. Although a very rough correlation to wafer mobility can be resolved here, we note that the magnitude of the phase-breaking time in the high-resistance regime does not appear to be distributed in simple accordance with the mobilities of the bulk wafers. To therefore summarize the results of our experiments:

(1) the phase-breaking time in open quantum dots exhibits a value of a few tens of picoseconds at low resistances, which increases by as much as an order of magnitude as the leads are narrowed to support just a few propagating modes;

(2) the phase-breaking time measured in the high-resistance regime shows considerable variations from device to device, indicative of a strong sensitivity of phase coherence to the specific disorder configuration within the device.

The influence of environmental coupling on the electrical behaviour of mesoscopic devices has been widely considered in the literature. For example, experimental studies have shown that the intrinsic properties of disordered quantum wires may be strongly obscured by the diffusion of phase-coherent electrons into their connecting probes [11]. In the case of the open quantum dots of interest here, environmental factors may be addressed by breaking the system up into discrete components whose interactions are defined through suitable coupling matrices [2]. With strong coupling between these components, the intrinsic properties of the isolated dot are modified by the filtering action of the quantum point contact leads. With

very weak coupling, however, the leads may be used to probe the unmodified spectrum of the isolated dot. As to how this might influence the phase coherence of electrons within the dot, we note from general considerations that the dephasing rate should be proportional to the density of final scattering states. Given such considerations, the behaviour in figure 1 implies that a suppression of the phase space available for scattering occurs as the number of modes in the quantum point contact leads is reduced. This conclusion is consistent with our previous numerical studies of these devices, which have shown how scarring arises from the selective excitation of dot eigenstates whose transverse momentum components match the quantized values in the point contact leads [3]. (A similar result is also obtained in a recent independent study, which, following on from the notion of beam collimation, points out the manner in which the contacts can dominate the quantum properties of the dots [12].)

The strong variations in phase coherence observed in different devices in the high-resistance regime (figures 1 and 4) imply a sensitivity of phase coherence to the specific disorder configuration within the device. One obvious source of this disorder is potential fluctuations within the two-dimensional electron gas layer, which arise from the discrete distribution of donors in the doped AlGaAs [13, 14]. Other possible sources of disorder may be introduced during the fabrication process and include unintentional irregularities in the patterned gate geometry and local degradation of the electron mobility in regions subject to electron beam exposure. The effect of such disorder is to mix the eigenspectrum of the originally clean quantum dot [15], as a result of which electrons injected into the device may populate additional eigenstates that would otherwise remain inaccessible in transport. As noted above, this increase in the phase space available for electron scattering is expected to induce a reduction in phase coherence, with the resulting value of the phase-breaking time reflecting the *specific* disorder configuration within the device. Furthermore, with disorder effective in mixing the eigenstates of the dot, varying the width of the point contact leads should no longer be effective in modulating the number of cavity states that participate in transport. This notion seems to be consistent with the results of experiment, in which devices exhibiting the smaller amplitude of fluctuation (stronger phase breaking) also exhibit a weaker variation of their phase-breaking time with lead opening (figure 4).

Since the disorder configuration within the dots is expected to be sensitive to thermal cycling, the preceding arguments suggest that the phase-breaking time should be similarly sensitive. This is indeed the case in experiment and a reduction of phase coherence due to thermal cycling has previously been exploited to study the weak-localization lineshape of individual quantum dots [16]. While we have not undertaken detailed studies of the manner in which the cycling process influences the phase-breaking process, the rate of pre-cooling to liquid nitrogen temperatures does appear to be important [17]. In particular, while the sample insert may be loaded directly into liquid helium from room temperature [18], the phase-coherent properties of devices cooled in this manner are generally found to be very poor. Consequently, all results presented here were obtained after first pre-cooling the devices to liquid nitrogen temperatures over a period of ten hours or more. As to why the rate of pre-cooling should be so important, a recent study has shown that the degree of disorder in mesoscopic devices may be dramatically reduced by an ordering of the ionization of donors in the AlGaAs [14]. The suggestion here is that rapid cooling of the samples may freeze this ionization into some fixed configuration, before the ordering process can be achieved. While further studies are required to investigate this possibility, we emphasize that the phase-coherent properties measured here are generally found to be quite stable at low temperatures, suggesting that the origin of the disorder is indeed static in nature.

In conclusion, studies of electron phase coherence in open quantum dots reveal evidence for a subtle interplay between geometry and materials-related factors. Suppressing the

influence of environmental coupling, by reducing the width of the quantum point contact leads, a strong suppression of dephasing is observed. The magnitude of the phase-breaking time in this high-resistance regime exhibits significant variations from device to device, indicative of a strong sensitivity of dephasing to the specific disorder configuration within the dot. In order to account for these observations, we have suggested an interpretation of phase breaking which invokes the discrete nature of the level spectrum in the open dots and which emphasizes the role of the quantum point contacts in selectively exciting cavity eigenstates. Our results therefore provide further dramatic evidence for the role of lead openings in determining transport through quantum devices.

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[17] We thank the referee for urging us to highlight the importance of this issue. In particular, there appears to be a general reluctance on the part of experimentalists to openly discuss issues associated with the 'black art' of successful transport measurements, presumably due to the fear of dismissal from the wider community.
[18] All measurements were performed using an Oxford Instruments Kelvinox-300 dilution refrigerator.