Dephasing in Open Quantum Dots

A. G. Huibers, M. Switkes, and C. M. Marcus
Department of Physics, Stanford University, Stanford, California 94305

K. Campman and A. C. Gossard
Materials Department, University of California, Santa Barbara, Santa Barbara, California 93106
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Shape-averaged magnetoconductance (weak localization) is used for the first time to obtain the electron phase coherence time τ_ϕ in open ballistic GaAs quantum dots. Values for τ_ϕ in the range of temperature T from 0.34 to 4 K are found to be independent of dot area, and are not consistent with the $\tau_\phi \propto T^{-2}$ behavior expected for isolated dots. Surprisingly, $\tau_\phi(T)$ agrees quantitatively with the predicted dephasing time for disordered two-dimensional electron systems. [S0031-9007(98)06449-7]

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Decoherence is the process by which the quantum mechanical properties of a microscopic system are transformed into the familiar classical behavior seen in macroscopic objects. Mesoscopic electronic systems, which exhibit strong coherent quantum mechanical effects such as weak localization and universal conductance fluctuations (UCF), are ideal for investigations of decoherence. The key quantity in these phenomena is the phase coherence time τ_ϕ, which determines the energy and length scales at which quantum behavior is seen. Considerable theoretical [1–4] and experimental [5–9] study has been directed toward understanding the mechanisms responsible for the loss of phase coherence (dephasing) and their dependence on temperature, dimensionality, and disorder.

Most studies of dephasing in mesoscopic systems have focused on disordered 1D and 2D conductors, where the dimensional crossover for quantum corrections to transport and interactions responsible for dephasing occurs when the sample width exceeds the phase coherence length $\ell_\phi = \sqrt{D\tau_\phi}$ and thermal length $\ell_T = \sqrt{D\hbar/k_BT}$, respectively ($D$ is the diffusion constant) [1,4]. At low temperatures electron-phonon scattering rates are small compared to electron-electron scattering rates [10] and two electron-electron scattering mechanisms dominate dephasing: a large-energy-transfer scattering mechanism, which causes dephasing with a rate $\tau_{ee}^{-1} \propto T^2$ [11]—in a 2D electron gas (2DEG) this rate is

$$\tau_{ee}^{-1} = \frac{\pi}{4}\frac{(k_BT)^2}{\hbar E_F}\ln\frac{E_F}{k_BT} \tag{1}$$

for $k_BT \ll E_F$, where E_F is the Fermi energy—and a small energy-transfer (Nyquist) scattering mechanism, which gives a rate $\tau_{\phi N}^{-1} \propto T^{2/(4-d)}$, where d is the dimensionality of the system ($d = 1, 2$) [1]. In a disordered 2DEG the Nyquist dephasing rate is

$$\tau_{\phi N}^{-1} = \frac{k_BT}{2\pi\hbar}\,\frac{\lambda_F}{\ell_e}\ln\frac{\pi\ell_e}{\lambda_F}, \tag{2}$$

where λ_F is the Fermi wavelength and ℓ_e is the elastic mean free path. The total dephasing rate due to electron-electron scattering is approximately the sum of these rates, $\tau_\phi^{-1} \approx \tau_{\phi N}^{-1} + \tau_{ee}^{-1}$ [6,12]. Measurements of $\tau_\phi(T)$ in disordered 2D and 1D semiconductors [6] and 1D metals [5] based on weak localization find good agreement with these theoretical results down to $\sim$0.1 K. In clean 2D systems ($\ell_e \sim \ell_\phi$) the dephasing rate is expected to coincide with τ_{ee}^{-1} from Eq. (1), without the Nyquist contribution, consistent with experiments in high-mobility 2DEG samples [7,13]. In isolated quantum dots (0D systems), a dephasing rate $\tau_\varphi^{-1} \propto \sim T^2$ is expected for intermediate temperatures ($\ell_T > L$ but $kT \gg \Delta$, where $\Delta = 2\pi\hbar^2/m^*A$ is the mean level spacing for a dot of area A) with a rate comparable to Eq. (1) for ballistic dots, $\ell_e > L$ [2,3,14]. To our knowledge, there has been no theoretical discussion of τ_ϕ in *open* quantum dots despite previous experimental investigation [8,9].

In this Letter, we use a novel method based on the 0D analog of weak localization to measure $\tau_\phi(T)$ in ballistic GaAs quantum dots with areas ranging from 0.4 to 4 μm^2 and single-mode point-contact leads. We find that τ_ϕ is independent of dot area and, surprisingly, that $\tau_\phi(T)$ is not proportional to T^{-2} but rather shows behavior similar to that seen in disordered 2D conductors, including both T^{-1} and T^{-2} contributions. These conclusions are verified with a comparison to $\tau_\phi(T)$ measured three other ways in the same dots.

Our primary technique for determining τ_ϕ is based on the magnetic field dependence of the weak localization correction to quantum transport, and is similar to standard methods used in diffusive 1D and 2D samples. This method is applied to quantum dots for the first time here, having only become possible due to recent theoretical developments [15,16] based on random matrix theory (RMT) [17]. For irregularly shaped quantum dots with two leads each supporting N channels (or lateral modes), RMT yields a zero-temperature average conductance $\langle g\rangle$ equal to the resistors-in-series value $(e^2/h)N$ at $B \neq 0$ but reduced to $(e^2/h)2N^2/(2N + 1)$ at $B = 0$ due to phase-coherent backscattering (or weak localization) [18]. Dephasing suppresses this difference

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$\delta g \equiv \langle g \rangle_{B \neq 0} - \langle g \rangle_{B=0}$ by limiting the time over which backscattered electrons may contribute to interference. To incorporate dephasing into a quantitative theory, a fictitious voltage probe, or "ϕ lead" supporting γ_ϕ modes is appended to the dot [19], where

$$\gamma_\phi = \frac{2\pi\hbar}{\tau_\phi \Delta}. \tag{3}$$

The RMT for this three-lead dot (two real leads plus the ϕ lead) then yields a suppressed weak localization correction [15]

$$\delta g \approx \frac{e^2}{h}\left(\frac{N}{2N + \gamma_\phi}\right) \tag{4}$$

that models the effect of dephasing. Note that γ_ϕ is proportional to dot area, so a larger dot will exhibit a smaller δg for a given τ_ϕ.

The ϕ-lead model was recently improved by Brouwer and Beenakker by distributing the phase breaking throughout the dot rather than concentrating it at the location of a single lead [16]. The resulting expression for δg in terms of γ_ϕ differs significantly from Eq. (4) for the case $N = 1$ (Fig. 2 inset), though nearly coincides with Eq. (4) for $N > 1$. We note that both the ϕ-lead model and its distributed extension [16] ignore the effects of Coulomb charging on δg, which may be important particularly at $N = 1$ [20]. The consistency between measured values of $\tau_\phi(T)$ using different methods and dot sizes suggests that any field-dependent charging effects are probably not corrupting the present measurement significantly.

Measurements on four quantum dots (Fig. 3 insets) with areas of 0.4 μm^2 (two dots), 1.9 and 4.0 μm^2 ($\Delta = 17.9$, 3.8, and 1.8 μeV, respectively) are reported. The dots are formed by gate depletion of a 2DEG located 160 nm below the surface of a $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure (sheet density $n = 1.8 \times 10^{11}$ cm^{-2}, mobility $\mu = 0.9 \times 10^6$ cm^2/V s, Fermi wavelength $\lambda_F =$ 60 nm and Fermi energy $E_F = 6.4$ meV). The elastic mean free path measured with gates undepleted is $\sim$6 μm, larger than all device sizes so that transport is ballistic within the dots. The dots were measured in a ^{3}He cryostat at temperatures ranging from 335 mK to 4 K using standard 4-wire lock-in techniques at 105 Hz with 0.5 nA bias current—small enough not to affect transport due to heating ($I_{\text{bias}} = 0.5$ and 1 nA give identical results at base temperature). At these temperatures, weak localization and UCF are comparable in magnitude, as seen in the gray traces of Fig. 1. By averaging over gate-voltage-controlled shape distortions, UCF is averaged away leaving only the weak localization correction. The measurement procedure is illustrated in Fig. 1. First, V_{pc1} and V_{pc2} are swept in a raster to find the plateau with $N =$ 1 channel in each lead (bracketed region lower left inset). While the leads are maintained at one channel each, the shape of the dot is distorted using V_{shape1} and V_{shape2}, creating an effective ensemble of dots. The 47 green points on the conductance landscape in the lower right inset in-

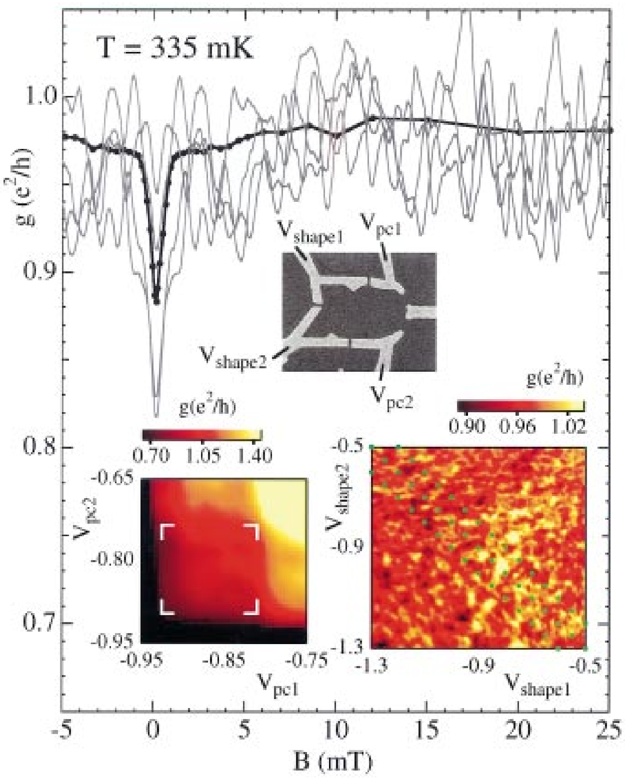

FIG. 1(color). Shape-averaged magnetoconductance (black) and four unaveraged conductance curves (gray) for the 4.0 μm^2 quantum dot (inset). Lower left inset: conductance as a function of V_{pc1} and V_{pc2} showing (bracketed) plateau with $N = 1$ channel in each point contact. Lower right inset: conductance through dot as a function of V_{shape1} and V_{shape2} with green circles marking the 47 points at which magnetoconductance was measured.

dicate the positions in (V_{shape1}, V_{shape2}) space of the measured ensemble samples. Figure 1 shows $g(B)$ at four of these 47 points, along with the average $\langle g(B) \rangle$ of all 47 used to determine δg.

Figure 2 shows δg at $N = 1$ as a function of temperature for the four devices. Using $\gamma_\phi(\delta g)$ from Ref. [16], each point in Fig. 2 is converted to γ_ϕ and then, using Eq. (3), to τ_ϕ. The resulting $\tau_\phi(T)$ is shown in Fig. 3. While dots with different areas have different values of δg, τ_ϕ appears to be independent of area. The high temperature roll-off of τ_ϕ seen in Fig. 3 for larger devices results from a breakdown of the model [16] when $\ell_\phi = v_F \tau_\phi$ becomes of order L, so that nonergodic trajectories dominate coherent backscattering. The inequality $L > \ell_\phi$ holds throughout the measured range of temperatures; however, $L \sim \ell_T = v_F \hbar / k_B T$ at 2.2, 0.97, and 0.69 K for the 0.4, 1.9, and 4.0 μm^2 dots, respectively. As seen in Fig. 3, the temperature dependence of τ_ϕ for all four dots falls between $\tau_\phi \propto T^{-2}$ and $\tau_\phi \propto T^{-1}$. The data cannot be fit by τ_{ee} alone (dashed line in Fig. 3) but are well fit by the sum of dephasing rates for *diffusive 2D systems,* Eqs. (1) and (2) (solid line in Fig. 3), if we choose $\ell_e = 0.25$ μm, giving $\tau_\phi^{-1}[\text{ns}^{-1}] \simeq 10.9\,(T[\text{K}]) + 6.1\,(T[\text{K}])^2$. We do not

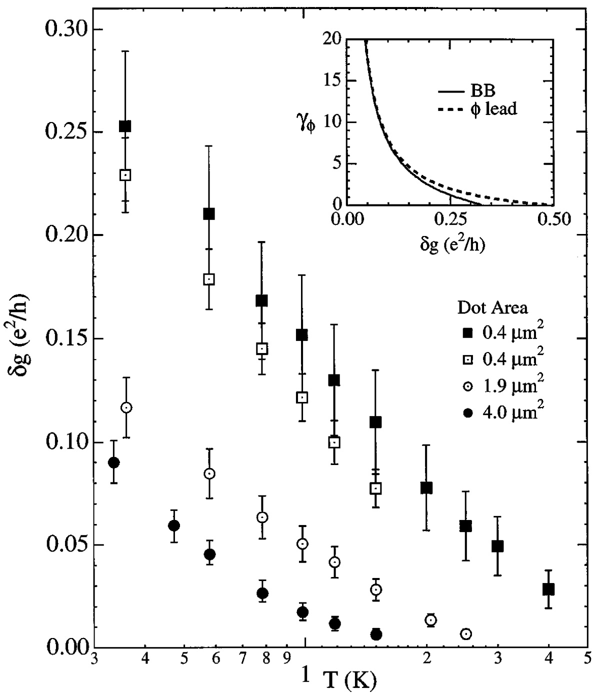

FIG. 2. Shape-averaged weak localization amplitude δg vs temperature T for the four measured devices. Error bars reflect uncertainty in δg as a result of conductance fluctuations remaining due to limited ensemble size. Inset: theoretical phase breaking rate $\gamma_\phi(\delta g)$ using ϕ-lead model [15] [Eq. (3)] and distributed voltage probe model (BB) [16].

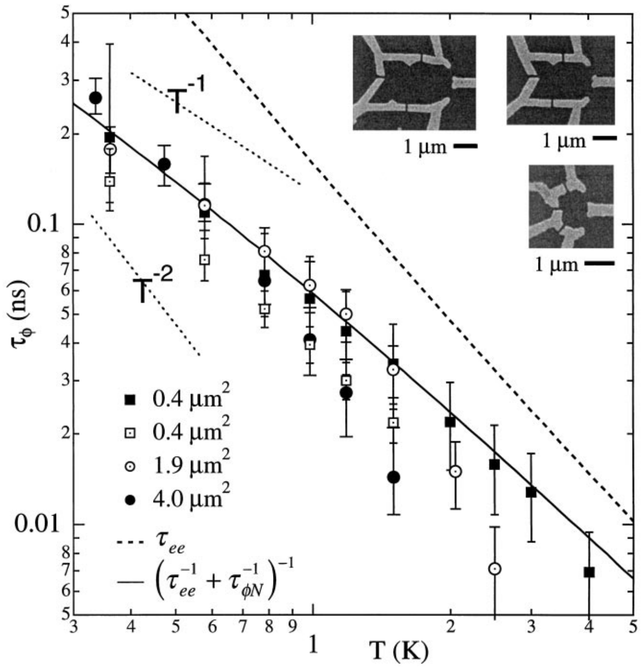

FIG. 3. Phase coherence time τ_ϕ determined from $N = 1$ weak localization. τ_{ee} from Eq. (2) (dashed line), and $\tau_\phi^{-1} = \tau_{\phi N}^{-1} + \tau_{ee}^{-1}$ for a 2D disordered system with $\ell_e = 0.25\ \mu$m (solid line) shown for comparison. Dotted lines indicate slopes corresponding to T^{-1} and T^{-2}, offset for clarity. Inset: micrographs of 4.0, 1.9, and 0.4 μm^2 dots.

know if the value of ℓ_e corresponds to any physical length in the problem; certainly it is much shorter than the ℓ_e of the unconfined electron gas. We note that $\tau_\phi(T)$ does not show a low-T saturation over the temperature range reported; subsequent measurements down to an electron temperature of 40 mK show some saturation below 100 mK, and a $\tau_\phi(T)$ consistent with the present data above 100 mK [21]. Direct application of microwave radiation (50 MHz–25 GHz) to the sample has also been shown to cause a saturation in $\tau_\phi(T)$ at higher temperatures but does not cause the Nyquist-like $\tau_\phi(T)$ dependence reported here [21]. The spin-orbit scattering time is expected to exceed the measured τ_ϕ by at least an order of magnitude over the temperature range studied [22]. Significant spin-orbit scattering would lead to a local maximum of $\langle g(B)\rangle$ at $B = 0$, which is not observed.

To check the results based on weak localization amplitude at $N = 1$ ($\delta g_{N=1}$), we compare to three other measurements of $\tau_\phi(T)$ in the same devices (Fig. 4). The first comparison is to $\tau_\phi(T)$ obtained from weak localization amplitude at $N = 2$ ($\delta g_{N=2}$), measured as above, and using Eqs. (3) and (4) to convert from $\delta g_{N=2}$ to τ_ϕ. The $\delta g_{N=2}$ and $\delta g_{N=1}$ results are consistent within experimental error as shown in Figs. 4(a) and 4(b) for the 0.4 and 4.0 μm^2 dots.

The second comparison is to $\tau_\phi(T)$ extracted from power spectra of UCF, a method described previously in Ref. [8]. This method makes use of the fact that UCF measured as a function of B in open quantum dots has an exponential power spectrum

$$S(f) = S(0)e^{-2\pi B_c f} \tag{5}$$

for $kT \gg \Delta$ [23] (f is magnetic frequency in cycles/mT) with a characteristic magnetic field B_c that depends on the dephasing rate

$$(B_c/\varphi_0)^2 = \kappa(2N + \gamma_\phi), \tag{6}$$

where κ is a geometry-dependent constant and $\varphi_0 = h/e$ is the quantum of flux [8]. Figure 4(c) shows power spectra of $g(B)$ for the 4.0 μm^2 dot, consistent with Eq. (5) over 3 orders of magnitude. A two-parameter fit of Eq. (5) to power spectra at each temperature gives $B_c(T)$ which yields $\tau_\phi(T)$ via Eq. (6), with κ chosen as a best fit to the $\delta g_{N=1}$ data. Figure 4(d) compares $\tau_\phi(T)$ determined from UCF power spectra with that from $\delta g_{N=1}$, showing good agreement over the whole temperature range.

The final comparison is to $\tau_\phi(T)$ extracted from the *width* of the Lorentzian dip in average conductance around $B = 0$ [24],

$$\langle g(B)\rangle = \langle g\rangle_{B\neq 0} - \frac{\delta g}{1 + (2B/B_c)^2}\,. \tag{7}$$

Figure 4(e) shows traces of shape-averaged $\langle g(B)\rangle$ for the 4.0 μm^2 dot, along with two-parameter (δg and B_c) fits to Eq. (7). Values for $\tau_\phi(T)$ in Fig. 4(f) are extracted from $B_c(T)$ using Eq. (6) with κ chosen to give a best

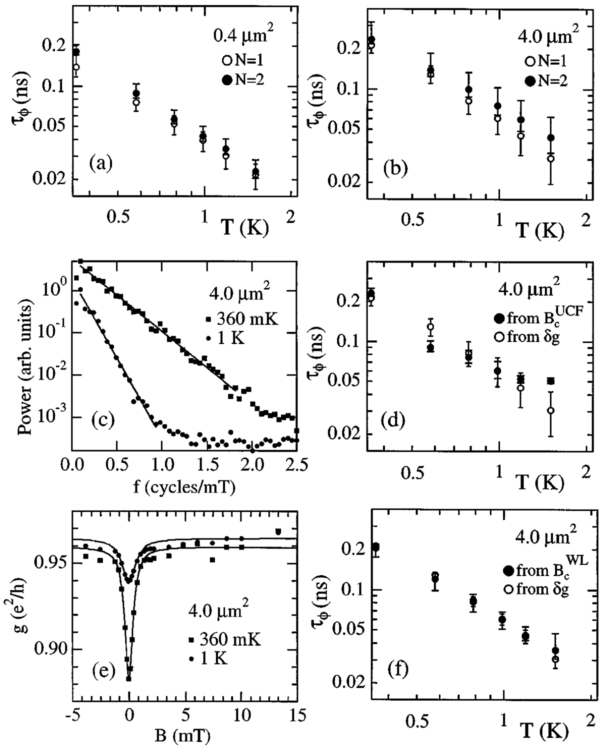

FIG. 4. (a),(b) Comparison of τ_ϕ extracted from average $N = 1$ and $N = 2$ weak localization amplitude for 0.4 and 4.0 μm^2 dots. (c) Fit of Eq. (5) to power spectral density for $N = 1$ conductance fluctuations and (d) comparison of τ_ϕ extracted from the characteristic field scale of UCF and from weak localization amplitude for 4.0 μm^2 dot. (e) Lorentzian fit [Eq. (7)] to average $N = 1$ weak localization line shape and (f) comparison of τ_ϕ extracted from the weak localization width of the fit, and from weak localization amplitude for 4.0 μm^2 dots.

fit to the $\delta g_{N=1}$ results. It is noteworthy that several very different methods of determining τ_ϕ agree within experimental error.

In summary, we have measured phase coherence times in open ballistic quantum dots using a new weak-localization method, as well as two other methods for comparison. We find (i) consistency between the methods, (ii) values for $\tau_\phi(T)$ that do not depend on dot area, and (iii) an unexpected agreement between the experimental $\tau_\phi(T)$ and the theoretical prediction for a disordered 2D system with effective mean free path on the order of the device size and inconsistency with the $\tau_\phi(T) \propto T^{-2}$ expected for isolated dots. In particular, $\tau_\phi(T)$ appears to have significant contributions proportional to both T^{-1} and T^{-2}, suggesting that perhaps some Nyquist-type dephasing mechanism is effective in open dots.

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