# Low-Temperature Saturation of the Dephasing Time and Effects of Microwave Radiation on Open Quantum Dots

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The dephasing time $\tau_\varphi$ of electrons in open semiconductor quantum dots, measured using ballistic weak localization, is found to saturate below ~100 mK, roughly twice the electron base temperature, independent of dot size. Microwave radiation deliberately coupled to the dots affects quantum interference indistinguishably from elevated temperatures, suggesting that direct dephasing due to radiation is not the cause of the observed saturation. Coulomb blockade measurements show that the applied microwaves create sufficient source-drain voltages to account for dephasing due to Joule heating.

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Phase coherent electronics have attracted considerable interest both because of their potential use as the basis of solid-state quantum information processing [1] and because of significant discrepancies between theory and experiment on the subject of low-temperature dephasing [2,3]. Dephasing, or quantum decoherence, results from interactions between a quantum system and its environment. In the context of mesoscopic physics [4], the quantum system is an electron or quasiparticle in a conductor and the environment includes phonons, radiation, magnetic impurities, and other electrons.

The theory of dephasing in low-dimensional conductors, as well as methods for extracting the time scale on which dephasing occurs, $\tau_\varphi$, from transport measurements, is by now well established [5]. Measurements of $\tau_\varphi$ in a variety of one- and two-dimensional (1D, 2D) disordered metals and semiconductors [2,6–8], clean 2D semiconductors [9], and zero-dimensional (0D) quantum dots [10,11] have been reported, with $\tau_\varphi$ typically in the range of picoseconds to tens of nanoseconds, depending on temperature. Interestingly, essentially all experiments show some saturation of $\tau_\varphi$ at low temperatures, the origin of which remains unresolved. This issue is quite important since an intrinsic saturation of $\tau_\varphi$ at low temperatures would signal a breakdown of Fermi-liquid behavior.

Quantum dots—small islands of charge connected to electronic reservoirs via conducting leads—are particularly useful for studying coherence effects because quantum corrections to the conductance of the dot are large, comparable to the average conductance itself. Another useful feature is that the same device that is used to measure $\tau_\varphi$ can also be used to measure the electron temperature, $T_{el}$, either via Coulomb blockade (CB) peak widths [12] or from the variance of conductance fluctuations, var($g$), the latter taking advantage of results from random matrix theory (RMT) [13] and nonlinear sigma model calculations [14] that assume the dot to be either disordered or chaotic.

This Letter contains two main results: First, we present evidence of a low-temperature saturation of $\tau_\varphi(T_{el})$ below $T_{el} \sim 100$ mK in clean quantum dots with single channel leads, based on measurements of ballistic weak localization. We further find that $\tau_\varphi(T_{el})$ is independent of dot size and shape throughout the measured temperature range, consistent with previous measurements [11]. Low-temperature saturation of $\tau_\varphi$ in quantum dots has been reported previously [10] based on less precise measurement methods or methods requiring sizable magnetic fields. Second, we investigate the possibility that the cause of saturation of $\tau_\varphi$ is unintentional irradiation, which can cause direct dephasing at amplitudes much too weak to induce heating [3,15]. Direct dephasing by microwave radiation, mixed with varying degrees of Joule heating, has been observed in experiments on disordered wires [16], films [17–19], and metal-oxide-semiconductor structures [20]. Neither theory nor previous experiment has addressed the case of quantum dots to our knowledge. Our investigation consists of applying microwave radiation to the sample over a range of amplitudes at frequencies from well above to well below $2\pi/\tau_\varphi$. We find that the radiation indeed reduces $\tau_\varphi$, but that the reduction appears well accounted for by electron heating rather than direct dephasing. From this observation we conclude that the saturation of $\tau_\varphi(T_{el})$ in the absence of applied radiation cannot be easily explained by unintentional microwave irradiation. Similar conclusions were recently reached by Mohanty and co-workers [21] based on similar microwave irradiation experiments on metal wires.

Measurements are reported for five devices, each formed using lithographically patterned gates 90 nm above a two-dimensional electron gas (2DEG) in a delta-doped $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure (Fig. 2 insets). A sheet density $\sim 2 \times 10^{11}$ cm$^{-2}$ and mobility

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$1.4 \times 10^5$ cm$^2$/V s give a mean free path of $\sim$1.5 $\mu$m, comparable to the device size (see Fig. 2 table). Measurements were carried out in a dilution refrigerator after slowly cooling the samples with a bias of +0.4 V on all gates to reduce switching noise. The base $T_{\mathrm{el}}$ was 45 mK in the saturation experiments (i.e., before adding external microwave apparatus) and 83 mK in the microwave irradiation experiments, which required the removal of a low-temperature shield. The base mixing chamber temperature was 28 mK. $T_{\mathrm{el}}$ was determined from CB peak widths measured at several temperatures [12]. Given the small biases used in the dephasing and temperature measurements, we can take $T_{\mathrm{el}}$ to be constant in the 2DEG, both inside and outside the dots; conductance fluctuation measurements discussed below support this assumption. All conductances were measured using analog lock-in amplifiers (PAR 124) with less than 2 $\mu$V ($<kT/e$) across the dot. Statistics of conductance data were gathered by sampling an ensemble of shape distortions controlled by two gates $V_{g1}$ and $V_{g2}$ (Fig. 1 inset) while simultaneously trimming the point contact gate voltages to maintain precisely one mode in each lead [11].

Dephasing time was extracted from the change in ensemble-averaged conductance, $\delta g = (\langle g \rangle_{B \neq 0} - \langle g \rangle_{B=0})$, upon breaking time-reversal symmetry with a small magnetic field [11]. Noninteracting RMT [13] yields a simple approximate expression for $\delta g$ that depends only on dephasing and the number of channels in the leads,

$$\delta g \sim [1/(2N + 1 + \gamma_\varphi)]e^2/h\,, \tag{1}$$

where $\gamma_\varphi = 2\pi\hbar/(\tau_\varphi \Delta)$ is the dimensionless dephasing rate (i.e., the number of dephasing channels), $\Delta = 2\pi\hbar^2/m^*A$ is the mean level spacing, and $A$ is the dot area. Equation (1) allows $\tau_\varphi$ to be extracted from $\delta g$ knowing only the area of the dot and the conductance of the leads. Figure 1(a) shows that the zero-dephasing limit for one-mode leads ($N = 1$), $\delta g = (1/3)(e^2/h)$, is approached in the smaller devices, indicating that $\gamma_\varphi < 1$ in these devices. Because $\gamma_\varphi$ depends on $A$, the same values of $\tau_\varphi$ in the larger devices yield large values of $\gamma_\varphi$, and correspondingly smaller $\delta g$, according to Eq. (1).

Conductance fluctuations are also reduced by dephasing, but, unlike $\delta g$, are further reduced by thermal averaging [13,22]. For broken time-reversal symmetry and $kT > \Delta$, the RMT result including thermal averaging can be well approximated by $\mathrm{var}(g) \sim (\Delta/6kT)f(\gamma_\varphi)$, where $f(\gamma_\varphi) = 2(2 + \gamma_\varphi)^{-1}(\sqrt{3} + \gamma_\varphi)^{-2}$, as discussed in Ref. [22]. Notice that for $\gamma_\varphi < \sim 1$, $\mathrm{var}(g) \propto T^{-1}$, so that var($g$) serves as a low-temperature electron thermometer. Values for $T_{\mathrm{el}}$ obtained from var($g$) are consistent with values obtained from CB peak widths over the full temperature range of the experiment.

Figure 2 shows the phase coherence time $\tau_\varphi$, extracted from $\delta g$ using Eq. (1), as a function of $T_{\mathrm{el}}$ measured from CB peak widths. Above $T_{\mathrm{el}} \sim 100$ mK, a dephasing rate

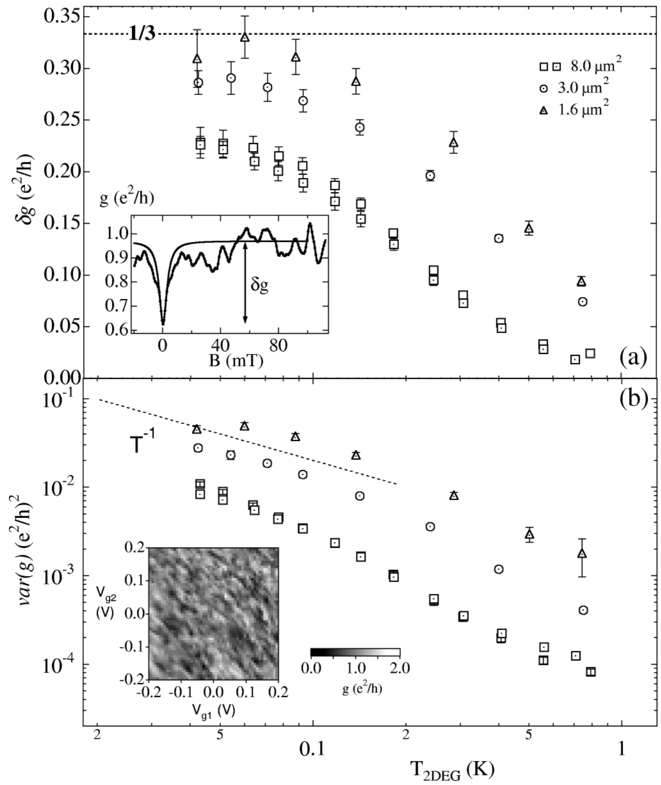


FIG. 1. (a) Weak localization amplitude $\delta g$ as a function of electron temperature $T_{\mathrm{el}}$ in dots with single mode leads and area $A = 1.6$ $\mu$m$^2$ (triangles), 3.0 $\mu$m$^2$ (circles), and 8.0 $\mu$m$^2$ (squares). Inset: Average conductance $\langle g(B) \rangle$ as a function of magnetic field $B$, from 20 traces for a 1.0 $\mu$m$^2$ device, showing weak localization at $B = 0$, with Lorentzian fit (solid curve). (b) Variance of conductance fluctuations, var($g$), as a function of $T_{\mathrm{el}}$ for the same devices, measured with broken time-reversal symmetry, $B > \Phi_0/A$. $T_{\mathrm{el}}$ is measured from CB peak width in the 8.0 $\mu$m$^2$ device. Both $\delta g$ and var($g$) are based on ensembles of $\sim$400 independent values of $g$ drawn from shape distortion landscapes. Lower inset shows a shape-distortion landscape for the 1.6 $\mu$m$^2$ device.

of the form $\tau_\varphi^{-1} \sim AT_{\mathrm{el}} + BT_{\mathrm{el}}^2$ is observed, consistent with previous experimental results [11], but not expected theoretically [23]. Below 100 mK, $\tau_\varphi$ appears to saturate.

Electron-electron interaction effects not accounted for within RMT are expected to enhance $\delta g$ by a factor of $\sim(1 + 0.24\Delta/kT)$ at $N = 1$, as well as enhance var($g$) by a factor $\sim(1 + 2\Delta/kT)$ for $N \gg 1$, according to recent theory [24]. Variance results for $N = 1$ are not known, nor are the effects of dephasing on these enhancements [24]. Nonetheless, these results suggest that interaction effects are small, particularly in the larger dots. For instance, for the 8 $\mu$m$^2$ device interactions enhance $\delta g$ by $\sim$5% at 45 mK and less at higher temperatures. More importantly, since the enhancement of $\delta g$ increases as temperature decreases, interaction effects alone cannot account for the observed saturation.

To investigate possible causes of the saturation of $\tau_\varphi(T_{\mathrm{el}})$, a set of quantum dots were deliberately irradiated with microwaves at frequencies ranging from well above

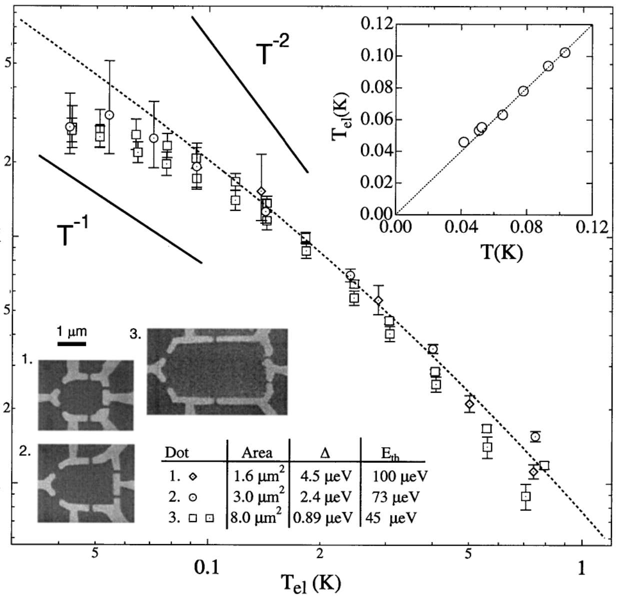


FIG. 2. Phase coherence time $\tau_\varphi$ as a function of $T_{\mathrm{el}}$, determined from $\delta g$, as described in text, along with empirical relation $\tau_\varphi[\mathrm{ns}] = (4.0T[K] + 9.0T[K]^2)^{-1}$. Lines show $T^{-1}$ and $T^{-2}$ dependencies. Upper inset: Electron temperature from CB peak width as a function of mixing chamber temperature, $T$, in the $3.0\ \mu\mathrm{m}^2$ device. Lower inset: micrographs and device parameters, with ballistic Thouless energy defined $E_{\mathrm{th}} = \hbar v_F/L$, where $L$ is the width of the device.

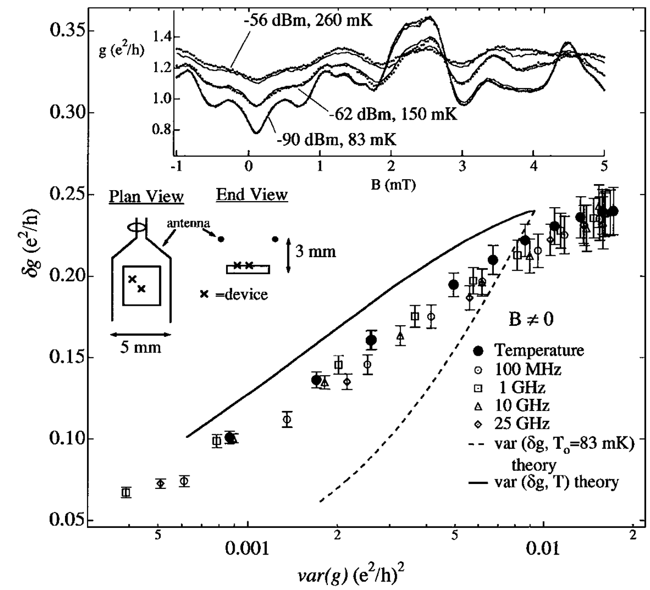


FIG. 3. Weak localization $\delta g$ versus conductance fluctuations var($g$) for the $3.0\ \mu\mathrm{m}^2$ dot parametrized by both $T_{\mathrm{el}}$ (solid circles) and microwave power at base temperature $T_{\mathrm{el}} =$ 83 mK, for frequencies ranging from 100 MHz to 25 GHz. Curves show RMT results for dephasing without heating at 83 mK (dashed curve) and dephasing due to heating (solid curve) using measured values of $\delta g$ as input to find $T_{\mathrm{el}}$ and hence var($g$). Inset: Single magnetoconductance traces at different microwave power levels at 700 MHz for base temperature (dotted curves) along with traces taken for increasing electron temperature (solid curves). In all cases, effects of heating and irradiation are indistinguishable.

to well below $2\pi/\tau_\varphi$. The aim was to intensify any direct dephasing without heating so it could be unambiguously observed. Microwaves were coupled into the dilution refrigerator via a 1.5 mm coaxial waveguide attached to an open biaxial antenna segment of width 5 mm, positioned 3 mm above the sample (Fig. 3 inset). Note that these dimensions are much smaller than the radiation wavelength ($\lambda = 30\ \mathrm{cm}/f[\mathrm{GHz}]$).

Figure 3 shows that the parametric dependence of $\delta g$ (sensitive to dephasing only) versus var($g$) (sensitive to temperature as well as dephasing) evolves the same when either the temperature or microwave power is increased. This would not be the case if the microwaves caused dephasing without heating: The dashed curve indicates the parametric dependence for a variable dephasing rate with $T_{\mathrm{el}}$ fixed at the base electron temperature, 83 mK, corresponding to dephasing without heating. On the other hand, the solid curve allows both temperature and dephasing to vary, using $\delta g$ to determine $T_{\mathrm{el}}$ (from Fig. 1). The qualitative agreement with this solid curve as well as the overall indistinguishability of microwave radiation from heating indicate that the only observable effect of the microwaves on electrons in open dots is heating. This conclusion is further supported by the individual magnetoconductance traces at elevated temperatures (Fig. 3 inset). Feature by feature, these traces are indistinguishable from traces taken at base temperature with an appropriate microwave power applied.

Having established that the applied microwaves appear to cause dephasing through heating, we can further infer the likely heating mechanism by examining the dependence of the effective electron temperature in the dot on microwave power, as well as rectification in the CB regime. Together, these data suggest that the applied microwaves induce microvolt-scale ac source-drain voltages sufficient to cause Joule heating within the dot. We have previously found that the temperature $T_{\mathrm{dot}}$ inside a single-mode ($N = 1$) quantum dot in the presence of a finite dc source-drain bias, $V_{\mathrm{sd}}^{(\mathrm{dc})}$, is well characterized by balancing Joule heating and out-diffusion of hot electrons, giving $T_{\mathrm{dot}} = [T_{\mathrm{res}}^2 + \alpha(3e^2/2\pi^2k^2)V_{\mathrm{sd}}^2]^{1/2}$, where $T_{\mathrm{res}}$ is the reservoir electron temperature and $\alpha \sim 1/2$ is the fraction of the dissipated power that heats the dot [25].

Figure 4(a) shows the effective ac source-drain voltage $V_{\mathrm{sd}}^{(\mathrm{ac})}$, extracted from $T_{\mathrm{dot}}$ and $T_{\mathrm{res}}$, as a function of microwave power $P$. The value for $T_{\mathrm{dot}}$ was found by two methods, first, by matching $\delta g$ and var($g$) data (Fig. 3) with those for increasing temperature, and, second, from CB peak widths. Figure 4(a) shows the expected dependence, $V_{\mathrm{sd}}^{(\mathrm{ac})} \propto P^{1/2}$, from Joule heating plus out-diffusion, but does not rule out other heating mechanisms such as direct absorption of radiation by electrons in the dot. Variability in the coupling of the radiation to

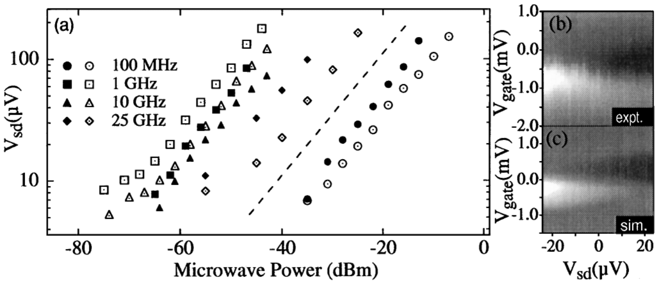


FIG. 4. (a) Estimated ac source-drain voltage $V_{sd}$ across the dot as a function of the microwave power $P$. Dot temperature used to infer $V_{sd}$ (see text) is from either CB peak widths (filled points) or $\delta g$ and var($g$) (open points) from the 3.0 $\mu$m$^2$ dot. Dashed line shows the expected slope $V_{sd} \propto P^{1/2}$, for the case of Joule heating balanced by out-diffusion of hot electrons. (b),(c) Gray-scale plots of (b) experimental and (c) simulated dc current in the vicinity of a CB diamond, as a function of gate voltage and a dc bias across the dot. Skewed branches of the diamond reflect ac biases induced by the microwaves. (b) Experiment: Base temperature data for a 1.0 $\mu$m$^2$ dot, microwave power at −37 dBm at 25 GHz. (c) Simulation: ac source-drain fluctuations with rms amplitude of 30 $\mu$V.

the 2DEG allows an overall horizontal shift in the data. At some frequencies (e.g., 100 MHz and 10 GHz) the two methods track closely, whereas at other frequencies the two methods give curves with an overall shift for unknown reasons.

Direct evidence that applied microwaves give rise to an ac source-drain voltage sufficient to cause dephasing purely from Joule heating can be seen in the CB "diamonds" shown in Fig. 4(b) as gray-scale plots of current as a function of $V_{sd}^{(dc)}$ and gate voltage $V_g$. Notice that a nonzero current flows at $V_{sd}^{(dc)} = 0$ (first positive, then negative, as $V_g$ is swept); i.e., the diamonds do not meet at a point but are skewed. This skewing *cannot* result from temperature alone and provides a direct measure of $V_{sd}^{(ac)}$ [26]. Simulations that include a dc + ac source-drain voltage and typically asymmetric CB diamonds [12] show a similar skewing, as seen in Fig. 4(c).

In summary, we have measured electron dephasing in quantum dots ranging in size over a factor of 5, and observe a $AT_{el} + BT_{el}^2$ dependence of the dephasing rate with an unexplained saturation below ~100 mK. Microwave radiation applied to the dots appears to cause dephasing only by heating, presumably through modulation of the source-drain voltage. Therefore, microwave coupling of the type investigated here does not appear to explain the observed saturation. It would be interesting in future experiments to compare broadband versus monochromatic radiation [27], radiation specifically coupled to the confining gates, and far-field or cavity radiation where $E$ and $B$ are of equal amplitude.

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