Dwell-Time-Limited Coherence in Open Quantum Dots

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(Received 2 September 2004; published 13 April 2005)

We present measurements of the electron phase coherence time τ_ϕ on a wide range of open ballistic quantum dots (QDs) made from InGaAs heterostructures. The observed saturation of τ_ϕ below temperatures $0.5\ \mathrm{K} < T_{\mathrm{onset}} < 5\ \mathrm{K}$ is found to be intrinsic and related to both the size and the openings of the QDs. Combining our results with previous reports on τ_ϕ in GaAs QDs, we provide new insight into the long-standing problem of the saturation of τ_ϕ in these systems: the dwell time becomes the limiting factor for electron interference effects in QDs at low temperature.

DOI: 10.1103/PhysRevLett.94.146802 PACS numbers: 73.21.La, 03.65.Yz, 73.23.Ad, 85.35.Ds

Decoherence is at the core of many physical phenomena ranging from the largest length scales (cosmology) down to the smallest scales (particle physics), as it stems from the unavoidable coupling of quantum systems with their environment. Nanostructured electron systems are essential in the study of coherent phenomena as they can reach dimensions smaller than the coherence length of the confined electrons at low temperature (T). Electron decoherence in such mesoscopic systems has recently generated much interest and many controversies [1]. At the center of the debate is the observed, while unexpected, saturation of the electron coherence time τ_ϕ at low T.

In metal films and nanowires, there is a strong controversy on whether the observed saturation of τ_ϕ can be attributed to the presence of dilute magnetic impurities [2]. Compared to metal structures, semiconductor heterostructures grown by molecular-beam epitaxy have a much lower level of defects and are essentially free of any magnetic impurities. This makes them ideal candidates for the investigation of the intrinsic decoherence at very low T. Surprisingly, open quantum dots (QDs) fabricated from high mobility GaAs heterostructures also revealed a saturation of τ_ϕ at low T [3–7]. In these experiments, the onset of saturation was found in the range $80\ \mathrm{mK} < T_{\mathrm{onset}} < 900\ \mathrm{mK}$. As in the case of metal nanostructures, the extrinsic vs intrinsic nature of the saturation has been heavily discussed. On one hand, ending a long debate, experiments showed that the saturation is not caused by unintentional irradiation that would raise the electron temperature [5]. On the other hand, the influence of the QD mean energy-level spacing $\Delta = \frac{2\pi\hbar^2}{m^* A}$ (where A is the QD area and m^* is the electron effective mass) on T_{onset} was questioned. In some cases it was found that $\Delta \sim kT_{\mathrm{onset}}$ [4,7], but significant discrepancies with this relation were obtained in other experiments [3,5,6] and will be confirmed in this work. Surprisingly, the actual *value* of τ_ϕ in the saturated regime (τ_ϕ^{sat}), while obviously fundamental to this problem, has attracted much less attention, although Bird *et al.* [8] reported on the relation between τ_ϕ at low T and the number of channels in the leads.

In this Letter, we analyze the T dependence of τ_ϕ in a set of InGaAs QDs, covering wide ranges of Δ, average QD conductance $\langle G \rangle$, and dwell time $\tau_d = \frac{2\pi\hbar}{\Delta N}$ [9], where N is the total number of quantum channels in the quantum point contacts (QPCs) [10]. This way, we extend the data range available from the literature to a total of 2 and 3 orders of magnitude for T_{onset} and τ_ϕ^{sat}, respectively. The main result of our work is that, for all investigated QD samples, we observe $\tau_\phi^{\mathrm{sat}} \approx \tau_d$. From this, we argue that the smallest of τ_ϕ and τ_d governs electron interferences in QDs. Since the electron escape rate is already taken into account in the τ_ϕ extraction methods, the long-debated saturation of τ_ϕ is found to be intrinsic to the physics of the QDs, but not due to the coherence time of the 2D electrons themselves.

For the purpose of our study, we present data from a total of six QDs fabricated on two different InGaAs/InAlAs heterostructures, labeled A and B. Compared to heterostructure B presented in Ref. [11], heterostructure A has a larger InAlAs spacer layer (10 nm) between the delta-doped layer and the two-dimensional electron gas (2DEG), which results in a larger electron mobility μ at low T in the 2DEG. Three QDs were patterned on each wafer, A_{1-3} and B_{1-3}, using electron-beam lithography and wet etching. Table I summarizes the main parameters of our QDs. Samples A_{1-3} and B_3 were measured after high-T (30–60 K) illumination with a red light-emitting diode, which explains their higher electron density. Figures 2 and 3 provide micrographs for each QD. We measured the conductance G vs the magnetic field B of each QD using a lock-in technique in the range $0.3\ \mathrm{K} < T < 20\ \mathrm{K}$, with a source-drain voltage V across the device always less than kT/e. Under such conditions, we found the G vs B data to be independent of V.

Figure 1(a) shows G vs B in sample A_1, at 1.7 K. The observed reproducible magnetoconductance fluctuations (MCFs) are the signature of electron interferences, and hence give access to τ_ϕ. Since we are interested in the determination of the absolute value of τ_ϕ, and not just its T dependence, we consolidate our data analysis by the use of two different methods to extract τ_ϕ from the MCFs. The

TABLE I. Electron density n_s and mobility μ, QD area A (taking into account a depletion length of ~25–40 nm, inferred from conductance measurements on narrow channels), average conductance $\langle G \rangle$ (in the B range where time-reversal symmetry is broken), and exponent b (see text).

Sample	n_s [10^{16} m^{-2}]	μ [m^2/V s]	A [μm^2]	$\langle G \rangle$ [e^2/h]	b
A_1	2.4	7	0.28	2.3	1
A_2	2.4	7	0.13	2.2	1
A_3	2.4	7	0.09	1.0	1
B_1	1.0	3	0.11	1.4	1.2
B_2	1.0	3	0.13	4.0	...
B_3	2.8	3	0.09	12.0	2/3

first one is based on the random matrix theory (RMT), which links the MCF variance var(G) to τ_ϕ through the following formula [12]:

$$\mathrm{var}\,(G) = \int_0^\infty \int_0^\infty f'(E) f'(E') \mathrm{cov}(E, E') dE dE', \quad (1)$$

where E and E' are energies, $f'(E)$ is the derivative of the Fermi function, $\mathrm{cov}(E, E') = \langle G \rangle^2/[(N + N_\phi)^2 + 4\pi^2(E - E')^2/\Delta^2]$ is the conductance correlator, and $N_\phi = 2\pi\hbar/(\tau_\phi \Delta)$. var($G$) is evaluated after subtracting a slowly varying background originating from ballistic effects inside the QD (the subtraction procedure is detailed in Ref. [11]). While var(G) vs T is shown in Fig. 1(b) for sample A_1 [13], Fig. 1(c) shows τ_ϕ vs T, obtained using a numerical evaluation of Eq. (1). The observed $\tau_\phi \sim T^{-1}$ is in agreement with Nyquist electron-electron scattering [11], and with previous works, where $\tau_\phi \sim T^{-c}$ with $2/3 < c < 3/2$ was reported [3–7,11].

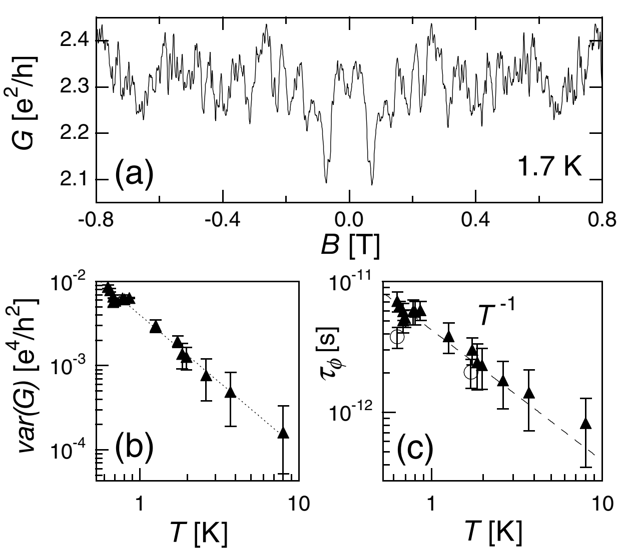

FIG. 1. (a) G vs B in A_1 at 1.7 K. (b) var(G) vs T in A_1, in the range 0.3 T $< B <$ 0.72 T. The dotted line is a fit to a $T^{-1.6}$ law. (c) τ_ϕ vs T extracted using RMT, Eq. (1) (triangles), and using the correlation field method (circles). The dashed line corresponds to $\tau_\phi \sim T^{-1}$ laws.

The second method to extract τ_ϕ is based on the high-B dependence of the MCFs [4,6]. It consists of analyzing the correlation field B_c of MCFs in a B range where the cyclotron radius is smaller than the QD diameter, so that electrons are confined to the edges of the cavity. In that range, B_c increases as the effective area for electron interferences decreases. B_c vs B is therefore directly related to τ_ϕ: $B_c(B) = 8\pi^2 m^* B/hk_F^2 \tau_\phi$ (k_F is the Fermi wave vector). Estimations of τ_ϕ obtained using both methods are in good agreement [Fig. 1(c)] [14]. Therefore, we conclude that our data analysis does not suffer from the limitations of the RMT in QDs with nonideal QPCs [15].

In order to discriminate between the possible origins of the saturation of τ_ϕ in our samples, we first investigate the effect of the QD area. With $\langle G \rangle$ close to e^2/h, both var(G) and τ_ϕ data from A_{1-3} and B_1 are presented in Fig. 2. For each QD, two temperature ranges, with distinct temperature dependences, are clearly visible. In both ranges, var(G) is well fitted by a T^{-p} law, with a smaller p in

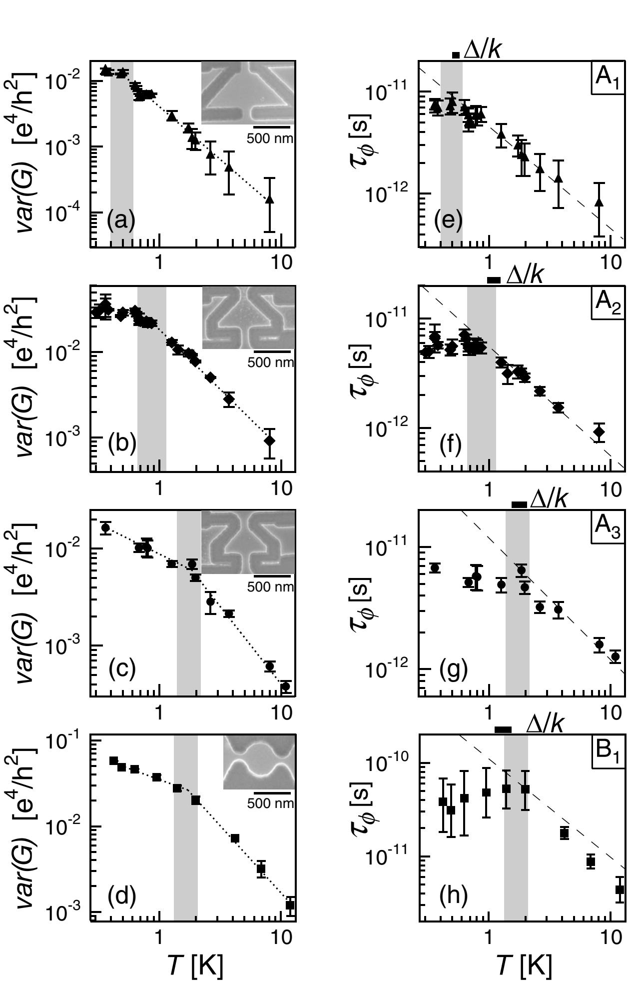

FIG. 2. (a)–(d) var(G) vs T in A_{1-3} and B_1. The shaded areas correspond to T_{onset}. Insets: samples micrographs (dark areas are etched). Dotted lines are fits to T^{-p}. (e)–(h) τ_ϕ vs T in A_{1-3} and B_1. Δ/k is indicated above each graph, with its error bar, as a black rectangle. Dashed lines: T^{-1} laws.

the low-T range. The crossing point of the two power-law fits then defines a transition temperature T_{onset} between the two regimes. Figures 2(a)–2(d) show T_{onset} with its error bar as a shaded area. It is worth noting that T_{onset} also corresponds to the onset for the saturation of τ_ϕ [as shown in Figs. 2(e)–2(h)], and increases as the QD area decreases. This result clearly shows that the saturation is neither related to the experimental setup, nor to $\langle G\rangle$, nor to the heterostructure material, since these parameters are essentially unchanged for all four samples.

More quantitatively, our data in Fig. 2 show that Δ/k matches T_{onset} very closely in samples A_{1-3} and B_1. At first sight, our data confirm some earlier reports that linked Δ and T_{onset} [4,7]. However, we will show hereafter that this rule is valid only in *some* cases and that the openings of the QDs also play a crucial role.

Based on the data presented above, samples B_2 and B_3 have been designed to present a large T_{onset} (small A) and a larger N than previous samples. The data for B_2 and B_3 (Fig. 3) show that T_{onset} reaches ~5.5 K (in B_3), much larger than in any previous report [16]. Clearly, increasing N results in a larger T_{onset}, so that two parameters (N and Δ) now have a similar influence on T_{onset}. Following these observations, it is natural to plot T_{onset} as a function of τ_d. Figure 4 gathers our data along with T_{onset} vs τ_d from previous works reporting a saturation of τ_ϕ vs T in GaAs QDs [3–6]. Clearly, T_{onset} rises when τ_d is reduced, and all data condense on a single curve, fitted by $T_{\mathrm{onset}} = 10^{-7}\tau_d^{-2/3}$ [K]. The wide range of τ_d over which this power law is observed is made possible thanks to the complementarity of our data with previous works, which focused on the large τ_d regime (small N and large A). Such a general trend, valid for QDs fabricated from different substrates and measured in different conditions, definitively rules out causes of saturation related to the wafer material or to the measurement system.

Next, we examine whether the relation between T_{onset} and τ_d is valid for QDs fabricated from any material. Recent measurements on an open bismuth QD [17] give a clue to answer this question. Based on the calculated $\tau_d \sim 8$ ps in the Bi QD, the fitted line in Fig. 4 gives $T_{\mathrm{onset}} \sim 2.5(\pm 1)$ K. The absence of any sign of saturation of τ_ϕ down to 0.3 K in the Bi QD suggests that the observed relation between T_{onset} and τ_d, while relevant for III–V heterostructure QDs, is indeed material dependent. Further support for this can be found in the dephasing theory. Whatever the dephasing mechanism, τ_ϕ vs T depends on materials parameters such as μ and n_s [1]. As we will see below, $\tau_\phi \approx \tau_d$ when $T = T_{\mathrm{onset}}$, so that τ_d vs T_{onset} is also material dependent.

In our quest for understanding the saturation of τ_ϕ, Fig. 5 is essential as it shows that τ_d is not only the relevant parameter for charting the evolution of T_{onset} in GaAs and InGaAs QDs, but also for determining τ_ϕ^{sat}. Indeed, we observe that the condition $\tau_\phi^{\mathrm{sat}} \approx \tau_d$ is satisfied over the 3 orders of magnitude covered by τ_d and τ_ϕ^{sat}. The consistency observed between the data is remarkable knowing that four different methods have been used to obtain τ_ϕ^{sat}. In the Bi QD of Ref. [17], $\tau_\phi < \tau_d$ down to the lowest measurement temperature investigated (0.3 K), which explains why a τ_d-related saturation of τ_ϕ would be observed only at lower T.

In addition to linking all previous reports on the saturation of τ_ϕ in QDs, our observation that $\tau_\phi^{\mathrm{sat}} \approx \tau_d$ gives new insight into the long-debated saturation of τ_ϕ. While more theoretical work is needed to provide a full explanation of the data in Fig. 5, we can elaborate on the possible origins of our observations. Below T_{onset}, decoherence does not occur during the time τ_d spent by electrons inside the QDs. Moreover, the escape rate is already accounted for in τ_ϕ extraction methods such as RMT. Therefore, the saturation could possibly be ascribed to a T-independent decoherence mechanism taking place in the QDs's openings. Alternatively, the saturation might originate from an abrupt change of the influence of τ_ϕ on MCFs or on the weak localization, occurring as $\tau_\phi \approx \tau_d$ [18], and altering the sensitivity of the τ_ϕ extraction methods.

In the framework of the first hypothesis, the contributions of two independent decoherence mechanisms natu-

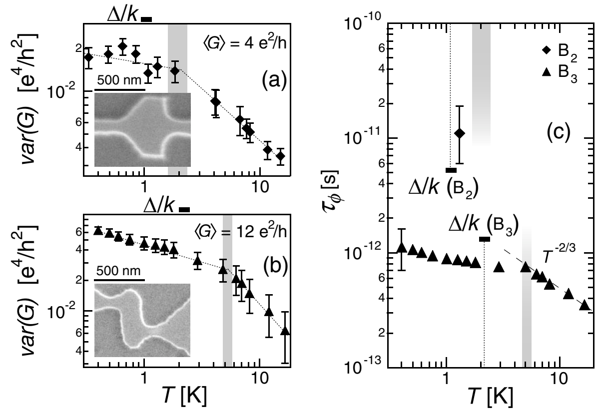

FIG. 3. (a),(b) var(G) vs T in B_2 and B_3. Insets: micrographs of the samples. (c) τ_ϕ vs T in B_2 and B_3. Dashed line: $T^{-2/3}$ law.

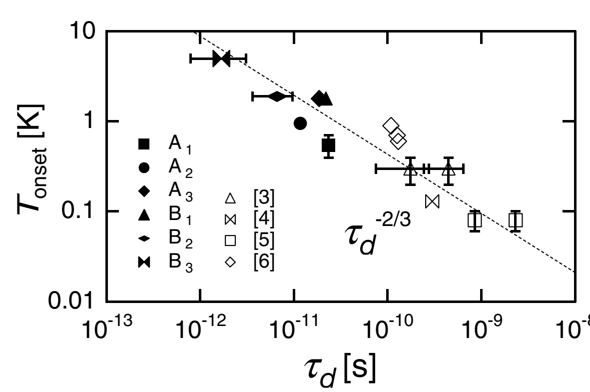

FIG. 4. T_{onset} vs τ_d in InGaAs (solid symbols) and in GaAs QDs (open symbols). The dotted line is a fit to a $\tau_d^{-2/3}$ law.

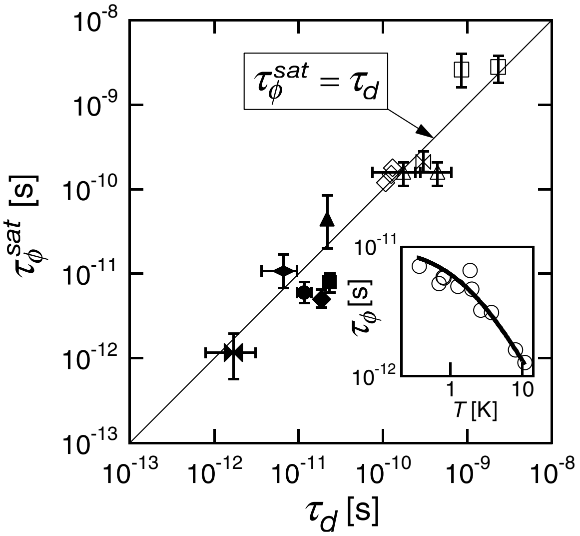

FIG. 5. $\tau_\phi^{\rm sat}$ vs τ_d (same legend as in Fig. 4). The solid line corresponds to $\tau_\phi^{\rm sat} = \tau_d$. Inset: τ_ϕ vs T in sample A_3. The solid line is a fit to Eq. (2).

rally leads one to use Matthiesen's rule [19] to derive the effective coherence time τ_ϕ in the QD:

$$\frac{1}{\tau_\phi} = \frac{1}{\tau_\phi^{\rm int}} + \frac{1}{\tau_d}, \quad (2)$$

where $\tau_\phi^{\rm int}$ corresponds to an "intrinsic" coherence time of the 2DEG, limited by phase breaking events occurring *inside* the QD (not at the openings). The inset of Fig. 5 shows that Eq. (2), together with the expression for $\tau_\phi^{\rm int} = aT^{-b}$ (the exponent b is given in Table I), provides a very good description of the data.

Finally, we emphasize that Eq. (2), valid for QDs, does not exclude a low-T saturation of $\tau_\phi^{\rm int}$. However, such a saturation could only be evidenced in QDs with a very large τ_d. In this respect, an interesting configuration is the Coulomb blockade regime where τ_d is orders of magnitude larger than in open QDs. In such nearly isolated QDs, no saturation of τ_ϕ vs T was observed [20], and very large values were found for τ_ϕ, consistent with the first explanation provided above.

In conclusion, we observe a saturation of the coherence time at low T in six different InGaAs open quantum dots. We analyze both the saturated coherence time $\tau_\phi^{\rm sat}$ and the temperature $T_{\rm onset}$ corresponding to the onset of saturation as a function of sample parameters. We find that the electron dwell time τ_d governs both $T_{\rm onset}$ and $\tau_\phi^{\rm sat}$ in our samples as well as in all previous works on GaAs QDs; i.e., the saturation of τ_ϕ vs T occurs as $\tau_\phi^{\rm sat} \approx \tau_d$. While providing new insight into the origin of the low-T saturation of τ_ϕ in open quantum dots, our observations apply to any confined electronic system.

The authors are indebted to P. W. Brouwer and R. A. Jalabert for useful discussions. This work has been supported by the FRIA (B. H., C. G., and S. F.), the European Commission (NANOTERA Project No. IST-2001-32517), and by the Belgian Science Policy through the Interuniversity Attraction Pole Program PAI (P5/1/1).

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