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Dephasing time of two-dimensional holes in GaAs open quantum dots: Magnetotransport measurements

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We report magnetotransport measurements of two-dimensional holes in open quantum dots, patterned as either a single dot or an array of dots, on a GaAs quantum well. For temperatures T below 500 mK, we observe signatures of coherent transport, namely, conductance fluctuations and weak antilocalization. From these effects, the hole dephasing time τ_ϕ together with an upper limit for the spin-orbit scattering time are extracted using the random matrix theory. The calculated τ_ϕ shows a T dependence close to T^{-2}, and its absolute value is found to be approximately one order of magnitude smaller than that reported for electrons.

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Mesoscopic systems have attracted considerable interest over the past decades since they are a potential source for novel generations of electronic devices. Within this context, semiconductor quantum dots have emerged as unique confined systems for studying spin phenomena and carriers properties such as characteristic transport times. Several research groups have focused on the dephasing time τ_ϕ and the spin-orbit relaxation time τ_{so} for electrons in quantum wires and quantum dots[1] for different materials including GaAs (Refs. 2 and 3) and InGaAs.[4,5] Up to now, only a few studies have been carried out on p-type nanostructures[6] because their experimental study is made difficult by the small amplitude of the holes' quantum interference effects. Here, we study p-type open quantum dots that provide unique insight into the coherent transport regime at low temperature T. Magnetotransport measurements display conductance fluctuations and weak antilocalization for T below ~500 mK. From these data, we deduce τ_ϕ and τ_{so} using the random matrix theory (RMT). The T dependence of the measured τ_ϕ is close to T^{-2}. Remarkably, its absolute value is approximately one order of magnitude smaller than that reported for electrons.

The samples were fabricated from a p-type GaAs quantum well grown by molecular beam epitaxy on a (311)A wafer. The two-dimensional hole system (2DHS) has a density $p=2.3\times10^{15}$ m^{-2} and a low-T mobility of 35 m^2/V s,[7] equivalent to a mean free path of 2.7 μm. The 2DHS was contacted with Be-Au Ohmic contacts. Two different dots with similar shapes but different areas[8] (1.4 μm^2 D1 and 4.5 μm^2 D2) were patterned using electron beam lithography and wet etching (inset to Fig. 1). A back gate and a Ti-Pt top gate controlled the hole density, the shape of the vertical confining potential, and to some degree the dots' openings. The measurements were performed in a dilution refrigerator with the magnetic field B applied perpendicular to the plane of the 2DHS.[9,10] The conductance of the dots was measured using a standard lock-in technique at a frequency of 15 Hz, with a current of 1 nA.

We first briefly comment on GaAs 2DHSs. In such systems, the spin-orbit interaction is strong and leads to a splitting of the valence band into heavy holes $(\text{spin}=\pm\frac{3}{2})$ and light holes $(\text{spin}=\pm\frac{1}{2})$. In the quantum well used to fabricate our samples, only the heavy hole subband is populated. Moreover, the spin-orbit interaction gives rise to a zero-magnetic-field spin splitting. The magnitude of this spin splitting can be probed by Shubnikov–de Haas (SdH) measurements.[11] In this work, we investigate two different configurations: $p=2.3\times10^{15}$ m^{-2} with an asymmetric confining potential (the frequencies measured in the SdH oscillations are 3.7 and 5.3 T), and $p=1.7\times10^{15}$ m^{-2} where the quantum well is made symmetric by means of the gate voltages (the two frequencies then merge to the same value at 3.4 T). Note that, in the latter configuration, even though the confining potential is symmetric and only one frequency is observed in the SdH data, the zero-magnetic-field spin splitting is still present.[12]

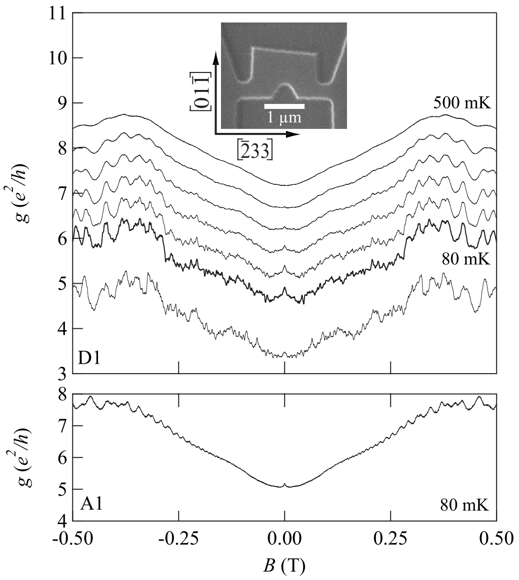

FIG. 1. Upper panel: Magnetoconductance of D1 for $p=2.3\times10^{15}$ m^{-2} at $T=80$ (bold trace), 95, 135, 200, 300, and 500 mK. For clarity, traces are shifted upward by $0.5e^2/h$. A magnetoconductance trace measured in a second cooldown is also shown and is shifted downward by $1.5e^2/h$. Inset: Scanning electron microscope picture of D1. Lower panel: Magnetoconductance of A1 for $p=2.3\times10^{15}$ m^{-2} at 80 mK.

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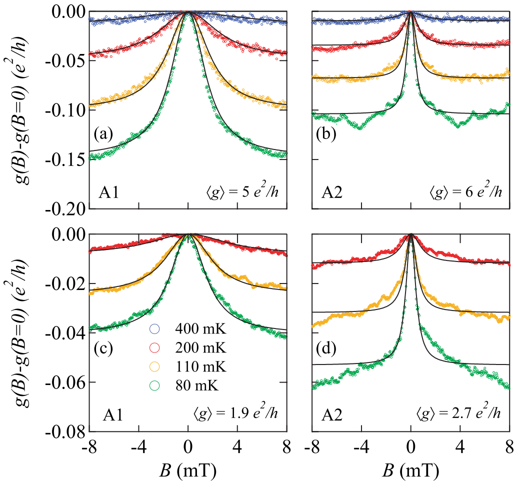

FIG. 2. (Color online) $g(B)-g(B=0)$ as a function of B at indicated temperatures for (a) A1 and (b) A2 at $p=2.3\times10^{15}$ m^{-2} as well as (c) A1 and (d) A2 at $p=1.7\times10^{15}$ m^{-2}. Solid lines show the fits of the WAL peak using the RMT. The mean conductance $\langle g\rangle$ at $B=0$ is given for each case.

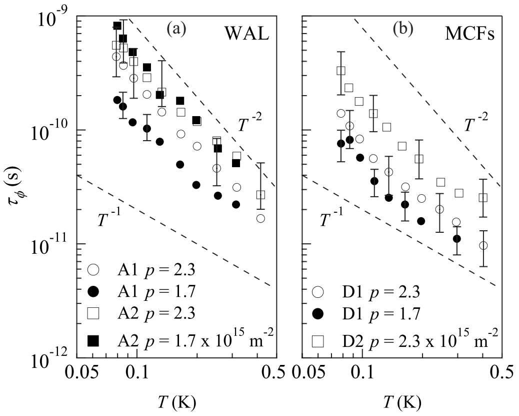

FIG. 3. Dephasing time τ_ϕ of holes as a function of T. (a) τ_ϕ extracted from the WAL correction to the conductivity in samples A1 and A2. (b) τ_ϕ calculated from the variance of the MCFs in samples D1 and D2. Open and solid symbols correspond to asymmetric and symmetric confining potentials, respectively. The dotted lines indicate various T dependencies. Error bars are determined from uncertainties in the number of modes in the quantum point contacts and in the dots areas.

We first present the magnetotransport data for the open quantum dots. The conductance g of D1 at $p=2.3\times10^{15}$ m^{-2} is plotted in the upper panel of Fig. 1 as a function of B for various temperatures. At the lowest temperatures, we observe reproducible magnetoconductance fluctuations (MCFs), symmetric with respect to $B=0$ T, that can be attributed to quantum interferences of holes inside the dot. When T is increased, these MCFs are strongly reduced in amplitude and disappear for $T\gtrsim500$ mK. At these high T's, only the slowly varying background remains, caused by ballistic effects in the cavity and the reduction of backscattering at the quantum point contacts.[13] From the mean conductance, we deduce that 5–6 modes are populated in each quantum point contact. We also note that, for $B>0.25$ T, SdH oscillations are visible in the dot's magnetoconductance traces. Similar data were obtained at $p=1.7\times10^{15}$ m^{-2} with two modes in each quantum point contact and also for D2 at $p=2.3\times10^{15}$ m^{-2} (not shown). Around $B=0$ T, a sharp peak is observed in the conductance of D1 at low T (Fig. 1, upper panel). This peak is reminiscent of the weak antilocalization (WAL) correction to the conductivity. However, the superposition of the MCFs, which are comparable in magnitude, prevents any quantitative analysis of the WAL effect. This is clearly evidenced by a comparison of the WAL peak for two different cooldowns (Fig. 1, upper panel).

In order to average out the MCFs and access the WAL correction to the conductivity,[3,14] we fabricated two additional samples made of arrays of 10×10 dots, spaced by 10 μm, with cavities similar to D1 and D2. These samples are denoted as A1 and A2 for the smaller and the larger dots, respectively. As expected, the conductance of the arrays is made of a slowly varying background, similar to that of the single dots, but without MCFs (lower panel of Fig. 1). For $T\lesssim500$ mK, a peak associated with WAL is observed in the magnetoconductance around $B=0$ T for both samples and for both investigated configurations (Fig. 2). Because the holes' trajectories enclose a smaller magnetic flux in a dot with a smaller area, the width of the WAL peak is found to be larger in the case of A1 than A2. Note that our hole WAL peaks spread over a B range approximately four times larger than in electron quantum dots with comparable areas.[14,15]

We now come to a more quantitative analysis of our data. To our knowledge, there has been no theoretical attempt to study the coherent transport of holes in quantum dots.[16] Generally, electron transport in open quantum dots is described using the random matrix theory. Although the RMT does not account for the complex band structure of GaAs hole systems under study here, it has been recently extended in order to take the spin-orbit interaction into account.[17–19] We use this framework to analyze our data and start with the study of the WAL peak that provides information on both dephasing and spin-orbit interaction in the quantum dots. We fit the WAL peak using Eq. (13) of Ref. 18 with $m^*=0.38m_e$, where m_e is the free electron mass. The fits are shown in Fig. 2 as solid curves. The three parameters of this model are τ_ϕ, τ_{so}, and c, where c is a geometrical factor. For each sample and configuration, c is determined from the fit to the lowest-T traces. We obtain values ranging from 0.03 to 0.06. The fits indicate that τ_{so} is too small ($\lesssim10^{-11}$ s) to be efficiently probed by the WAL in our samples and further confirm that the quantum dots are in a strong spin-orbit coupling regime. We therefore extract the hole τ_ϕ in the quantum dots by setting $\tau_{so}=0$ in the fits. The T dependence of τ_ϕ in samples A1 and A2 is plotted in Fig. 3(a) and is discussed below.

The analysis of the MCFs also gives a measure of the carrier dephasing time. The RMT allows us to extract τ_ϕ from the variance of the dot's conductance, var(g), according to[19]

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

where E and E' are energies, $f'(E)$ is the derivative of the Fermi function, and cov(E,E') is the conductance correlator,

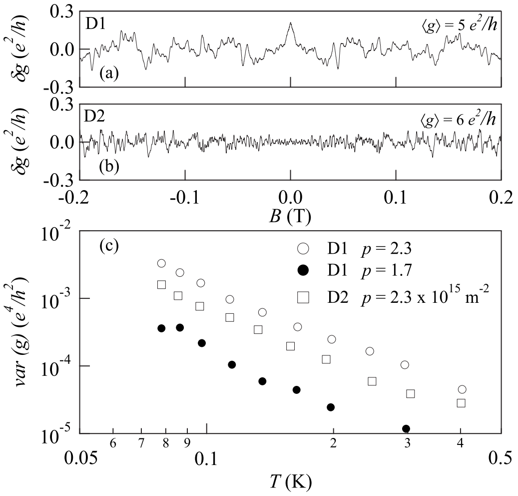

FIG. 4. Magnified view of the MCFs of (a) D1 and (b) D2 at $p = 2.3 \times 10^{15}$ m^{-2} and $T = 80$ mK after background subtraction (see text). The mean conductance $\langle g \rangle$ is calculated in the range $-0.2 < B < 0.2$ T. (c) Variance of the MCFs as a function of T for D1 and D2.

given by Eq. (29) of Ref. 19. Before calculating var(g), we isolate the MCFs from the background by applying a high-pass filter to the traces.[20] Filtered traces are shown in Fig. 4 for D1 and D2 at $p = 2.3 \times 10^{15}$ m^{-2} and $T = 80$ mK. Once the background is removed, we calculate the variance of the MCFs in the range $0.04 < B < 0.2$ T. The MCF variance is plotted in Fig. 4(c) as a function of T for D1 at $p = 2.3$ and 1.7×10^{15} m^{-2} and for D2 at $p = 2.3 \times 10^{15}$ m^{-2}. Once the MCF variance is extracted, we calculate the hole τ_ϕ using Eq. (1). As established from the analysis of WAL, we set $\tau_{so} = 0$ in the calculation. The value of τ_ϕ deduced from the MCFs is shown in Fig. 3(b) as a function of T.

The hole dephasing time determined from our data is shown in Fig. 3. In Fig. 3(a) we show τ_ϕ extracted from the fits to the WAL peak of samples A1 and A2. Figure 3(b) shows τ_ϕ deduced from the variance of samples D1 and D2. For all investigated cases τ_ϕ exhibits a T dependence that is close to T^{-2}. The dephasing time does not change significantly when the number of modes in the leads is reduced from ~6 to ~2. While values of τ_ϕ extracted from the MCF analysis are slightly smaller, the results obtained from these two different methods are in excellent agreement.[21]

By comparing τ_ϕ in our hole samples with data reported for electrons in GaAs open quantum dots,[1–3] we observe that τ_ϕ is approximately one order of magnitude smaller for holes. Generally, the expected mechanisms leading to dephasing at low T in quantum dots are carrier-carrier scattering[3] as well as geometrically related mechanisms such as the dwell-time limiting effect[5] and environmental coupling.[22] While the T^{-2} dependence of τ_ϕ in our dots can be explained within the Fermi liquid theory in terms of large-energy-transfer carrier-carrier scattering,[23] its value is expected to decrease only by a factor of ~3 for holes with respect to electrons, because of their smaller Fermi energy and lower mobility. This reduction factor does not explain the small value of τ_ϕ extracted for our quantum dots. However, Fermi liquid theory has been formulated for electrons and might not be directly applicable to 2D holes. Moreover, in 2DHSs other mechanisms such as intersubband scattering can contribute to the total hole dephasing.

We now compare τ_ϕ extracted for our dots with values measured in 2DHSs. Unfortunately, in a GaAs (311) 2DHS, the magnetoconductance around $B = 0$ originates from a combination of different factors,[24] making the extraction of τ_ϕ difficult. Nevertheless, τ_ϕ measurements have been reported for low-density (311) GaAs, as well as for (100) GaAs and InGaAs p-type quantum wells.[9,25] Extracted τ_ϕ values in these 2DHSs are consistent with τ_ϕ measured in our quantum dots. This indicates that the small value of τ_ϕ observed in our samples is likely related to scattering mechanisms in the 2DHS.

In conclusion, we performed magnetotransport measurements in holes confined to GaAs open quantum dots. We observe clear evidence of coherent transport (MCFs and WAL) inside the dots when $T < 500$ mK. Data analysis is performed within the RMT and provides a value for τ_ϕ together with an upper limit for τ_{so}. Our results demonstrate that both τ_ϕ and τ_{so} are smaller than those measured for electrons in similar systems.

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[21] An effective mass $m^* = 0.38 m_e$ (heavier heavy holes) has been used in our calculations of τ_ϕ. Using $m^* = 0.2 m_e$ (lighter heavy holes) reduces the extracted value of τ_ϕ by a factor of ~ 2 for both sets of data.

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