Effect of a perpendicular magnetic field on the zero-bias anomaly in two-dimensional electron systems

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The low-energy electronic density of states (DOS) in GaAs/AlGaAs-based two-dimensional systems is investigated at mesoscopic length scales. Using nonequilibrium magnetotransport spectroscopy we find resonances in the DOS to be extremely sensitive to perpendicular magnetic fields as small as a few millitesla and to oscillate reproducibly as a function of the field. Since these resonances (also called zero-bias anomalies) are discussed as an indication of spontaneous spin polarization at low temperature, this Brief Report demonstrates a strong sensitivity of such possible polarization to magnetic fields.

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The density of states (DOS) in low-dimensional electron systems strongly depends on the quantum confinement, leading to distinct differences between systems of different dimensions. Furthermore, electron-electron interactions can modify the DOS, for example, by creating resonances that enhance or decrease the DOS. At low temperature, such resonances have been reported in many systems and are most often probed with nonequilibrium transport spectroscopy. This spectroscopy is carried out by recording the differential conductance (dI/dV) as a function of source-drain bias V_{SD}, showing the DOS resonances as local peaks or dips in dI/dV. The resonances are visible at zero source-drain bias, which corresponds to the Fermi energy E_F, naming the resonances zero-bias anomaly (ZBA). In quantum dots such resonances are well understood and explained by Coulomb interaction or spin interaction.[1,2] Similarly, in quantum wires both confinement and electron-electron interaction lead to resonances in dI/dV in nonequilibrium transport spectroscopy. Interestingly, low-energy resonances (at low source-drain bias and temperature) centered around the Fermi energy are discussed as an indication for spontaneous spin polarization (SSP) by many-body Coulomb interaction or localized spins,[3–5] which is heavily researched in two, one, and zero dimension.

Recently, even in two dimensions, two distinctly different types of resonances in the DOS have been reported, which possibly are also connected to spontaneous spin polarization.[5–7] It was proposed that the splitting of the resonance in dI/dV in the absence of a magnetic field is closely connected to spontaneous polarization of conduction electrons, making nonequilibrium transport spectroscopy an excellent tool to investigate SSP. Several studies on the behavior of zero-bias anomalies have since been carried out, analyzing many of their characteristics. However, its sensitivity to perpendicular magnetic field has not been probed yet.

In this Brief Report we demonstrate a striking and unexpected coupling of perpendicular magnetic fields to the low-energy DOS of two-dimensional (2D) conduction electrons in GaAs/AlGaAs heterostructures. With nonequilibrium magnetoconductance spectroscopy we show that the DOS changes rapidly as a function of perpendicular magnetic field ($B_\perp$) on a scale of only ≈ 5 mT. We demonstrate that these DOS fluctuations are coupled to Aharonov-Bohm (AB)-type oscillations, which is counterintuitive because the zero (weak)-field DOS in a 2D nonmagnetic system is generally expected to change by strong localization or by Coulomb interactions, but not by interference.

Perpendicular field nonequilibrium magnetoconductance spectroscopy is used to probe the DOS in $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructures with the 2D electron gas (2DEG) located 300 nm below the surface. Silicon δ doping with $n_{Si}=0.7-2.5\times10^{12}$ cm^{-2} and a 60–80 nm spacer between the 2DEG and silicon layer results in an as-grown electron density of $n_{2D}=1-1.5\times10^{11}$ cm^{-2} with mobilities $\mu=1-3\times10^{6}$ cm^2/V s. Nonmagnetic titanium/gold gates are thermally deposited on the surface in a layout shown in Figs. 1(a) and 1(b). Voltage V_C is fixed at a value between −0.8 to −1.0 V for the duration of the experiment and depletes electrons underneath the gate, thereby defining an 8-μm-wide mesa electrostatically. The voltage on the center gate (V_G) varies n_{2D} and the Fermi energy E_F in the active 2×8 μm^2 region of the device with operating electron densities $n_{2D}=0.5-2\times10^{10}$ cm^{-2}. Figure 1(c) shows a typical linear conductance $G(V_G)$ trace for such systems at $T=40$ mK and in the absence of a magnetic field.

A two-probe ac+dc technique with ac voltage $V_{ac}\ll k_BT$ is used to measure the differential conductance dI/dV of the active region, thereby probing the DOS.[6,7] In the absence of a magnetic field, dI/dV reveals two types of resonances at $V_{SD}=0$. Depending on E_F, either a single resonance (type-I ZBA) or a split resonance (type-II ZBA) in the nonequilibrium transport spectroscopy is observed. As E_F is varied with voltage V_G, the type of resonance interchanges periodically as shown in Fig. 1(d). The oscillatory modulation of the resonance type with E_F can also be demonstrated by plotting the half width at half maximum of the type-II ZBA splitting (referred to as Δ) as a function of n_{2D}.[7]

To investigate the magnetoconductance, a magnetic field is applied perpendicular to the plane of the 2DEG and the appearance of the resonance is recorded for increasing field strength. Both V_G and V_C are kept constant for each experiment so that only $B_\perp$ is varied for each graph, respectively (Figs. 2–4). The upper field limit is 100 mT to ensure that Landau-level spacing is small enough to ignore quantum

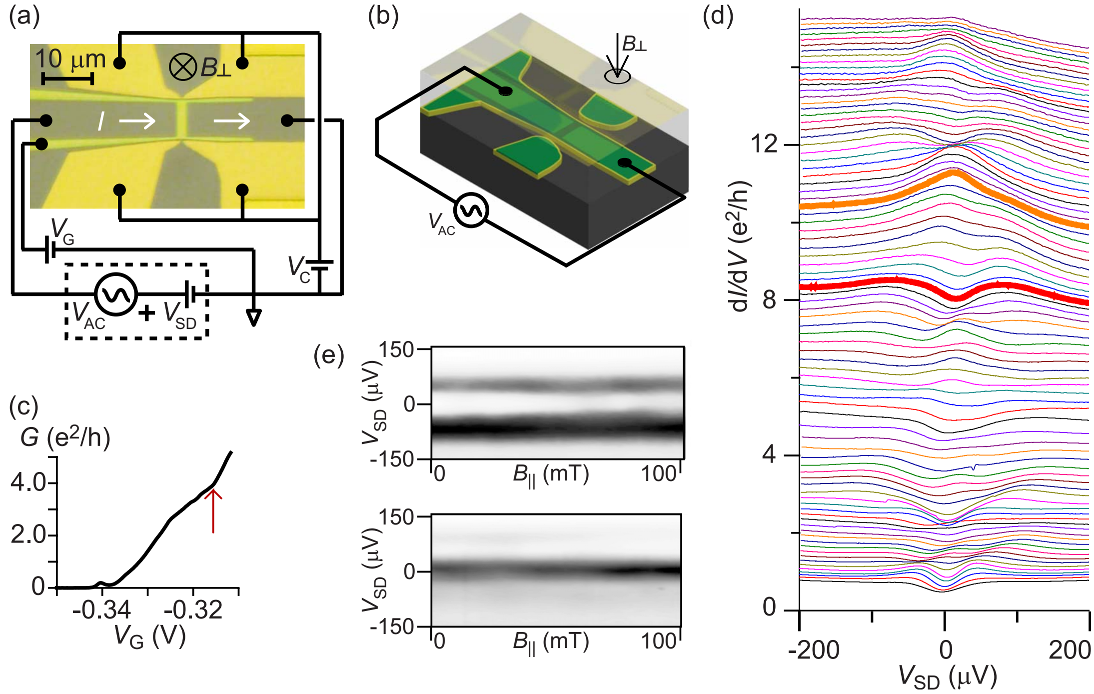

FIG. 1. (Color online) (a) Optical microscope image of a typical 2×8 μm^2 device, showing electrical setup. (b) Three dimensional illustration showing ac setup. The 2DEG and the active area for applied gate voltages is shown in green (gray) and dark green (dark gray), respectively. (c) Conductance G as a function of V_G for a typical device. (d) $dI/dV(V_{SD})$ over a range of n_{2D} (low n_{2D} at lower G). Two types of resonances are visible at E_F: a single peaked and a split peaked. (e) Dependence of type-I ZBA (bottom) and type-II ZBA (top) on parallel magnetic field up to 100 mT. Both show no field dependence. Black is high dI/dV while white is low dI/dV.

Hall physics. To cancel the effect of the magnetic field on the series resistance of the macroscopic 2DEG, individual V_{SD} traces at constant fields are vertically shifted.

In Fig. 2(a), a surface plot of dI/dV for a type-II resonance with $\Delta\approx 25$ μeV is shown in a perpendicular magnetic field up to 40 mT and at $n_{2D}=1.55\times 10^{10}$ cm^{-2}. The white lines are a guide to the eye and demonstrate that not only the linear conductance but also the splitting magnitude Δ is modulated. The modulation has a periodicity $\delta B_\perp \approx 9-10$ mT and indicates a periodic fluctuation of the DOS in the mesoscopic region. In Fig. 2(b), this is further clarified by individual DOS resonances at various values of $B_\perp$. The periodic modulation of Δ is only observed for $B_\perp \lesssim 50$ mT and becomes significantly more complex and chaotic for higher fields. This is shown in the surface plot of Fig. 2(c) for a field up to 100 mT. Remarkable also is the amplitude of the modulation of Δ (see Fig. 3). The graph on the top shows $G(B_\perp)$ and the bottom graph shows $\Delta(B_\perp)$ for the same field

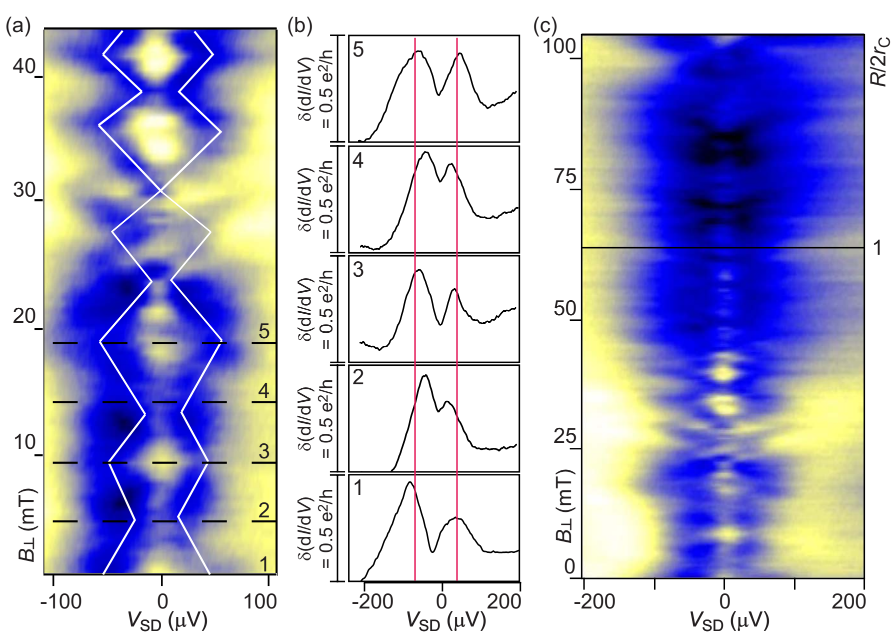

FIG. 2. (Color online) (a) $dI/dV(V_{SD},B_\perp)$ of type-II ZBA in low $B_\perp$ shows a modulation with period $\delta B_\perp\approx 9-10$ mT. White line: guide to the eye. Blue (black) is high dI/dV while white is low dI/dV. (b) Individual traces at fields indicated in Fig. 2(a). (c) Perpendicular field dependence at the same electron density up to $B_\perp=105$ mT. The black line indicates the commensurability condition $2r_C=R$. Blue (black) is high dI/dV while white is low dI/dV.

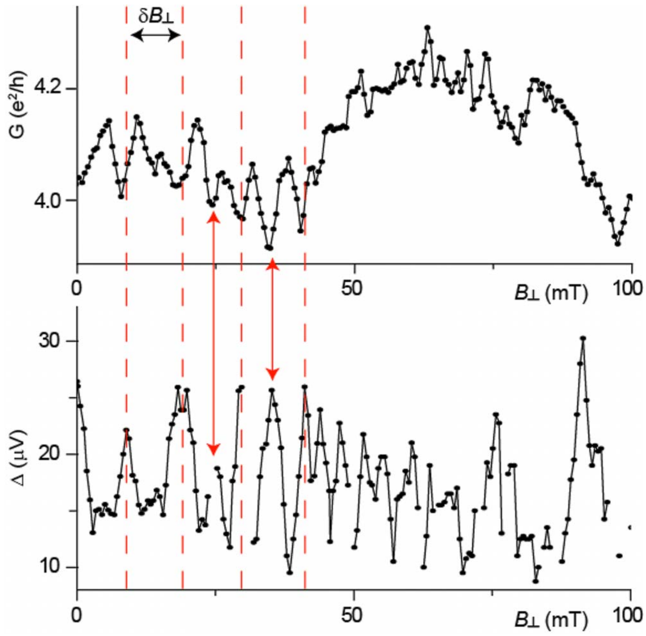

FIG. 3. (Color online) Top: $G(B_\perp)$ shows periodic modulation with period $\delta B_\perp$. Bottom: Δ shows a modulation with same period. For increasing fields, AAS-type effects at half the period set in and become stronger with increasing field (arrows). At higher fields the periodicity vanishes.

axis up to $B_\perp = 100$ mT. Minima in the linear magnetoconductance fall on the same fields as maxima in Δ. However, the amplitude of the oscillation is strikingly different. The modulation of G is maximal $\approx 5\%$, while the modulation of Δ is typically about 50%, a factor of 10 stronger. A second feature is observed in Fig. 3. In an intermediate field range $B_\perp \approx 10-50$ mT, double frequency oscillations can be observed as peaks in Δ (or minima in G) that appear midway between the AB-type resonances. These are indicated by vertical arrows in Fig. 3 but can also be seen in the surface plots.

To understand the origin of resonance behavior, we first confirm that the oscillation of Δ as a function of $B_\perp$ is an effect arising from the orbital phase of the conduction electrons. dI/dV's for both type-I and type-II resonances in a magnetic field parallel to the direction of the current and up to $B_\parallel = 100$ mT are shown in Fig. 1(e). No modulation of either resonance can be seen, confirming that the modulation arises from perpendicular magnetic fields. Second, we consider possible origins of the resonance itself. Several mechanisms can influence the DOS, for example, Coulomb interaction leads to an exchange correction $\propto \sqrt{n_{2D}}$ within the Hartree-Fock model. However, while this modifies the DOS, it leads to a smooth and monotonic correction[8] contrary to the fluctuating n_{2D} dependence observed in our experiments. Furthermore, spontaneous spin fluctuations and ferromagnetic instabilities in low-density mesoscopic systems may lead to magnetic behavior;[9] but our experiments are mostly carried out at densities far away from the strongly localized regime, where these effects are expected to be small. Another possible origin for resonances is the formation of one or more quantum dots by disorder in the mesoscopic region. To investigate such a possibility, the characteristic energies of Coulomb blockade diamonds are calculated. The charging energy of a quantum dot depends on its capacitance, which is $C = 8\epsilon_0\epsilon_r r$,[10] leading to the charging energy[11] $U_{\text{charging}} = e^2/8\epsilon_0\epsilon_r r$ with a dot radius r. The observed peaks in the differential conductance at $eV_{\text{SD}} \approx \pm 50$ μeV then correspond to $U_{\text{charging}} \approx \pm 50$ μeV and thus to a dot area $\pi r^2 \approx 40$ μm^2. However, such an area is too large to be embedded in the mesoscopic 2×8 μm^2 device. Moreover, it also far exceeds the Fermi wavelength $\lambda_F = 2\pi/k_F \approx 0.25$ μm, making a dot of this size too large for the observation of quantum effects.

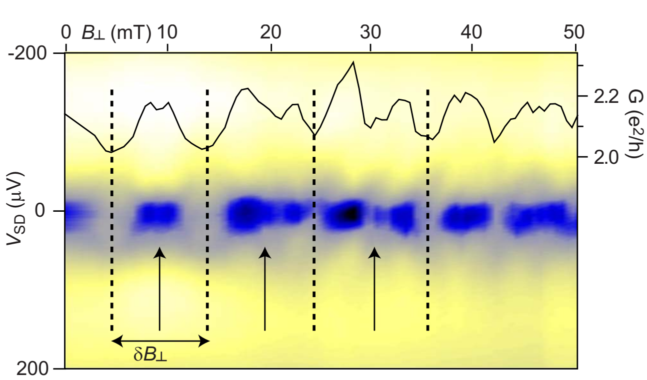

FIG. 4. (Color online) For type-I ZBA, low $B_\perp$ does not change Δ. However, G is periodically suppressed with period $\delta B_\perp$ by AB-type effects and, for increasing fields, AAS-type effects at half the period become stronger (arrows). Blue (black) is high dI/dV while white is low dI/dV.

While this demonstrates that Coulomb blockade is not the origin of the resonances, the existence of a quantum dot can lead to a Kondo resonance in the DOS if the dot was occupied by an unpaired electron. The position of the resonance in nonequilibrium transport spectroscopy is then determined by Kondo physics and not by Coulomb interaction. The Kondo resonance can also appear if several smaller quantum dots were formed in the mesoscopic region, for example, by disorder. Such a model of disorder-localized spins can explain the appearance of the DOS resonances with the observed energies and has been proposed previously.[7] It is further supported by the disorder-dependent behavior of the resonances—about 25% of electron densities display no periodic modulation of Δ with $B_\perp$ (not shown). However, although the Kondo effect is discussed for disorder-formed localized spins,[6] it alone cannot explain all observations. The Kondo effect is a local effect at the site of localized spins and, thus, it is not affected by the conduction-electron orbital phase or small perpendicular magnetic fields. However, for several localized spins, indirect magnetic exchange interaction can set in, which is a nonlocal effect.[4,7,12] The exchange interaction between such spins with distance R from each other is mediated by Friedel oscillations. The nature and strength of the interaction J depends on the conduction-electron density and can be affected by $B_\perp$.[13,14] Theoretical models describe the dependence of J on $B_\perp$ for two extreme cases: (1) chaotic electron trajectories in irregularly enclosed regions[13] and (2) two localized spins interacting along an AB ring.[14] In both cases the magnitude of J shows an oscillatory dependence on the enclosed magnetic flux Φ, which is random in the first case and regular in the latter. For low $B_\perp$ ($\lesssim 50$ mT), the observed oscillations are regular; so, it will be analyzed whether the AB-ring model can be employed for the explanation of the results. For such a model, $\Delta \propto |J|$ is expected to vary in $B_\perp$ according to[14–16]

$$J(\Phi) \propto J(\Phi = 0)\left[2 + 2\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)\right] \tag{1}$$

with the magnetic flux Φ and the flux quantum $\Phi_0 = h/e$. The period of the observed oscillation is $\delta B_\perp \approx 9-10$ mT, which provides an estimate of $R \approx \sqrt{\Phi_0/\delta B_\perp} = 650$ nm, in excellent agreement with that reported recently,[7] suggesting that the AB-ring model can be used to describe the observations.

The validity of the model is further supported by the analysis of the field dependence of type-I ZBAs. When the spins are noninteracting, i.e., $\Delta \propto |J| \approx 0$, the spin effects are local and Δ is expected to be insensitive to $B_\perp$. This is expressed in Eq. (1) by $J(\Phi)=0$ for all Φ if $J(\Phi=0)=0$. Such behavior is confirmed in Fig. 4, a nonequilibrium magnetotransport spectroscopy of type-I ZBA, where no field modulation of Δ is observed. Nonetheless, the field still modulates $G(B_\perp)$, which can be identified as AB-type interference that is expected in 2D regions with quasiregular potential fluctuations.[7,17,18] These oscillations are, however, distinctly different from the $\Delta(B_\perp)$ oscillations—while the $G(B_\perp)$ oscillations are a pure interference effect, the Δ oscillations represent a modulation of the exchange interaction J. Such modulation affects any possible spin polarization and magnetic interaction between localized spins.

The observations thus reinforce the previously proposed model of a quasiperiodic arrangement of localized spins in the mesoscopic region possibly arising from conduction-band fluctuations and leading to spontaneous spin polarization by indirect exchange interaction. Moreover, the results demonstrate a yet unknown sensitivity of the resulting DOS resonances to magnetic fields, allowing for the field tunability of the exchange interaction strength. The model is also supported by the previously mentioned additional peaks in Δ (or minima in G), appearing midway between the AB-type resonances at intermediate field strengths, as demonstrated by vertical arrows in Figs. 3 and 4. In a system with quasiregular potential fluctuations, these can be identified as Al'tshuler-Aronov-Spivak (AAS)-type oscillations with a $\delta B_\perp$ period corresponding to a variation of Φ by $h/2e$.[18,19] At higher fields, above the commensurability condition ($R = 2\hbar k_F/eB_\perp$, the black line in Fig. 2(c) at $B_\perp \approx 65$ mT), the regularity of the oscillation is suppressed. Such commensurability dependence of AB-type oscillations has been observed before in systems with regular conduction-band fluctuations.[15,20]

In summary, we present nonequilibrium transport spectroscopy of mesoscopic 2DEGs in low perpendicular magnetic fields and at low temperature. We demonstrate that resonances in the density of states are extremely sensitive to the strength of an external field. As these ZBAs are believed to be connected to spontaneous spin polarization, the observations indicate that even tiny external fields could directly affect the degree of such polarization.

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