Shubnikov–de Haas–like Quantum Oscillations in Artificial One-Dimensional $LaAlO_3/SrTiO_3$ Electron Channels

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The widely reported magnetoresistance oscillations in $LaAlO_3/SrTiO_3$ heterostructures have invariably been attributed to the Shubnikov–de Haas (SdH) effect, despite a pronounced inconsistency with low-field Hall resistance measurements. Here we report SdH-like resistance oscillations in quasi-1D electron waveguides created at the $LaAlO_3/SrTiO_3$ interface by conductive atomic force microscopy lithography. These oscillations can be directly attributed to magnetic depopulation of magnetoelectric subbands. Our results suggest that the SdH oscillations in 2D $SrTiO_3$-based systems may originate from naturally forming quasi-1D channels.

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$SrTiO_3$-based interfaces, and, in particular, the $LaAlO_3/SrTiO_3$ (LAO/STO) interface [1], combine the motif of semiconductor heterostructures such as GaAs/AlGaAs, with the wide-ranging physical phenomena of complex oxides. The LAO/STO system exhibits a wide range of gate-tunable phenomena, including superconductivity [2,3], magnetism [4], spin-orbit coupling [5,6], and electron pairing without superconductivity [7]. Transport at LAO/STO interfaces is complicated by a ferroelastic transition within STO at $T = 105$ K [8,9]. A variety of local probe methods have documented how ferroelastic domains strongly break translational invariance and favor highly anisotropic transport along ferroelastic domain boundaries [10–13].

Given the relatively high carrier densities of oxide heterostructures, prospects for achieving quantum Hall phases under reasonable laboratory conditions appear remote. The electron density of STO-based heterostructures is approximately 2 orders of magnitude higher ($n_{2D} \sim 10^{13}$–10^{14} cm^{-2}) than typical III–V heterostructures, while the electron mobility is significantly lower ($\mu \sim 10^3$–10^4 cm^2/V s). A typical carrier density at the 2D LAO/STO interface is $n_{2D} = 5 \times 10^{13}$ cm^{-2}, nearly a half electron every nm^2, with 100 filled Landau levels is expected for a typical laboratory-achievable magnetic field $B = 10$ T.

Despite the low mobility, STO-based heterostructures show distinctive features of quantum transport. The most striking signature is quantum oscillations, which have been widely attributed to the Shubnikov–de Haas (SdH) effect, a precursor to the integer quantum Hall effect. The frequency and temperature dependence of SdH oscillations reveal critical information about the electron density, carrier mobility, quantum scattering time, and effective mass [14]. For the STO-based systems, SdH oscillations have been extensively reported [15–28]. However, major discrepancies have been observed among all the reports in the literature, as summarized below.

i) The carrier density extracted from SdH oscillations ($n_{2D}^{SdH} \sim 10^{12}$ cm^{-2}) is significantly lower than what is determined by low-field Hall measurements ($n_{2D}^{Hall} \sim 10^{13}$–$10^{14}$ cm^{-2}). Values of $n_{2D}^{Hall}/n_{2D}^{SdH}$ can range from slightly over 1 [29] to 25 [18] for δ-doped STO.

ii) The number of distinct SdH frequencies for a given device is found to vary from one [15,17,19] to four [24], with considerable variation in the effective mass of the high-mobility carriers. The corresponding band assignment also ranges from d_{xy} orbital [21] to d_{xz}/d_{yz} orbital [27] to hybridization of the two orbitals [24].

In short, the overall phenomenology of SdH oscillations is widely reported; however, there is a lack of internal consistency among quantitative values for $n_{2D}^{Hall}/n_{2D}^{SdH}$ or agreed explanation for the discrepancies is still lacking. Disagreements between n_{2D}^{Hall} and n_{2D}^{SdH} of more than a few percent in III–V semiconductor heterostructures are unusual. The large and variable deviations in expected values for $n_{2D}^{Hall}/n_{2D}^{SdH}$ have not been satisfactorily explained.

Here we report SdH-like quantum oscillations in an artificial quasi-1D electron channel formed at the LAO/STO interface. As a function of magnetic field and electrical gating, we observe a transition between quasi-1D and quasi-2D behavior and extract characteristic parameters such as the carrier density and width. These electron waveguides exhibit clean ballistic transport at carrier densities as low as 320 μm^{-1} (or equivalently 8×10^{11} cm^{-2} by considering 40 nm characteristic width), significantly lower than what has been reported for bulk 2D heterostructures. The magnetotransport shows characteristic SdH-like oscillations that arise due to magnetic depopulation of the magnetoelectric subbands within the quasi-1D channel. All the carriers can be fully accounted for due to the observation of conductance quantization, unlike the 2D case, where carrier-density measurements of SdH oscillations and Hall effect disagree. We compare the well-understood electron transport within these artificial electron waveguides with naturally formed channels that have been found to arise at ferroelastic domain boundaries and suggest that previously reported SdH oscillations are in fact manifestations of naturally formed quasi-1D channels.

The electron waveguides are fabricated using conductive atomic force microscopy (cAFM) lithography at the LAO/STO interface, as described in Ref. [30]. Starting from an insulating 3.4-unit-cell-LAO/STO interface, nanoscale conducting paths can be "written" through a surface protonation process [31,32]. Tunnel barriers or insulating regions are created through an "erasure" procedure involving surface deprotonation. Novel properties such as electron pairing without superconductivity [7] and tunable electron-electron interactions [33] have previously been revealed by studying quantum transport in similarly designed nanostructures.

Figure 1(a) shows a schematic of the overall device structure. The electron waveguide consists of a 50-nm-long linear segment surrounded by two narrow insulating barriers, coupled to source and drain electrodes. The electron density within the waveguide depends on the side-gate voltage V_{sg} and the overall electrostatic confinement produced by the cAFM writing process. In the regime considered here, the cyclotron frequency $\omega_c = e|B|/m_e^*$ is greater than the characteristic frequency of lateral confinement ω_y ($\omega_c > \omega_y$) in magnetic fields ($B > \sim 3$ T), where e and m_e^* are electron charge and effective mass.

Well-resolved magnetoresistance oscillations are observed at higher magnetic fields over a range of gate voltages $V_{sg} \sim 0$–100 mV; one such example appears in Fig. 1(b). Following the analysis of previous reports [15–24,26–28], we subtract a smooth background to reveal resistance oscillations that are clearly visible and periodic in $1/B$ [Fig. 1(c)]. A Fourier analysis shows a sharp peak at 26 T with a smaller secondary peak at 7 T.

The magnetoresistance oscillations clearly resemble the SdH effect; however, for an electron waveguide, it is more appropriate to consider the total conductance, which can be subject to Landauer quantization in the ballistic regime. Within this framework, the conductance is given by

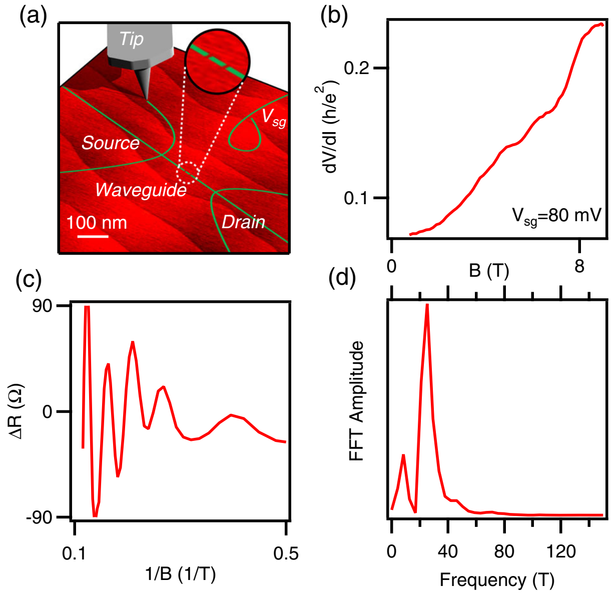

FIG. 1. The magnetoresistance of an electron waveguide. (a) Schematics of the electron waveguide. (b) The magnetoresistance at $V_{sg} = 80$ mV. (c) SdH-like oscillations after subtracting a smooth background from (b). (d) FFT analysis shows two distinct peaks.

$G = (e^2/h)\sum_i T_i(\mu)$, whereby each energy subband that is occupied (at a given chemical potential μ) contributes e^2/h [with transmission probability $T_i(\mu)$] to the overall conductance G [34]. Within this framework, the conductance increases in steps of e^2/h every time the chemical potential crosses a subband energy minimum. Magnetic fields can depopulate these subbands, leading to an overall decrease in conductance with increasing field strength. Figure 2(a) shows the same data as Fig. 1, plotted as conductance in units of e^2/h, as a function of V_{sg}. Clear conductance steps are observed, while the overall slope decreases with increasing magnetic field. The conductance versus magnetic field at fixed gate voltage [Fig. 2(b)] shows quantization at integer values of e^2/h, with "oscillations" occurring as magnetoelectric subbands are depopulated with increasing field strength. The energy spacing $\hbar\omega$ in a magnetic field, where $\omega = \sqrt{\omega_c^2 + \omega_y^2}$, is dominated by Landau level spacing $\hbar\omega_c$ in the regime where $\omega_c \gg \omega_y$. With increasing magnetic field, the occupation of the subbands is gradually depopulated as $\hbar\omega$ grows [Fig. 2(b)]. For example, at $V_{sg} = 60$ mV, the number of occupied subbands is reduced from 10 to 3 by increasing the B field from 0 to 9 T. Finite source-drain bias (V_{sd}) spectroscopy [Fig. 2(c)] at $B = 9$ T shows clustering of I-V curves and half-plateaus, which provide yet another confirmation of ballistic electron transport.

In 2D electron systems, Landau levels form flat bands; the condition to completely fill level n satisfies $n = (\pi\hbar/|e|B)n_{2D}$, which yields $n \propto 1/B$. In a quasi-1D

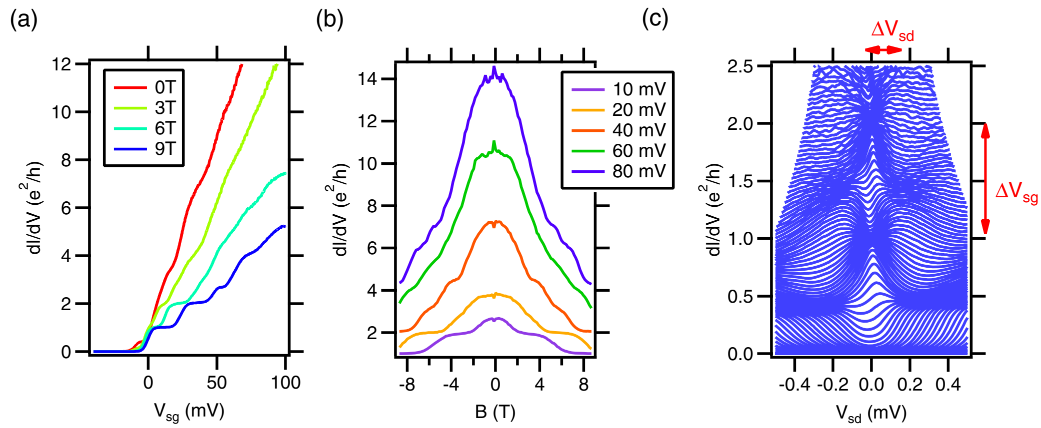

FIG. 2. Magnetic depopulation effect of the electron waveguide. (a) Differential conductance dependence on V_{sg} in various magnetic fields $B = 0$, 3, 6, and 9 T. Full conductance quantization is observed at high magnetic fields. (b) Magnetic depopulation for various V_{sg} (10–80 mV). For a fixed V_{sg}, the number of occupied magnetoelectric bands decreases with increasing magnetic fields, signifying magnetic depopulation effect. (c) Finite-bias spectroscopy at 9 T. Differential I-V curves ranging from $V_{\mathrm{sg}} = -10$ to 60 mV are clustering together where conductance is quantized. The arrows indicate the parameters ($\Delta V_{\mathrm{sd}} \sim 0.22$ mV, $\Delta V_{\mathrm{sg}} \sim 25.2$ mV) to extract the lever arm $\alpha = e\Delta V_{\mathrm{sd}}/\Delta V_{\mathrm{sg}} = 0.009$ eV$/V$.

electron waveguide, however, lateral confinement causes the magnetoelectric subbands to exhibit a parabolic shape. The filling of the nth subband is given by [35]

$$n \approx c\left(\frac{n_{2\mathrm{D}}}{l_y}\right)^{\frac{2}{3}} \omega_y^{\frac{2}{3}}/\omega, \tag{1}$$

where $c = (\frac{3}{4}\pi)^{\frac{3}{2}}(\hbar/2m_e^*)^{\frac{1}{3}}$ is a constant and l_y is the characteristic width of the electron waveguide, which determines the lateral confinement $\omega_y = (\hbar/m_e^* l_y^2)$. From Eq. (1), it is clear that the dependence of n on $1/B$ is nonlinear in low magnetic fields and crosses over to a linear regime as $\omega \to \omega_c$ in high magnetic fields. By fitting Eq. (1), it is possible to extract key electron waveguide parameters, including the effective 2D carrier density $n_{2\mathrm{D}}$ and width l_y. At higher densities, population of higher-energy vertical waveguide modes is expected, leading to a new series of SdH oscillations, one for each vertical subband.

The subband index n_i is assigned by referencing the resistance minima after subtracting a smooth background in varying magnetic field and V_{sg}, as shown in Fig. 3. Generally, the waveguide width increases with increasing V_{sg}. The lateral confinement frequency ω_y is large for small V_{sg}, leading to a saturation in the number (~3 in $V_{\mathrm{sg}} = 10$ mV) of depopulated subbands in 0–9 T B field range, compared to the high V_{sg} case (~7 in $V_{\mathrm{sg}} = 60$ mV). Figure 3(b) shows the dependence of n_i on $1/B$. Indeed, the relationship is linear at higher magnetic fields and highly nonlinear at low magnetic fields, suggesting a crossover between 2D and 1D in the electron waveguide when tuning the magnetic field.

Fitting to Eq. (1) shows good agreement with data [Fig. 3(b)]. The effective 2D carrier density increases from $n_{2\mathrm{D}} = 8 \times 10^{11}$ to 2.4×10^{12} cm^{-2} as the gate voltage is increased from $V_{\mathrm{sg}} = 20$ to 100 mV (Fig. 4). It is worth noting that the electron density is 1 order of magnitude lower than what is typically reported for 2D interfaces and 2 orders of magnitude lower than what is predicted for the "polar catastrophe" model.

More insights into the electronic properties of the interface can be obtained from the transconductance map dG/dV_{sd} [Fig. 3(c)], which shows the subband structure. The lateral confinement energies $E_y = \hbar\omega_y \sim 100$ μeV and $E_z = \hbar\omega_z \sim 500$ μeV can be readily read-out. Since the confinement frequency $\omega_{y,z} = (\hbar/m_{y,z}^* l_{y,z}^2)$, the in-plane effective mass $m_y^* = 0.5m_e$ and out-of-plane effective mass $m_z^* = 2.4m_e$ can be extracted by taking $l_y = 40$ nm at $V_{\mathrm{sg}} = 20$ mV and a typical $l_z = 8$ nm [30], where m_e is the free electron mass. Other parameters, including the pairing strength and g factor, can be also routinely extracted [30].

The phenomena of SdH-like oscillations observed in artificially constructed quasi-1D waveguides bears a remarkable resemblance to many reports of SdH oscillations at the 2D LAO/STO interface. We propose that SdH oscillations reported for the 2D LAO/STO interface can also be accounted for by 1D transport. The ferroelastic domain patterns that have been revealed by various imaging techniques, including scanning superconducting quantum interference device microscopy [11], scanning single-electron transistor microscopy [10], and low-temperature scanning electron microscopy [12], points to a highly inhomogeneous landscape that is markedly different from analogous III–V semiconductor heterostructures. It is quite plausible that the transport along these ferroelastic domain boundaries may be significantly more ballistic than previously assumed. In that case, naturally forming ferroelastic domain walls would spontaneously lead to transport behavior that may vary from one device to another and

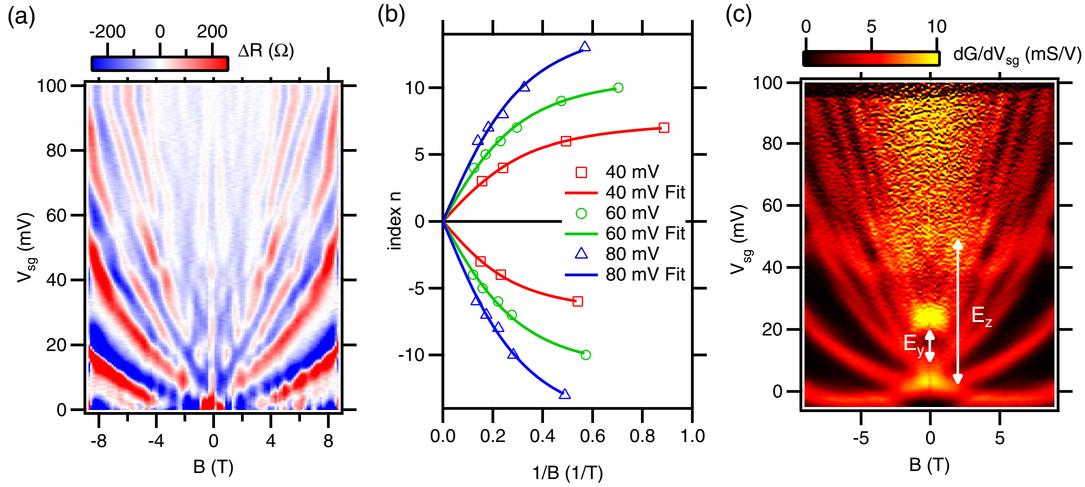

FIG. 3. Tunable magnetoelectric subbands. (a) Resistance oscillations after subtracting a smooth background. (b) Subband index versus $1/B$ for $V_{sg} = 40$ (red), 60 (green), and 80 mV (blue). Solid lines are fitting results. The subband indices are extracted by looking at the resistance minimum of (a). (c) Transconductance map showing lateral and vertical confinement energies $E_y \sim 100$ μeV (at $V_{sg} = 20$ mV) and $E_z \sim 500$ μeV (between the first two vertical bands), respectively.

from one cooldown to another. Furthermore, inhomogeneous broadening of SdH oscillations would be expected if there are spatial variations in lateral confinements.

Inconsistencies in the number of distinct SdH oscillation frequencies among different reports can be understood by recognizing that electron waveguides can support both vertical and lateral modes. Analysis of a waveguide under harmonic lateral and vertical confinement [30] reveals a family of modes, each of which is expected to yield SdH-like quantum oscillations, with one distinct frequency for each vertical mode. For example, Fig. 1(d) shows two distinct frequencies.

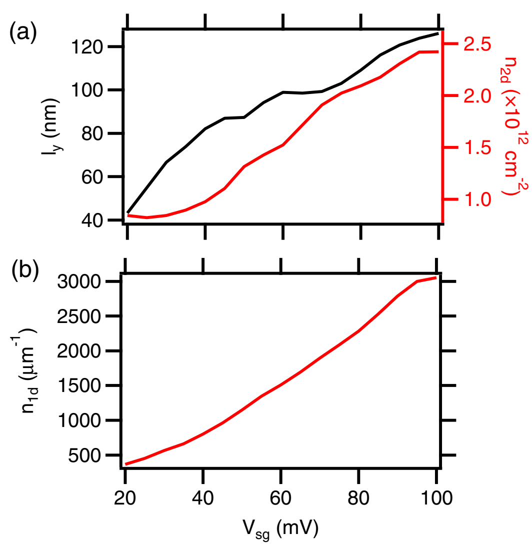

FIG. 4. Fitting results. (a) Extracted 2D carrier density and characteristic width of the waveguide. (b) Corresponding linear carrier density dependent on V_{sg}.

The discrepancy in carrier-density measurements between SdH oscillations and Hall measurements has been attributed to a number of factors at the 2D LAO/STO interface. For example, it has been suggested that coexisting high- and low-mobility carriers occupy different Ti d orbitals or multiple subbands [27]. However, SdH oscillations with a single frequency have been reported below the critical density (1.6×10^{13} cm^{-2}) of Lifshitz transition [36], where only the d_{xy} orbital is supposed to be occupied [17]; in that work, $n_{2D}^{Hall}/n_{2D}^{SdH} \sim 5$. In the work reported here, the carrier density extracted by magnetic depopulation is consistent with the SdH oscillation measurement in the literature ($n_{2D}^{SdH} \sim 10^{12}$ cm^{-2}). Furthermore, all of the carriers are accounted for since full conductance quantization is observed; i.e., there is no discrepancy in the carrier-density measurements.

To extend the applicability of these results in a single nanowire to the more complex geometry in most 2D experiments, one needs to consider how an ensemble of ferroelastic domains would influence 2D transport. Overall, there is growing evidence that 1D channels have anomalously high mobility [37] and are ballistic on micrometer scales [38]. Recent work by Frenkel *et al.* [13] indicate that anisotropic flow in a 100-μm-scale device can be as large as 50% at low temperature. Devices such as these are expected to exhibit quasiballistic transport along ferroelastic domain boundaries and, therefore, will be subject to resistance oscillations associated with magnetic depopulation of 1D subbands. Future experiments that combine one or more spatially resolved measurements with high magnetic fields could help to spatially resolve the regions that are contributing maximally to resistance oscillations in 2D structures.

In summary, we have used cAFM lithography at the LAO/STO interface to create quasi-1D channels whose magnetotransport characteristics bear a strong resemblance to 2D SdH-like transport widely reported at the LAO/STO interface. By analyzing the results within the framework of quantum channels, inconsistencies in accounting for "missing electrons" are resolved. Our results suggest that the nonuniform distribution of carriers due to naturally formed domain walls at the 2D LAO/STO interfaces brings additional confinements of carriers, which cause discrepancies in analyzing SdH oscillations at the 2D interfaces. More experiments are clearly required to investigate whether this framework can fully explain quantum oscillations observed at the LAO/STO interface and to characterize mesoscopic structures in which transport along naturally formed ferroelastic domains exist. However, so far, this framework has been the only one that can account for all of the observed phenomena.

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