A high-mobility electronic system at an electrolyte-gated oxide surface

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Electrolyte gating is a powerful technique for accumulating large carrier densities at a surface. Yet this approach suffers from significant sources of disorder: electrochemical reactions can damage or alter the sample, and the ions of the electrolyte and various dissolved contaminants sit Angstroms from the electron system. Accordingly, electrolyte gating is well suited to studies of superconductivity and other phenomena robust to disorder, but of limited use when reactions or disorder must be avoided. Here we demonstrate that these limitations can be overcome by protecting the sample with a chemically inert, atomically smooth sheet of hexagonal boron nitride. We illustrate our technique with electrolyte-gated strontium titanate, whose mobility when protected with boron nitride improves more than 10-fold while achieving carrier densities nearing $10^{14} \text{ cm}^{-2}$. Our technique is portable to other materials, and should enable future studies where high carrier density modulation is required but electrochemical reactions and surface disorder must be minimized.

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A conventional field effect transistor is controlled by the voltage on a metal electrode separated from the channel by a thin insulating dielectric. The maximum applied voltage is determined by the dielectric breakdown field, beyond which the resistance of the dielectric sharply drops, shorting the metal electrode to the channel. For a typical high-quality dielectric, the breakdown field limits the accumulated carrier density to $\sim 10^{15}$ cm$^{-2}$ (ref. 1). Although for special cases such as ferroelectrics stronger modulation is possible $^{2-4}$. Electrolyte gating circumvents dielectric breakdown by eliminating the metal/dielectric interface: an electrolyte is applied directly to the surface of interest and polarized, drawing one charged species to the surface and building a large electric field $^{5}$. Carrier densities $\sim 10^{15}$ cm$^{-2}$ can be induced by electrolyte gating $^{6}$, facilitating the discovery of superconductivity in new parameter regimes $^{7,8}$ and the creation of novel photonic devices $^{9}$, among other advances.

While very effective at modulating surface properties, electrolyte gating also introduces disorder. The deposition of contaminants on the sample is difficult to control, a problem that is compounded by the possibility of surface-degrading electrochemical reactions. Recent studies have further suggested that chemical modification of the surface of interest, rather than electrostatics, is primarily responsible for the marked changes in electronic properties in some electrolyte-gated systems $^{10-12}$.

Motivated by these challenges, we consider the well-studied two-dimensional electron system (2DES) created by electrolyte gating at the surface of strontium titanate (STO) $^{13-19}$. The transport properties of this surface 2DES closely resemble those of the 2DES at the lanthanum aluminate/strontium titanate (LAO/STO) interface. However, the highest reported low-temperature electron mobility in the STO 2DES is about 1,000 cm$^2$ V$^{-1}$ s$^{-1}$, at an electron density of $3 \times 10^{13}$ cm$^{-2}$ (refs 13,14,16,19); for the same density, the LAO/STO 2DES has mobility up to 10,000 cm$^2$ V$^{-1}$ s$^{-1}$ (ref. 20). We demonstrate that by protecting the STO channel with a thin boron nitride (BN) dielectric impermeable to the ions of the electrolyte $^{21}$, the mobility of the resulting electrolyte-gated 2DES substantially increases over a wide density range, surpassing 12,000 cm$^2$ V$^{-1}$ s$^{-1}$ at a density of $4 \times 10^{15}$ cm$^{-2}$ in our best sample.

Results

**BN-protected STO samples.** Each of our samples consists of a single crystal of STO partially covered by an atomically flat BN flake (Fig. 1a). The BN flake conforms to the substrate without trapping contaminants, as evidenced by the 0.4 nm terrace steps of the underlying STO seen in the topography of the BN (Fig. 1b). The substrate is masked by a thick insulator except in a Hall-bar-shaped channel area (Fig. 1c); the electrolyte induces negligible carrier density in the masked regions. In this work, we consider four BN-covered STO samples—denoted A, B, C and D—with BN thicknesses measured to be 0.6, 1.0, 1.2 and 1.5 nm, respectively, by atomic force microscopy (see Supplementary Note 1 for lateral dimensions and thickness measurement details). For each sample, we collect low-temperature magnetotransport data over multiple cooldowns at different coplanar gate voltages $V_{\text{gate}}$.

**Mobility and carrier density.** The striking improvement in 2DES quality with a BN spacer is evident in the magnetotransport properties of Sample A, which is covered by a 0.6-nm thick flake (Fig. 2a,b). The five cooldowns of Sample A, numbered 1 through 5, correspond to different $V_{\text{gate}}$ settings. Although higher $V_{\text{gate}}$ typically induces higher density, this is not always the case because of hysteresis (see Methods) and because of drifting offset voltages from electrochemical reactions at the gate electrode. To extract density and mobility, we perform a simultaneous fit to the sheet resistance $\rho_{xx}$ and the Hall coefficient $\rho_{xy}/\mu_0 H$, where $\rho_{xy}$ is the Hall resistance, $\mu_0$ is the magnetic constant, and $H$ is the applied magnetic field. As is typical in the STO 2DES literature, we assume that the magnetotransport behaviour can be described by two bands $^{22}$. Although quantum oscillation data suggest several bands (discussed below), a two-band description often fits the data, providing reliable numbers for average mobility and total density (Supplementary Note 2). For LAO/STO, a two-band fit with four parameters (densities $n_1$, $n_2$, mobilities $\mu_1$, $\mu_2$) captures the approximate shapes of $\rho_{xx}$ and $R_{xy}$, but deviates from the data at higher fields $^{22}$. We encounter the same difficulty: the two-band model cannot simultaneously fit the nonsaturating linearmagnetoresistance and nearly saturated Hall coefficient observed up to 31 T in our samples (Supplementary Note 2) and in LAO/STO samples $^{22}$. Inclusion of a third band cannot generally reproduce our high-field data, and where a three-band fit does work, the required densities are unrealistically large, frequently exceeding $10^{16}$ cm$^{-2}$ with mobility $\sim 1$ cm$^2$ V$^{-1}$ s$^{-1}$. We instead fit to a two-band model in which the sheet resistance of each band contains a term linear in applied field: $\rho = \rho_0 + \rho_1 B$, where $\rho_0$ is the zero-field resistivity. The zero-field mobilities $\mu_i = \rho_{xx} / \rho_{xy}$ are extracted from the slopes of the linear fits. Figure 2c shows the extracted $\mu_i$ for each sample at a range of densities.
Figure 2 | High-mobility magnetotransport in Sample A over a range of densities. (a) Sheet resistance $\rho_{xx}$ (symmetrized in field) for 5 cooldowns, labelled 1, 2, 3, 4 and 5, with $V_{\text{gate}} = 2.7, 2.25, 2, 1.5$ and 1.8 V, respectively. Dashed black curves result from two-band fits with linear magnetoresistance, performed simultaneously on the data in a and b. The BN is 0.6 nm thick. (b) Hall coefficient $R_H = \rho_{xy}/\mu H$ (symmetrized in field) for the same 5 cooldowns as in a and fits (dashed black curves). (c) Extracted carrier densities $n_1$ and $n_2$ for the two bands for each cooldown; $n_{\text{tot}} = n_1 + n_2$. (d) Extracted carrier mobilities $\mu_1$ and $\mu_2$ for the two bands for each cooldown; $\mu_{\text{avg}} = (n_1\mu_1 + n_2\mu_2)/n_{\text{tot}}$. (e) Quantum oscillations in $\partial \rho_{xx}/\partial H$ as a function of inverse applied magnetic field for Cooldown 1. For clarity, the signal has been smoothed and a quadratic background has been subtracted. The oscillations commence at $\sim 3$ T for all cooldowns. (f) Magnitude of the Fourier transform of e, showing a peak at $\sim 50$ T, corresponding to a density $\sim 2 \times 10^{12}$ cm$^{-2}$.

Our two-band fits with linear magnetoresistance provide an excellent match to the data (Fig. 2a,b). These fits exclude the low-field region, where the magnetotransport properties are affected by magnetic moments in the STO (ref. 26 and Supplementary Note 2). We find a high-mobility band with density $n_1$ between $6 \times 10^{12}$ and $5 \times 10^{13}$ cm$^{-2}$ (Fig. 2c) and mobility $\mu_1$ between 8,000 and 17,000 cm$^2$ V$^{-1}$ s$^{-1}$ (Fig. 2d), as well as a low-mobility band with a similar density $n_2$ and mobility $\mu_2$ that grows with decreasing $n_2$. The total induced density $n_{\text{tot}}$ can reach $9 \times 10^{13}$ cm$^{-2}$ (Fig. 2c) with an average mobility $\mu_{\text{avg}} = (n_1\mu_1 + n_2\mu_2)/n_{\text{tot}}$ approaching 8,000 cm$^2$ V$^{-1}$ s$^{-1}$ (Fig. 2d). The average mobility for Cooldown 4 exceeds 12,000 cm$^2$ V$^{-1}$ s$^{-1}$. These mobilities match (for lower densities) and exceed (for higher densities) the highest reported mobilities in LAO/STO 2DESes, and are 10 times larger than the mobilities reported in the literature for electrolyte-gated STO 2DES at any carrier density. Our conclusions are unchanged if we instead calculate $\mu$ and $n$ by naively dividing $R_H$ by $\rho_{xx}$ or if we fit with the four-parameter, two-band model (Supplementary Note 2).

Quantum oscillations. Quantum oscillations appear above $\sim 3$ T in both $\rho_{xx}$ and $\rho_{xy}$ for all cooldowns. The $\rho_{xx}$ oscillations from Cooldown 1 (Fig. 2e) show a primary oscillation frequency of $50$ T (Fig. 2f), corresponding to a carrier density near $2 \times 10^{12}$ cm$^{-2}$. This contrasts with the results of the two-band Hall transport fits, in which both bands are at least 10 times more populated. For a typical cooldown, we can identify multiple quantum oscillation frequencies corresponding to densities $\sim 10^{12}$ cm$^{-2}$, regardless of the total density measured by the Hall effect. The strongest oscillations thus appear for the lowest Hall densities (see Cooldown 5 in Fig. 2a), as the bands that produce quantum oscillations now constitute a substantial fraction of the carriers. Our findings resemble quantum oscillation data collected on the highest mobility LAO/STO 2DES, in which multiple bands of density $\sim 10^{12}$ cm$^{-2}$ show quantum oscillations, and total Hall densities $\sim 10^{13}$ cm$^{-2}$ or lower are required for strong oscillations in $\rho_{xx}$ (refs 28,29). The presence of low-density oscillating bands does not strongly impact the shapes of $\rho_{xx}$ and $R_H$, so the two-band model still captures most of the device behaviour (Supplementary Note 2).

Discussion
The maximum mobility that we have achieved in each of our four BN-covered samples is significantly higher than the maximum mobility that we have achieved in any uncovered STO sample (Fig. 3a). The mobility improvement with BN results in part from the added separation between the 2DES and the disordered structure nearly identical to that of graphene, we anticipate a single layer of graphene is known to be permeable to protons but impermeable to other small chemical species, including He atoms and Li$^+$ ions. Because BN has a lattice structure nearly identical to that of graphene, we anticipate a similar diffusion resistance for even our thinnest BN barriers. The energy barrier to diffusion is so high (ref. 32 calculates 10 eV for Li$^+$ across graphene) that we still expect impermeability with $V_{\text{gate}}$ dropped across our BN. An electrolyte-gated gold sample covered by 6 nm of BN behaved in accordance with these expectations: a gold oxide film is readily grown on uncovered...
accumulation. For comparison, we include primarily by electrostatics (open red circles) fall below dimensional and remains conductive at zero gate voltage\(^1^4\). While defined as apparent capacitance between the electrolyte and the 2DES, accumulation can account for our data by considering the TiO\(_2\) single crystals\(^1^0\) and VO\(_2\) thin films\(^1^1\) have found evidence that BN can limit chemical reactions during electrolyte gating.

Capacitances: that of the double layer formed by the ions density and two orders of magnitude below from oxygen vacancies\(^3^3\). Another study of STO concluded that vacancy creation and electrostatic carrier accumulation in tuning electrolyte, calling into question the relative roles of oxygen suppression of the source-drain current, which was interpreted as STO found that injecting oxygen gas into the electrolyte should enable electrolyte gating experiments that require high carrier mobility, high carrier density and chemical stability of the surface.

Methods
Sample fabrication. Our samples were fabricated on (100) strontium titanate substrates from either Shinkosha Co. (Japan) or Crytec GmbH (Germany); the vendor for each sample is specified in Supplementary Table 1. The surfaces of Shinkosha crystals were TiO\(_2\)-terminated as received. We prepared a nominally TiO\(_2\)-terminated surface on the Crytec samples by the method described in ref. 36. A BN flake was transferred onto the STO surface using the water-based process described in ref. 37, followed by an anneal for 4 h at 500 °C in an Ar/O\(_2\) atmosphere. An ohmic contact pattern was defined in PMMA via e-beam lithography at 10 kV, after which the sample was milled with Ar ions at 300 V to etch away the exposed BN and about 40 nm of the underlying STO. Ohmic contacts (10 nm titanium, 40 nm gold) were then deposited into the milled trenches by e-beam evaporation. Finally, an insulating mask with holes to expose the Hall bar and the coplanar gate was patterned using 10 kV e-beam lithography. The mask material was either cross-linked PMMA or sputtered alumina; in both cases a negative process was used so that the channel was not exposed to the e-beam.

Low-temperature measurement. Before measurement of each sample, we cleaned the sample surface of resist residues by a brief exposure to a remote oxygen plasma. We then covered the Hall bar and coplanar gate with a drop of the isotropic liquid 1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonyl)amide (EMI-TFSI) and placed the sample inside the vacuum chamber of our cryostat (either a dilution refrigerator with base temperature 40 mK or a variable-temperature insert reaching 350 mK or 1.5 K). We polarized the electrolyte at around 290 K, in either high-temperature measurement.

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exceeded the superconducting critical current in all samples, suppressing the superconducting features that would otherwise appear for some cooldowns in Fig. 2 (see also Supplementary Note 5). The sample was then warmed to near room temperature, melting the electrolyte. We always set \( V_{	ext{emo}} \) to zero in between cooldowns, which introduces some hysteresis in \( V_{	ext{emo}} \).

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