Giant supercurrent drag effect between graphene and LaAlO$_3$/SrTiO$_3$ interface

Ran Tao$^{1,2}$, Lin Li$^{1,2,*}$, Linhai Guo$^{1,2}$, Xiaodong Fan$^{1,2}$, Lijun Zhu$^{1,2}$, Yuedong Yan$^{1,2}$, Zhenyu Zhang$^1$, Changgan Zeng$^{1,2,*}$

$^1$International Center for Quantum Design of Functional Materials (ICQD), Hefei National Laboratory for Physical Sciences at the Microscale, and Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

$^2$CAS Key Laboratory of Strongly-Coupled Quantum Matter Physics, and Department of Physics, University of Science and Technology of China, Hefei, Anhui 230026, China

*Correspondence and requests for materials should be addressed to C. Z. (cgzeng@ustc.edu.cn), or L. L. (lilin@ustc.edu.cn).

Recent advances in the manufacturing of graphene-based heterostructures have enabled the investigation of interlayer interaction phenomena in a wide parameter space and led to the discovery of intriguing interlayer correlated effects. Here, via utilizing the double-layer two-dimensional electron systems consisting of graphene and the superconducting LaAlO$_3$/SrTiO$_3$ heterointerface, the anomalous interlayer interaction between normal conductor and superconductor is explored via drag measurements. Negative drag signals are observed in the vicinity of the superconducting transition, and the emergence of an equivalent drag current flowing in the superconducting drag layer is verified. This effect is highly tunable by multiple external fields and exhibits giant current coupling ratio up to 50 in the zero-temperature limit,
which may find its applications in designing novel superconducting electronic devices. Furthermore, the polarity and the special exponential-like temperature dependence of the current coupling ratio point to a brand-new mechanism. This study provides deep insight for future theoretical studies of interlayer coupling involving superconductors.

Frictional drag effect is a transport phenomenon where a charge current ($I_{\text{drive}}$) flowing in the drive layer induces a voltage drop ($V_{\text{drag}}$) in the drag layer between two closely spaced but electrically isolated conductors$^1$. As a direct measure of the interlayer coupling, drag effect has been adopted as an effective tool to detect elementary excitations$^{2,3}$, and more importantly, to realize intriguing interlayer correlated effects$^{4-6}$, like excitonic superfluidity$^{7-9}$ and even-denominator fractional Hall effects$^{10,11}$. Recently, novel graphene-based heterostructures have renewed the interest in the interlayer drag effect$^{12-19}$ due to their attractive properties, such as the high-tunability of carrier density across electrons and holes and the accessibility of ultra-small interlayer separation, which enable the investigation of interaction phenomena in a wide parameter space that could not be explored using conventional bilayer electron systems. Many novel interaction phenomena have been reported, including giant drag and magneto-drag effect near the charge neutrality point$^{13,14}$, and magnetic-field-induced superfluid state with largely-enhanced robustness$^{18,19}$.

Consequently, it is natural to consider replacing one of the layers with a superconductor$^{20-27}$. In this hybrid structure, the drag test offers a promising method to detect the fluctuations of superconducting order parameters especially in the vicinity of the superconducting transition temperature$^{23}$. The interactions between normal and superconducting carriers may lead to the supercurrent drag effect$^{20,22}$ that has been originally proposed to exist in $^3$He-$^4$He mixture$^{28,29}$ and neutron stars$^{30}$. Furthermore, the potential formation of indirect hybrid excitons is quite intriguing. In fact, such experimental studies have been conducted in bilayer systems consisting of normal metal and superconducting metal films. Nevertheless, drag signals with contradictory polarities were observed in the vicinity of the superconducting transition in different studies$^{21,22}$, and the corresponding theoretical understanding is yet to be clear$^{20,23}$. It is important to emphasize that in these previous work both the normal conductor and the superconductor are not tunable, and the finite thickness of both of the layers induces
inhomogeneous coupling along the z-direction. Furthermore, the relatively large interlayer spacing can potentially lead to a relatively weak response.

The recent developments in two-dimensional (2D) superconductor as well as the advancements in the manufacturing of heterostructures enable revisiting these exotic interlayer interactions in novel 2D electron systems. Here via utilizing hybrid structure consisting of graphene and LaAlO$_3$/SrTiO$_3$ (LAO/STO) heterointerface, the drag behaviors between a normal conductor and a superconductor are systematically investigated. In addition to the high carrier mobility and ambipolar tunability of the graphene layer, LAO/STO also possesses intriguing physical properties such as interfacial conduction, magnetism, and especially the 2D superconductivity that can be easily tuned via electrostatic gating. In addition, the ultra-thin LAO layer functions as a natural insulating spacer located between the graphene and the LAO/STO conducting interface with a thickness down to 2 nm. Such a device enables the investigation of the interlayer coupling effects between normal and superconducting carriers with improved tunability, and moreover, the systematic collection of reliable data for elucidating the underlying mechanism.

The schematic of the double-layer electron system consisting of graphene and 5-uc LaAlO$_3$/SrTiO$_3$ is depicted in Fig. 1a (denoted as G-LAO/STO). Macro-scale graphene (~2 mm) grown via chemical vapor deposition instead of the one obtained from mechanical exfoliation is used to avoid nanofabrication-induced damage on the electronic performance of LAO/STO (see Methods for the experimental details). The pristine 2D superconductivity of LAO/STO interface is well-maintained in the final device, manifesting as the observation of the typical Berezinskii-Kosterlitz-Thouless (BKT) transition (see Note 1 for details). Furthermore, the interfacial superconductivity of LAO/STO can be easily tuned (Fig. 1b) using the back-gate voltage ($V_{BG}$) applied to the STO substrate, similar to previous work. The impact of $V_{BG}$ on the doping level of graphene is negligible (Figs. S1a,b), demonstrating the perfect shielding effect of LAO/STO. On the other hand, both the carrier type and the density of the graphene layer can be tuned with the interlayer gate-voltage ($V_{int}$) utilizing LAO as the dielectric layer, with negligible impact on the electronic performance of the LAO/STO interface (Fig. S1c).

The drag measurements are conducted by applying DC drive current $I_{drive}$ to the graphene layer and measuring the induced $V_{drag}$ at the LAO/STO interface (Fig. 2a, see Methods for the experimental
Figure 2b depicts the obtained drag resistance \( R_{\text{drag}} = \frac{V_{\text{drag}}}{I_{\text{drive}}} \) as a function of temperature \( T \). The \( T \)-dependent resistance curve of LAO/STO interface is also plotted for comparison. Figure 2b demonstrates a negative drag signal accompanying the superconducting (SC) transition of the LAO/STO interface (Fig. 2b), while no detectable drag signal is observed when the LAO/STO interface is either at the normal state or the fully SC state. Thus, \( R_{\text{drag}} \) exhibits a non-monotonic dependence on temperature reaching a maximum at \( T \sim 0.195 \) K. Applying a moderate magnetic field significantly enlarges the SC transition zone of LAO/STO, while the temperature range for the non-zero drag signal is enlarged accordingly (see Fig. 2c and Fig. S2 for the parallel and perpendicular field cases, respectively). In addition, the peak of \( R_{\text{drag}} \) shifts towards lower temperatures, consistent with the decrease of \( T_c \) for LAO/STO. As the magnetic field is further increased to 3 T, the quench of LAO/STO interfacial superconductivity and the disappearance of the drag signal occur simultaneously. This correlation becomes more apparent by sweeping the magnetic field, during which non-zero drag signal only occurs in the transition region between the normal state and the SC state (Fig. 2d).

The validity of these findings is verified by conducting systematic tests. First, several possible origins of the emergent drag signal, including the leakage/tunneling effect, thermoelectric effect or pure electrostatic field can be easily excluded (see Note 2 for details). Besides, \( V_{\text{drag}} \) shows good linear dependence on \( I_{\text{drive}} \) within 700 nA (see Fig. S3c), verifying the feasibility of using an \( I_{\text{drive}} \) of ±400 nA in the drag measurements. Deviation from a linear relation at relatively large \( I_{\text{drive}} \) should be arising from the Joule heating effect that depresses the superconductivity of the LAO/STO interface. Note that when the drive and drag layers are interchanged, i.e., LAO/STO interface functions as the drive layer, while graphene functions as the drag layer, significant fluctuations of \( V_{\text{drag}}-I_{\text{drive}} \) curve hinders the acquisition of accurate drag signal values (Fig. S6). Similar fluctuations have also been observed in drag measurements of graphene-GaAs heterostructures\(^{40}\), and have been identified as a consequence of phase coherent quantum transport that normally emerges at low temperatures\(^{12,41}\).

The strong correlation between drag signal and superconducting transition, and the asymmetric behavior upon interchanging the drive and the drag layer, are in agreement with the observations in a previous study\(^{22}\) where it was claimed that the supercurrent drag has been detected. That is, the interlayer interaction is considered to induce a current flow in the superconductor (drag layer). The as-induced drag current \( I_{\text{drag}} \) was considered to be a part of the driving current but with a different
scattering time, which can be calculated from the expression \( V_{\text{drag}} = I_{\text{drag}} \times R_{\text{LAO/STO}} \). The observations presented in this work can be roughly explained using this phenomenological relationship: \( R_{\text{drag}} \) should be zero while the drag layer is at the normal state or the SC state, since \( I_{\text{drag}} = 0 \) and \( R_{\text{LAO/STO}} = 0 \) for these two cases, respectively. The peak of \( R_{\text{drag}} \) is attributable to the competition between the increasing \( I_{\text{drag}} \) and the decreasing \( R_{\text{LAO/STO}} \) with decreasing temperature in the SC transition region. To further validate this picture, a special double source measurement, i.e., applying current both to the graphene and the LAO/STO interface and measuring the voltage drop in the LAO/STO layer, is conducted in a different G-LAO-STO device (see Note 3 and Fig. 2e for details). Linear superposition relation is found between the obtained open circuit voltage induced by the drag effect and the conventional Ohmic contribution (Fig. 2f), demonstrating the emergence of an equivalent current flow in the superconducting drag layer, originating purely from interlayer interactions. Consequently, in the following sections, this observation is referred to as the supercurrent drag effect where its systematical evolution behavior and the microscopic mechanism are further explored.

The high tunability of the LAO/STO interfacial superconductivity, together with the relatively wide 2D SC transition region arising from the finite-size effect (see Note 4), enable us to investigate the drag effect in a wide parameter space. In particular, the phase diagram of LAO/STO interface as a function of temperature and carrier density can be mapped out by tuning \( V_{\text{BG}} \), as demonstrated in Fig. 3a. A superconducting dome with a maximum \( T_c \approx 205 \) mK at \( \sim 27 \) V is obtained by varying \( V_{\text{BG}} \). Here, for simplicity, \( T_c \) is defined as the temperature at which the resistance falls below 10\% of its value at \( T = 0.4 \) K. The dome-like behavior agrees well with previous studies\(^ {37,42} \), further demonstrating that the pristine superconductivity of LAO/STO interface in the present G-LAO/STO device is well maintained. Next, systematic drag measurements are conducted to obtain a similar phase-diagram for \( R_{\text{drag}} \) (Fig. 3b). As clearly shown in Fig. 3b, the regions where \( R_{\text{drag}} \) is non-zero also constitute a dome-like shape with respect to \( V_{\text{BG}} \). More strikingly, when the \( T_c \) curves of LAO/STO are superimposed in Fig. 3b, an excellent overlap is obtained among the data sets over the entire gate-voltage range. The magnetic field (\( B \))-\( V_{\text{BG}} \) phase diagrams of \( R_{\text{LAO/STO}} \) and \( R_{\text{drag}} \) also demonstrate a similar agreement, as depicted in Fig. 3c and Fig. 3d, respectively.

Here we would like to address that drag effect in the present G-LAO/STO device is significantly enhanced compared to studies performed on conventional systems\(^ {22} \), since the value of the obtained
drag resistance is an order of magnitude larger. Next, we introduce the concept of current coupling ratio \( r = I_{\text{drag}}/I_{\text{drive}} \) according to previous study\(^{22}\) in order to take into account the resistance of the superconductor layer. Since \( I_{\text{drag}}/I_{\text{drive}} = (V_{\text{drag}}/R_{\text{LAO}/\text{STO}})/I_{\text{drive}} = R_{\text{drag}}/R_{\text{LAO}/\text{STO}} \), \(|r|\) can be calculated from Figs. 3a and 3b. Figure 4a clearly illustrates the dome shaped \(|r|\) versus \( V_{\text{BG}} \) profile. At constant \( V_{\text{BG}} \), \(|r|\) first increases monotonically with decreasing \( T \) (Fig. 4b), and then becomes unable to obtain upon the entrance of the fully SC state of the LAO/STO (\( R_{\text{LAO}/\text{STO}} \sim 0 \)), where the absolute error approaches infinity. Notably, the maximum value of \(|r|\) reaches \(~0.3\) from the mapping data (Fig. 4a). As a comparison, \(|r|\) is on the order of \( 10^{-3} \) for the study in which \( \text{AlO}_x \) (\( \text{Au}/\text{Ti} \)) serves as the superconductor (normal conductor) layer\(^{22}\). The high value of \(|r|\) in the present G-LAO/STO device can be further verified via the above mentioned double source measurement (Figs. 2e and 2f), as detailed in Note 3 and Fig. S8 in the Supplementary Information. There are two main advantages associated with the substantially enhanced interlayer coupling: the ultra-small interlayer spacing, and the uniform interlayer interaction in the \( z \)-direction, which benefit from the 2D nature of the two layers. Besides, the relatively low carrier densities of graphene (LAO/STO interface) compared to the normal metal (superconducting metal) can lead to a reduced screening effect on the interlayer interaction, which may also contribute to the large drag effect.

Several mechanisms have been theoretically proposed to explain the experimentally observed drag signal in the vicinity of superconducting transition for conventional systems. One typical explanation is the interlayer Coulomb interaction between the electrons in the normal conductor and Cooper pair in the superconductor\(^{20}\). Since this model is based on the interlayer momentum transfer, the as-induced drag signal should be positive (negative) when the carrier polarity in the two layers is different (the same)\(^4,12\), even though one of the layers is replaced with the superconductor. However, for the data presented above, the carrier types of the graphene and LAO/STO interface are hole and electron, respectively. The negative polarity of the observed drag signal could thus exclude such a pure Coulomb interaction mechanism. Another possible origin is the inductive interference between the electrons in the normal conductor and the mobile vortices in the superconductor\(^{23}\), in which the local mobile vortices induced by the local fluctuating electric field in the superconductor layer are considered to be the key factor. According to this mechanism, the drag signal should be always positive. Hence, it can
also be easily excluded considering the negative polarity of drag signal obtained in the present G-LAO/STO device (see Note 6 for more evidences).

To further explore the underlying mechanism for the observed supercurrent drag effect, a more quantitative analysis on the current coupling ratio $|r|$ is conducted. Note that $|r|$ increases monotonically with decreasing temperature, consistent with the superfluid density $n_s$ profile in a superconductor\textsuperscript{43}. For LAO/STO, $n_s$ can be described as $n_s = n_0[1 - (T/T_s)^2]$, where $n_0$ is the superfluid density at zero temperature, $T_s$ the temperature where Cooper pair start to emerge\textsuperscript{43,44}. We thus used similar formula ($|r| = r_0[1 - (T/T^*)^2]$) trying to fit the $|r|$ vs $T$ curve, but failed (Fig. 4b), suggesting that the interlayer interaction is not purely determined by the superconductor layer. In contrast, we finally revealed that the temperature dependence of $|r|$ actually can be well-fitted using the expression: $|r| \sim r_0 \exp(-T^2/2T^*^2)$ \textsuperscript{(1)} (Fig. 4b, see Fig. S11 for the results of another device), where $r_0$ represents the current coupling ratio at zero temperature, and $T^*$ determines the rate of change of $|r|$. This equation can be extrapolated to the temperature region where $|r|$ cannot be experimentally obtained (as discussed above). Figure 4c demonstrates that Equation \textsuperscript{(1)} can be applied to most of the curves taken under different $V_{BG}$, and the extracted $r_0$ and $T^*$ are shown in Fig. 4d. It is clear that $r_0$ exhibits a typical non-monotonic behavior, with its maximum occurring around the peak of the superconducting dome of the LAO/STO interface (Fig. 3b). Strikingly, the maximum value of $r_0$ can reach $\sim$50. That is, in the zero-temperature limit applying a drive current can induce a 50 times larger secondary current in the superconductor layer in close proximity, which may prove to be useful in the further development of superconducting electronic devices. Such a strong interlayer coupling should be related to the non-dissipative nature of the superconducting current, as well as the as-mentioned advantages benefiting from the 2D nature of the two layers used in this work.

The observed large supercurrent drag effect is still attributable to the interaction between the normal and superconducting carriers, although the underlying microscopic coupling mechanism remains to be explored. Actually, upon further investigation, we found that the drag signal remains negative upon tuning the graphene layer across the Dirac point via $V_{int}$ (Fig. S12), implying a carrier-polarity-independent microscopic origin, which is still consistent with the inductive interference mechanism to some extent. Nevertheless, $R_{drag}$ reaches a maximum when the graphene layer is at the Dirac point, demonstrating the anti-correlations between the drag signal and the carrier density of the drive layer,
which shares some similarities to that of Coulomb interaction model. The abundant characteristics revealed in the present study may offer important insight for future theoretical studies.

In conclusion, the interlayer coupling effect in bilayer electron systems consisting of graphene and LAO/STO heterostructure is systematically investigated via drag measurements, in which non-zero drag signal is observed only when LAO/STO is within the superconducting transition regime. Further investigations reveal that such an effect should originate from the introduction of a current flow in the superconductor layer. Utilizing the 2D nature of the two layers, the as-obtained supercurrent drag effect possesses high tunability, with the magnitude of coupling ratio much larger than that in previous studies based on conventional materials. Though much effort is still needed to clarify the intrinsic nature and the microscopic contributions, the intriguing evolution behaviors presented in this work under multiple external fields will definitely prove to be useful as a reference for future theoretical studies. Furthermore, the realization of an anomalous interlayer coupling ratio makes this 2D hybrid structure an attractive candidate for developing novel superconducting electronic devices.

**Methods**

**Device fabrication:** LAO/STO heterostructures were fabricated using pulsed laser deposition similar to those described in our previous study\(^4\)\(^5\). The high-quality of the as-prepared samples, e.g. ultra-flat surfaces and good interfacial conductivity, were carefully verified prior to the following procedures. Monolayer graphene sheets were grown on Cu foils by chemical vapor deposition\(^4\)\(^6\). Large-scale and uniform graphene flakes (~2 mm in size) were chosen and then transferred directly onto LAO/STO surface following a similar method reported previously\(^4\)\(^7\),\(^4\)\(^8\). For the transport measurements, Al wires were connected to the LAO/STO interface and the graphene layer using ultrasonic welding and silver conductive paint, respectively. Ti/Au contacts (5/50 nm) were fabricated on the back side of the STO substrates to apply the back-gate voltage \(V_{BG}\).

**Transport measurements:** The transport measurements were performed in an Oxford Instruments Triton Dilution Refrigerator. During the drag measurements, DC mode was adopted to avoid the possible influence of capacitive reactance in AC measurements\(^1\)\(^3\). Keithley 6220/6221 and 2182A were employed to supply the currents in the drive layer and measure the voltage drops in the drag layer, respectively. To eliminate the voltage background of 2182A, the current was actually applied using a
bipolar mode, and the voltage was obtained by taking the average of the measured voltages at positive and negative currents.

References:
1. Narozhny, B. & Levchenko, A. Coulomb drag. Rev. Mod. Phys. 88, 025003 (2016).
2. Pillarisetty, R. et al. Coulomb drag near the metal-insulator transition in two dimensions. Phys. Rev. B 71, 115307 (2005).
3. Laroche, D., Gervais, G., Lilly, M. & Reno, J. 1D-1D Coulomb drag signature of a Luttinger liquid. Science 343, 631-634 (2014).
4. Gramila, T., Eisenstein, J., MacDonald, A. H., Pfeiffer, L. & West, K. Mutual friction between parallel two-dimensional electron systems. Phys. Rev. Lett. 66, 1216 (1991).
5. Sivan, U., Solomon, P. & Shtrikman, H. Coupled electron-hole transport. Phys. Rev. Lett. 68, 1196 (1992).
6. Yamamoto, M., Stopa, M., Tokura, Y., Hirayama, Y. & Tarucha, S. Negative Coulomb drag in a one-dimensional wire. Science 313, 204-207 (2006).
7. Eisenstein, J. & MacDonald, A. H. Bose–Einstein condensation of excitons in bilayer electron systems. Nature 432, 691-694 (2004).
8. Kellogg, M., Eisenstein, J., Pfeiffer, L. & West, K. Vanishing Hall resistance at high magnetic field in a double-layer two-dimensional electron system. Phys. Rev. Lett. 93, 036801 (2004).
9. Tutuc, E., Shayegan, M. & Huse, D. A. Counterflow measurements in strongly correlated GaAs hole bilayers: evidence for electron-hole pairing. Phys. Rev. Lett. 93, 036802 (2004).
10. Suen, Y., Engel, L., Santos, M., Shayegan, M. & Tsui, D. Observation of a ν=1/2 fractional quantum Hall state in a double-layer electron system. Phys. Rev. Lett. 68, 1379 (1992).
11. Eisenstein, J., Boebinger, G., Pfeiffer, L., West, K. & He, S. New fractional quantum Hall state in double-layer two-dimensional electron systems. Phys. Rev. Lett. 68, 1383 (1992).
12. Kim, S. et al. Coulomb drag of massless fermions in graphene. Phys. Rev. B 83, 161401 (2011).
13. Gorbachev, R. et al. Strong Coulomb drag and broken symmetry in double-layer graphene. Nat. Phys. 8, 896-901 (2012).
14. Titov, M. et al. Giant magnetodrag in graphene at charge neutrality. Phys. Rev. Lett. 111, 166601 (2013).
15. Li, J. et al. Negative Coulomb drag in double bilayer graphene. Phys. Rev. Lett. 117, 046802 (2016).
16. Lee, K. et al. Giant frictional drag in double bilayer graphene heterostructures. *Phys. Rev. Lett.* **117**, 046803 (2016).

17. Liu, X. et al. Frictional Magneto-Coulomb Drag in Graphene Double-Layer Heterostructures. *Phys. Rev. Lett.* **119**, 056802 (2017).

18. Liu, X., Watanabe, K., Taniguchi, T., Halperin, B. I. & Kim, P. Quantum Hall drag of exciton condensate in graphene. *Nat. Phys.* **13**, 746-750 (2017).

19. Li, J., Taniguchi, T., Watanabe, K., Hone, J. & Dean, C. Excitonic superfluid phase in double bilayer graphene. *Nat. Phys.* **13**, 751-755 (2017).

20. Duan, J.-M. & Yip, S. Supercurrent drag via the Coulomb interaction. *Phys. Rev. Lett.* **70**, 3647 (1993).

21. Giordano, N. & Monnier, J. Cross-talk effects in superconductor–insulator–normal-metal trilayers. *Phys. Rev. B* **50**, 9363 (1994).

22. Huang, X., Bazán, G. & Bernstein, G. H. Observation of supercurrent drag between normal metal and superconducting films. *Phys. Rev. Lett.* **74**, 4051 (1995).

23. Shimshoni, E. Role of vortices in the mutual coupling of superconducting and normal-metal films. *Phys. Rev. B* **51**, 9415 (1995).

24. Kamenev, A. & Oreg, Y. Coulomb drag in normal metals and superconductors: Diagrammatic approach. *Phys. Rev. B* **52**, 7516 (1995).

25. Lobos, A. M. & Giamarchi, T. Dissipative phase fluctuations in superconducting wires capacitively coupled to diffusive metals. *Phys. Rev. B* **82**, 104517 (2010).

26. Levchenko, A. & Norman, M. R. Proposed Giaever transformer to probe the pseudogap phase of cuprates. *Phys. Rev. B* **83**, 100506 (2011).

27. Yang, F. & Wu, M. Gauge-invariant microscopic kinetic theory of superconductivity in response to electromagnetic fields. *Phys. Rev. B* **98**, 094507 (2018).

28. Andreev, A. & Bashkin, E. Three-velocity hydrodynamics of superfluid solutions. *Sov. Phys. JETP* **42**, 164 (1976).

29. Leggett, A. J. A theoretical description of the new phases of liquid He3. *Rev. Mod. Phys.* **47**, 331 (1975).

30. Alpar, M., Langer, S. A. & Sauls, J. Rapid postglitch spin-up of the superfluid core in pulsars. *Astrophys. J.* **282**, 533-541 (1984).

31. Saito, Y., Nojima, T. & Iwasa, Y. Highly crystalline 2D superconductors. *Nat. Rev. Mater.* **2**, 1-18 (2016).

32. Novoselov, K. S. *et al.* Electric field effect in atomically thin carbon films. *Science* **306**, 666-669 (2004).

33. Ohtomo, A. & Hwang, H. A high-mobility electron gas at the LaAlO3/SrTiO3 heterointerface. *Nature* **427**, 423-426 (2004).
34. Thiel, S., Hammerl, G., Schmehl, A., Schneider, C. W. & Mannhart, J. Tunable quasi-two-dimensional electron gases in oxide heterostructures. *Science* **313**, 1942-1945 (2006).
35. Brinkman, A. *et al.* Magnetic effects at the interface between non-magnetic oxides. *Nat. Mater.* **6**, 493-496 (2007).
36. Reyren, N. *et al.* Superconducting interfaces between insulating oxides. *Science* **317**, 1196-1199 (2007).
37. Caviglia, A. *et al.* Electric field control of the LaAlO$_3$/SrTiO$_3$ interface ground state. *Nature* **456**, 624-627 (2008).
38. Schlom, D. G. & Mannhart, J. Interface takes charge over Si. *Nat. Mater.* **10**, 168-169 (2011).
39. Chen, Z. *et al.* Carrier density and disorder tuned superconductor-metal transition in a two-dimensional electron system. *Nat. Commun.* **9**, 1-6 (2018).
40. Gamucci, A. *et al.* Anomalous low-temperature Coulomb drag in graphene-GaAs heterostructures. *Nat. Commun.* **5**, 1-7 (2014).
41. Price, A., Savchenko, A., Narozhny, B., Allison, G. & Ritchie, D. Giant fluctuations of Coulomb drag in a bilayer system. *Science* **316**, 99-102 (2007).
42. Joshua, A., Pecker, S., Ruhman, J., Altman, E. & Ilani, S. A universal critical density underlying the physics of electrons at the LaAlO$_3$/SrTiO$_3$ interface. *Nat. Commun.* **3**, 1-7 (2012).
43. Manca, N. *et al.* Bimodal phase diagram of the superfluid density in LaAlO$_3$/SrTiO$_3$ revealed by an interfacial waveguide resonator. *Phys. Rev. Lett.* **122**, 036801 (2019).
44. Prozorov, R. & Giannetta, R. W. Magnetic penetration depth in unconventional superconductors. *Supercon. Sci. Technol.* **19**, R41 (2006).
45. Liang, H. *et al.* Nonmonotonically tunable Rashba spin-orbit coupling by multiple-band filling control in SrTiO$_3$-based interfacial d-electron gases. *Phys. Rev. B* **92**, 075309 (2015).
46. Li, X. *et al.* Large-area synthesis of high-quality and uniform graphene films on copper foils. *Science* **324**, 1312-1314 (2009).
47. Qi, J. *et al.* Controlled ambipolar tuning and electronic superlattice fabrication of graphene via optical gating. *Adv. Mater.* **26**, 3735-3740 (2014).
48. Cheng, L. *et al.* Photoconductivity of graphene in proximity to LaAlO$_3$/SrTiO$_3$ heterostructures: phenomenon and photosensor applications. *Phys. Rev. Appl.* **6**, 014005 (2016).

**Acknowledgments**

This work was supported by the National Natural Science Foundation of China (Grant Nos. 11974324, 11804326, U1832151), Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDC07010000), National Key Research and Development Program of China (Grant No. 2017YFA0403600),
Anhui Initiative in Quantum Information Technologies (Grant No. AHY170000), and Hefei Science Center CAS (Grant No. 2018HSC-UE014). Part of this work was carried out at the USTC Center for Micro and Nanoscale Research and Fabrication.

**Author contributions**

C.Z. and L.L. conceived the project; R.T. and L.L. performed the experiments with assistance from L.G., X.F., L.Z. and Y.Y.; L.L., R.T. and C.Z analyzed the data and wrote the manuscript; Z.Z. contributed to data interpretation and presentation. All authors contributed to the scientific discussion and manuscript revisions.

**Additional information**

Correspondence and requests for materials should be addressed to C.Z. (cgzeng@ustc.edu.cn), or L.L. (lilin@ustc.edu.cn).

**Competing financial interests**

The authors declare no competing interests.
Figure 1. The G-LAO/STO device. a) Schematic illustration of the G-LAO/STO device. b) Resistance of LAO/STO ($R_{\text{LAO/STO}}$) as a function of temperature for $V_{\text{BG}}$ from -200 to 200 V in steps of 50 V. c) Resistance of graphene ($R_{\text{graphene}}$) as a function of $V_{\text{int}}$ measured at 50 mK. $V_{\text{BG}}$ is set as -200 V during the measurement.
Figure 2. Interlayer drag effect in the G-LAO/STO device. a) Schematic illustration of the set-up for drag measurements. b) Drag resistance ($R_{\text{drag}}$) and normalized resistance of the LAO/STO interface ($R/R_n$) as a function of temperature. $R_n$ is the resistance of the LAO/STO interface at 500 mK where the LAO/STO interface is at the normal state. The SC regime corresponds to the SC state of LAO/STO, i.e. $R_{\text{LAO/STO}} \sim 0$. c) Temperature dependent $R_{\text{drag}}$ and $R/R_n$ measured under 1 T and 3 T in-plane magnetic field ($B_{||}$), respectively. d) $B_{||}$ dependent $R_{\text{drag}}$ and $R/R_n$ measured at 100mK. e) Schematic illustration for double source measurement. f) $V_{\text{LAO/STO}}$ as a function of $I_{\text{LAO/STO}}$ and $I_{\text{graphene}}$. Measurement was taken at $T = 50$ mK and $V_{BG} = -70$ V in a G-LAO/STO device in which 10uc-LAO was used. The dash line corresponds to $V_{\text{LAO/STO}} = 0$ V.
Figure 3. Phase diagrams for the observed drag signal. a) $R/R_n$ and b) $R_{\text{drag}}$ as a function of $V_{BG}$ and temperature $T$. $R_n$ is the resistance of the LAO/STO interface at 400 mK measured under zero magnetic field and the corresponding $V_{BG}$. c) $R/R_n$ and d) $R_{\text{drag}}$ as a function of $V_{BG}$ and $B_{||}$, the measurements were conducted at 100 mK. The orange dashed lines in a-d correspond to $R/R_n = 10\%$. 
Figure 4. Detail analysis on the interlayer current coupling ratio. a) Calculated coupling ratio $|r|$ as a function of $V_{BG}$ and $T$. b) $|r|$ as a function of $T$ at $V_{BG}=0$ V and the corresponding fitting curves obtained using different formulas. Inset: the semi-logarithmic scale plot in the low temperature region. c) $|r|$ vs $T^2$ plotted on a semi-logarithmic scale for varying $V_{BG}$. The gray dashed lines are the fitting curves using $|r| \sim r_0 \exp(-T^2/2T^*^2)$. d) Extracted $r_0$ and $T^*$ as a function of $V_{BG}$ from c.