Quantum interference in an interfacial superconductor

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The two-dimensional superconductor that forms at the interface between the complex oxides lanthanum aluminate (LAO) and strontium titanate (STO) has several intriguing properties and is not set apart from conventional superconductors. Most notably, an electric field can be used to tune its critical temperature, revealing a dome-shaped phase diagram reminiscent of high-\(T_c\) superconductors. So far, experiments with oxide interfaces have measured quantities that probe only the magnitude of the superconducting order parameter and are not sensitive to its phase. Here, we perform phase-sensitive measurements by realizing the first superconducting quantum interference devices (SQUIDs) at the LAO/STO interface. Furthermore, we develop a new paradigm for the creation of superconducting circuit elements, where local gates enable the in situ creation and control of Josephson junctions. These gate-defined SQUIDs are unique in that the entire device is made from a single superconductor with purely electrostatic interfaces between the superconducting reservoir and the weak link. We complement our experiments with numerical simulations and show that the low superfluid density of this interfacial superconductor results in a large, gate-controllable kinetic inductance of the SQUID. Our observation of robust quantum interference opens up a new pathway to understanding the nature of superconductivity at oxide interfaces.

A SQUID consists of two Josephson junctions (JJs) embedded in a superconducting loop. When a magnetic flux \(\Phi\) threads through this loop, it changes the relative difference in the superconducting phase of the two JJs giving rise to periodic oscillations in the supercurrent. This basic principle has been used with great success to study a variety of material systems. For example, standard superconductors have been combined with other materials such as ferromagnets, topological insulators and nanowires to often reveal non-trivial current-phase relations. Such phase-sensitive measurements have also emerged as a powerful tool to study more exotic superconductors such as the ruthenates and high-\(T_c\) cuprates. Whether the 2D superconductor formed at the LAO/STO interface is also unconventional is still not clear. However, to address this issue one must move beyond standard bulk transport measurements. Recent tunnelling studies and transport spectroscopy of confined structures exemplify this point. In this context, a probe of the superconducting phase could provide complementary information about the microscopic origin of the superconductivity, but such experiments have not yet been undertaken. To address this, we realize SQUIDs at the LAO/STO interface that enable the observation of robust quantum interference in this interfacial superconductor.

We fabricate the SQUIDs using two distinct approaches (see the Supplementary Information for full details). The first involves the creation of weak links using nanoscale physical constrictions (C-SQUIDs), a technique that has been used extensively in a wide variety of superconductors. Figure 1a shows a schematic of the C-SQUID. Black areas are superconducting, whereas the beige regions remain insulating due to the presence of an amorphous LAO (a-LAO) mask. Each arm of the loop is interrupted by a narrow constriction (see the AFM image in Fig. 1b). We ensure that the width of the constriction (<100 nm) is less than/comparable to the superconducting coherence length of LAO/STO. The C-SQUID has the advantage that it requires only a single lithography step and is simple to characterize.

The second approach used to define SQUIDs, although more involved, is novel and unique to the LAO/STO interface. We exploit the sensitivity of \(T_c\) to the field effect to create an electrostatically defined SQUID (E-SQUID). By applying negative voltages to the local top gates (see schematic in Fig. 1c), we deplete the regions below them. These locally depleted regions serve as the weak links, thus enabling the formation of independently tunable JJs in each arm. Figure 1d shows an AFM image of one such gate-defined JJ. Although other examples of gate-tunable JJs do exist, they necessarily involve physical interfaces between two dissimilar materials. In contrast, LAO/STO provides a unique material platform in which a single superconductor can be electrostatically modified to allow the in situ creation and tuning of JJs in a perfectly reversible manner. In this work we study two C-SQUID devices (C-SQ1 and C-SQ2) and one E-SQUID device (E-SQ3). A back gate can be used to tune the global electronic properties of the devices and measurements are performed in a dilution refrigerator with a base temperature of 40 mK.

Figure 1e shows a voltage–current (\(V–I\)) curve for C-SQ1 at 40 mK, which displays a distinct supercurrent branch (the inset shows the measurement configuration). To establish the presence of Josephson coupling we test whether the devices show clear SQUID behaviour. We apply a current bias close to the critical current \(I_c\) and monitor the voltage drop as a function of the perpendicular magnetic field \(B\). Figure 1f shows that all of the devices undergo periodic oscillations in \(B\). As we expect these oscillations to be periodic in the flux threading through the SQUID, a reduction in the loop area should result in a larger period in \(B\). This is precisely what we observe when we compare C-SQ1 (upper panel) and C-SQ2 (middle panel), where C-SQ2 is designed to have a smaller loop area. E-SQ3 also shows similar periodic oscillations (lower panel) when the top gates are appropriately tuned (discussed in more detail below). The period \(\Delta B\) for each of the traces in Fig. 1f can be determined by Fourier analysis (Fig. 1g) to be 19 \(\mu\text{T}\).
31 μT and 21 μT for C-SQ1, C-SQ2 and E-SQ3, respectively. This gives us an effective loop area \( A_{eff} = \Phi_0/\Delta \phi \) (\( \Phi_0 = h/2e \) is the flux quantum, \( h \) is Planck’s constant, and \( e \) is the electron charge), which is consistently larger than the lithographically defined central (insulating) area. For superconducting structures that are much larger than the magnetic field penetration depth this difference arises from the Meissner effect in the superconducting region, which focuses the applied field into the centre of the SQUID loop. Even for 2D SQUIDs with dimensions smaller than the penetration depth (Pearl length) the fluxoid quantization can lead to a large flux-focusing effect\(^{19}\). We confirm this via numerical simulations of the 2D current distributions in thin-film superconductors\(^{20}\), which include the (weak) Meissner effect of the shielding currents (see the Supplementary Information for details of the simulations and flux-focusing factors). Taking into account the exact geometry of the devices, we find that the calculated periods (circles in Fig. 1g) agree well with the experiments.

Although the \( V(\Phi) \) oscillations clearly demonstrate the successful creation of SQUIDs at the LAO/STO interface, analysis of \( I_c(\Phi) \) oscillations provides a more quantitative understanding of the factors that determine the SQUID response. In the absence of thermal fluctuations the maximum critical current \( I_{\text{max}} \) across the SQUID is set by the Josephson coupling energy and the minimum critical current \( I_{\text{min}} \) is determined by the screening parameter \( \beta_s = I_{\text{max}}/\Phi_0 \) (where \( L \) is the total inductance of the SQUID loop). In other words \( L \) plays a crucial role in determining the visibility, \( \text{Vis} = (I_{\text{max}} - I_{\text{min}})/I_{\text{max}} \), of the \( I_c(\Phi) \) oscillations. The exact relation between \( \text{Vis} \) and \( \beta_s \) can be obtained by numerical simulations (see the red curve in Fig. 2c). To experimentally determine \( \text{Vis} \), we keep the back gate voltage \( (V_{bg}) \) fixed and record \( V-I \) curves for different values of \( \Phi \) (Fig. 2a) to estimate \( I_{\text{max}} \) and \( I_{\text{min}} \) (Fig. 2b). We find that for \( V_{bg} = 4V \), \( I_{\text{max}} = 88nA \) and \( \text{Vis} = 0.3 \).

From Fig. 2c we estimate \( \beta_s \) to be 2.1, giving \( L = 50nH \). This is nearly three orders of magnitude larger than the estimated geometric inductance of the SQUID loop. This additional inductance of the superconductor arises from the kinetic energy stored in the Cooper pairs and is known as the kinetic inductance \( (L_k) \). In general it can be expressed as \( L_k \propto (m^* n_d d) \), where \( m^* \) is the effective mass of the charge carriers, \( n_d \) is the superfluid density and \( d \) is the thickness of the superconductor. The 2D nature of the LAO/STO interface \( (d = 10nm) \), combined with an extremely low \( n_d \) value\(^{22}\) and large \( m^* \) value\(^{23}\), naturally result in a greatly enhanced \( L_k \). Although for most SQUID designs the contribution of \( L_k \) can be neglected, here the SQUID response is in fact dominated by \( L_k \). Thus, an analysis of the \( I_c(\Phi) \) oscillations, as described above, allows us to estimate the \( L_k \) of our SQUID loop.

Figure 2d shows that the kinetic inductance of the SQUID can be continuously tuned with the back gate (see the Supplementary Information for details of the analysis and error estimates). To our knowledge this is the only intrinsic superconductor where the kinetic inductance can be tuned \textit{in situ} via the field effect. Increasing \( V_{bg} \) induces more carriers at the LAO/STO interface which in turn increases the superfluid density\(^{22}\). This results in an overall decrease in \( L_k \). In addition to the back gate voltage, we expect the temperature to also have a substantial effect on \( L_k \). Increasing the temperature should reduce \( n_d \), thereby increasing \( L_k \). Indeed, Fig. 2e clearly shows that \( L_k \) increases with temperature. We therefore find that both the back gate and temperature dependence of \( L_k \) are mutually consistent with the picture that the SQUID modulations are determined predominantly by the kinetic inductance. We compare our results in Fig. 2e with numerical simulations, solving the London equations for our geometry\(^{24}\). Using the Ginzburg–Landau expression for the London penetration depth \( \lambda_L(T) = \lambda_L(0)/(1 - T/T_c)^{1/2} \) (ref. 24) and the experimentally...
determined $T_c = 213$ mK, we find a good agreement between the experiments and simulations (blue curve). For the Pearl length $\lambda_p(T) = 2k(T)^3/d$ we obtain a value of 3 mm at $T = 40$ mK, which is similar in magnitude to the value obtained via scanning SQUID measurements. Furthermore, we find that $I_c$ is dominated by the constrictions, which behave as quasi-1D structures connected to the 2D bulk superconducting reservoirs (see the Supplementary Information for a full description of the calculations).

The C-SQUIDs describe a simple yet effective way to demonstrate quantum interference at the LAO/STO interface. However, they do not allow one to locally control the weak links. In contrast to previous studies with a single top gate, two JJs (that is, $I_c \neq I_{cl}$, see SQUID schematic in inset to Fig. 4c) in each of the arms. We note that this process is completely reversible, whereby removing the gate voltages brings the device back to its original state, with no JJs.

The sensitivity of the JJs to the top gate voltages defines an optimal operating range for the E-SQUID. To quantify this we keep the right gate fixed at $V_r = -3.8$ V and monitor the visibility for different values of $V_l$ as shown in Fig. 3d–e. The left inset shows the voltages applied to the left/right gates (these measurements were performed during a different cool-down from the ones described in Fig. 3a–c, and therefore the absolute values of the voltages are somewhat different). When the left gate is relatively open (Fig. 3d) the oscillations are hardly visible ($V_l \sim 0$). As $V_l$ is made more negative the visibility increases, reaching a maximum value of 0.3 (Fig. 3f). By depleting the region below the left gate even further, the oscillations disappear again. This continuous transition can be physically understood as follows. As the top gates act locally, their influence on the superconducting banks is minimal. Therefore the maximum visibility is obtained when both JJs have the same critical current. This condition is satisfied for Fig. 3f ($V_l = -3.8$ V, $V_r = -2.9$ V). Tuning $V_l$ away from this optimal condition thus increases the asymmetry between the two JJs resulting in a reduced visibility.

For SQUIDs with a small loop inductance the dominant source of asymmetry arises due to unequal values of critical current in the two JJs (that is, $I_{cl} = I_{cl}$, see SQUID schematic in inset to Fig. 4c). On the other hand, when $L_{cl}$ is large (as is the case for LAO/STO) one must consider the combined effects of asymmetries in $L_c$ and $L_{cl}$ in the loop configuration over a smaller range. Here we observe distinct SQUID oscillations (Fig. 3c), thereby demonstrating the existence of an electrostatically defined JJ in each of the arms. We note that this process is completely reversible, whereby removing the gate voltages brings the device back to its original state, with no JJs.

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the two arms of the SQUID loop (see ref. 28 for a description about asymmetric SQUIDs). The most important consequence of such asymmetry is that the $I_c(\Phi)$ curves are offset along the $\Phi$ axis (Fig. 4a). Such offsets arise due to the large $L_s$, which produces a substantial self-flux ($\Phi_s$), in addition to the applied flux $\Phi$. When the phase drop across each JJ reaches $\pi/2$, $I_c$ reaches its maximal value $I_{\text{max}} = I_{d1} + I_{d2}$ and $\Phi_s(+) = I_{d1}L_s - I_{d2}L_s$. Reversing the direction of current bias results in the same magnitude of self flux, but now of the opposite sign (that is, $\Phi_s(-) = -\Phi_s(+)$). Thus $\Delta \Phi = 2(I_{d1}L_s - I_{d2}L_s)$, where $\Delta \Phi = \Phi_s(+) - \Phi_s(-)$. 

Figure 3 | Tunable Josephson junctions in E-SQUIDs. a, $V-I$ curves for different combinations of $V_1$ and $V_2$, with $V_{bg} = -1$ V. Inset: Schematic of the device. b, Zoom-in of the blue trace in a, c. 2D plot showing SQUID oscillations with the top gates optimally tuned ($V_1 = -3.4$ V, $V_2 = -3.8$ V). d-g. Variation in the visibility of the modulations as $V_1$ is reduced, with $V_2$ held constant. The values of $V_1$ and $V_2$ for each panel are indicated in the left inset. These measurements were performed during a different cool-down as compared with a-c, resulting in slightly different values of gate voltages.

Figure 4 | Controllable asymmetry in E-SQUIDs. a, $I_c(\Phi)$ oscillations for a symmetric (S) SQUID (dashed black curve) and an asymmetric (A) SQUID with large $L_s$ (solid blue curve). The maximum and minimum values of $I_c$ shift along the $\Phi$ axis by $\Delta \Phi$. b, $I_c(\Phi)$ oscillations with $V_1$ fixed and selected values of $V_2$. Black (blue) dashed line indicates the symmetric (asymmetric) configuration. c, Variation of $\Delta \Phi$ with $I_{\text{max}}$ extracted from b and d but also including more values of the top gate voltage. The dashed lines show linear fits. Inset: Schematic of an asymmetric SQUID. d, $I_c(\Phi)$ oscillations for fixed $V_1$ and varying $V_2$ values.
By controlling the two JJs in our E-SQUID we study the effects of such asymmetry in the SQUID response. In particular, we show that the ability to independently tune the critical current of each JJ gives us an alternative method to extract the kinetic inductance. We start with an electrostatic configuration identical to the one in Fig. 3c and plot $I_c(\Phi)$ (black curve in Fig. 4b). The black dashed line confirms that there are no discernible offsets on the $\Phi$ axis and the SQUID is in a symmetric configuration. We now hold $V_c$ constant (and thus $I_c$ does not change) and make $V_l$ less negative (increase $I_{cl}$). We find that the $I_c(\Phi)$ curves move towards the left (right) for positive (negative) current bias. The blue dashed line clearly indicates that $\Delta \Phi$ acquires a negative sign. Performing the same experiment with $V_l$ fixed and opening the right gate, we expect $I_c$ to decrease, thereby inducing a self-flux in the opposite direction. This sign reversal of $\Delta \Phi$ can be seen in Fig. 4d.

The variation of $\Delta \Phi$ with $I_{cl\max}$ is plotted in Fig. 4c. The blue (red) points correspond to measurements performed with $V_l$ varying while the other gate is fixed. As $\Delta \alpha \Phi/\Delta I_{cl} \approx 2 \Delta \psi_{n}$ and $\omega (\Delta \alpha \Phi/\Delta I_{cl}) \approx 2 \Delta \psi_{n}$, linear fits to these points (dashed lines) allow us to estimate $L_{k} \approx 31 \text{ nH}$ and $L_{K} \approx 36 \text{ nH}$. This difference is within the error bars of our estimates and we conclude that any intrinsic asymmetry in the $L_{k}$ values of the two arms is small. Thus, the observed shifts along the $\Phi$ axis arise from a combination of the large $L_{k}$ and unequal critical currents of the JJs. This is a particularly important finding in the context of LAO/STO because it suggests that any mesoscopic inhomogeneities in the superfluid density29,30 average out over a lengthscale of a few micrometres and do not have a considerable effect on the operation of these SQUIDs. Furthermore, even if such inhomogeneities are present, using the E-SQUID it is always possible to appropriately tune the critical current of the JJs to minimize the effects of self-flux.

The ability to probe the phase of the superconducting order parameter opens the door to answer more specific questions about the pairing symmetry. To do so, one could create more involved devices by combining the LAO/STO superconductor with an s-wave superconductor via JJs oriented along specific crystal axes. From a technological perspective, our studies of the E-SQUID demonstrate the operation of a completely new variety of JJs that are both electrostatically defined and electrostatically controlled. Such an architecture for creating JJs eliminates any detrimental effects of the physical interfaces between dissimilar materials. Detailed transport spectroscopy studies should determine whether such electrostatic interfaces are in fact superior.

Received 11 December 2015; accepted 23 May 2016; published online 11 July 2016

References


Acknowledgements

We thank T. Klappwijk, A. Gerdesi, A. Alchemov, A. Brinkman and J. Mannhart for useful discussions and feedback about the preliminary results. This work was supported by The Netherlands Organisation for Scientific Research (NWO/OCW) as part of the Frontiers of Nanoscience program, the Dutch Foundation for Fundamental Research on Matter (FOM), the Deutsche Forschungsgemeinschaft (DFG) via Project KO 1303/13-1 and EU-FP6-COST Action MP1308.

Author contributions

E.M. fabricated the devices. S.G. performed the transport measurements with help from E.M. S.G. and A.M.R.V.L.M. analysed the data. R.W., R.K. and D.K. carried out the numerical simulations and Y.M.B. provided theoretical support. L.M.K.V. and A.D.C. supervised the project. S.G. wrote the manuscript with input from all co-authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.G. and A.D.C.

Competing financial interests

The authors declare no competing financial interests.