Plain s-wave superconductivity in single-layer FeSe on SrTiO$_3$ probed by scanning tunnelling microscopy

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Single-layer FeSe film on SrTiO$_3$(001) has recently come to the fore as an interfacial superconducting system, with a transition temperature that is significantly enhanced with respect to bulk FeSe. The mechanism for this enhancement, and indeed for the superconductivity itself, is therefore of great interest. Although the film has a simple Fermi surface topology, its pairing symmetry is unclear. By using low-temperature scanning tunnelling microscopy, we have systematically investigated the superconductivity of single-layer FeSe/SrTiO$_3$ films, and report a fully gapped tunnelling spectrum and magnetic vortex lattice in the film. Quasi-particle interference patterns reveal scatterings between and within the electron pockets, and put constraints on possible pairing symmetries. By introducing impurity atoms onto the sample, we show that magnetic impurities such as Cr and Mn can locally suppress the superconductivity, but non-magnetic impurities (Zn, Ag and K) do not. Our results indicate that single-layer FeSe/SrTiO$_3$ has a plain s-wave pairing symmetry, with an order parameter that has the same phase on all Fermi surface sections.

Iron selenide (FeSe) has the simplest structure among iron-based superconductors, with a bulk transition temperature ($T_c$) of 8 K (ref. 1). Recently, the discovery of enhanced superconductivity in single-layer FeSe on SrTiO$_3$(001) has attracted tremendous interest$^{1-11}$, not only for the possible new $T_c$ records of Fe-based superconductors and interfacial superconductors (65 K (refs 3–5) or even higher$^{11}$), but also the intriguing mechanism that enhances the pairing. Thus, it is of great importance to understand the pairing symmetry and underlying electron structure of single-layer FeSe/SrTiO$_3$(001). Angle-resolved photoemission spectroscopy (ARPES) revealed that such films have only electron Fermi surfaces$^{5-3}$, similar to those of the alkali metal intercalated iron selenides (A$_i$Fe$_{1-x}$Se$_x$, A = K, Cs...). This seriously challenges the original $s_\pm$-pairing scenario proposed for the iron pnictides, which relies on the coupling between the electron pockets and the hole pockets at the Brillouin zone centre$^{22,23}$. In addition, both ARPES (refs 3–5) and previous STM studies$^{19-21}$ have found a fully gapped superconducting state in single-layer FeSe, indicative of the absence of gap nodes. Various possible pairing symmetries have been proposed for such systems with only electron pockets$^{24-27}$, such as plain $s$-wave pairing$^{24-26}$, ‘quasi-nodeless’ $d$-wave pairing$^{27,28}$, and several new types of $s_\pm$ pairing that involve the ‘folding’ of the Brillouin zone and band hybridization$^{19}$, orbital dependent pairing$^{29}$, or mixing of the even- and odd-parity pairing$^{30}$. Apart from the plain $s$-wave pairing, all the other proposed pairing symmetries involve a sign change of the order parameter on different sections of the Fermi surface. To distinguish these scenarios, phase-sensitive measurements are required, plus detailed knowledge of the superconducting gap.

STM has been shown to be able to provide information on the pairing symmetry by measuring the local response of superconductivity to impurities (in-gap impurity states)$^{22-24}$ and through quasi-particle interference (QPI) patterns$^{25-27}$. Here we report a low-temperature STM study on the surface structure, superconducting state and pairing symmetry of single-layer FeSe/SrTiO$_3$(001). The samples were grown using the molecular beam epitaxy (MBE) method under ultrahigh vacuum. We observed a fully developed superconducting gap and a magnetic vortex lattice, which confirms the high quality of the sample. The domain boundaries in the film are found not to be detrimental to the superconductivity. We then performed QPI mapping, where scatterings between and within the electron pockets are clearly present. The intensities of these scatterings as functions of energy near the superconducting gap edge, as well as their magnetic field dependence, are incompatible with $d$-wave pairing, which would induce a sign change between adjacent M points of the unfolded Brillouin zone. Furthermore, by means of the controlled introduction of magnetic (Cr, Mn) and non-magnetic (Zn, Ag, K) atoms onto the sample surface as impurities, we found that Cr and Mn impurities induce pronounced bound states within the superconducting gap, whereas Zn, Ag and K impurities do not induce any such states. These results provide evidence of a phase-unchanging plain $s$-wave (or $s_\pm$ to differ from the $s_\pm$ case) pairing state in single-layer FeSe/SrTiO$_3$(001).

The experiment was conducted in a commercial STM (Unisoku) at a temperature of 4.2 K. The sample preparation and experimental details are described in the Methods. Figure 1a shows the typical topography of single-layer FeSe/SrTiO$_3$(001). The surface is atomically flat, with winding, irregularly distributed domain boundaries. Figure 1b shows a closer image of such a boundary. Weak 2 $\times$ 1 reconstructions can be observed within individual domains, oriented along different directions for adjacent domains.

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The spatial dependence of the $b$ gives values for $V_c = 3\text{ mV}$ (a). The zero-bias conductance $a$ shows a series of spectra taken along a line cut across $I_c = 29\text{ nA}$, which is measured at 4.2 K within a single domain. A $I_c = 10\text{ V}$, $I = 100\text{ pA}$, $\Delta V = 1\text{ mV}$). $d$ shows a series of spectra taken along a line cut across a vortex core. At the core centre, a conductance peak with slight asymmetry near zero bias is observed. Such a vortex state is expected for fully gapped superconductors, and implies the film is in the clean regime. Away from the core centre, the vortex state splits into two symmetric peaks, which eventually merge into the gap edges. Similar behaviour has been observed in the $s$-wave superconductor NbSe$_2$ (refs 30) and also in Fe-based superconductors such as LiFeAs (ref. 31). Fitting the line profile of Fig. 2b gives values for the Ginzburg–Landau coherence length ($\xi$) along the [100] and [110] directions of 3.18 nm and 2.45 nm, respectively (Fig. 2c). The anisotropy of $\xi$ is expected to be related to the anisotropy of the superconducting gap and the underlying Fermi surface.

To further examine the electronic structure of single-layer FeSe, we performed $dI/dV$ mappings to reveal the QPI patterns. Here a clean $60 \times 60\text{ nm}^2$ area is chosen for the mapping (see Supplementary Fig. 3). Figure 3a–f shows the fast Fourier transformation (FFT) of such maps taken at various energies (see Supplementary Fig. 4 for further real-space maps and FFTs). The FFTs are four-fold symmetrized, as we observe no significant C4–C2 symmetry breaking in the QPI patterns, although there exist $2 \times 1$ reconstructions in the film (see Supplementary Fig. 5 for more details). Ring-like scattering structures and Bragg spots of the top Se lattice and underlying Fe lattice can be observed in the FFTs. It is known that QPI is caused by scatterings between states with the same energy. As observed by ARPES (refs 3–5) and sketched in Fig. 3g, single-layer FeSe/SrTiO$_3$ has, in principle, two almost

Figure 1 | Surface topography and superconducting gap spectrum of single-layer FeSe/SrTiO$_3$ (001). a, Large-scale topographic image of the film ($150 \times 150\text{ nm}^2$, $V_s = 3\text{ V}$, $I = 50\text{ pA}$). b, Topographic image around a domain boundary ($20 \times 9\text{ nm}^2$, $V_s = 30\text{ mV}$, $I = 50\text{ pA}$). The white spots and numbers indicate the locations where the spectra in d were taken. c, A typical $dI/dV$ spectrum taken on the film shows the superconducting gap (set point: $V_s = 30\text{ mV}$, $I = 100\text{ pA}$, $\Delta V = 1\text{ mV}$). d, A series of spectra taken along a line crossing the domain boundary, as marked in b. The set point is the same as in c.

(see also Supplementary Fig. 1, the same notation is used below). We note that the domain structures were also reported in previous STM studies, in which the domains are separated by discontinuous boundaries. However, here the atom lattice extends continuously across the boundary. This difference may be due to some subtle change of post-annealing conditions or substrate preparation, which has yet to be investigated. Detailed analysis shows that there is a 1/2-unit-cell offset along the [110] (Fe–Fe) direction between adjacent domains (Supplementary Fig. 2a), which is the same as reported in ref. 10. The surface structure observed here is consistent with the model proposed in ref. 28, which ascribed the formation of the $2 \times 1$ reconstructions and domains to ordered oxygen vacancies in SrTiO$_3$.

The typical superconducting gap spectrum of the film is shown in Fig. 1c, which is measured at $4.2\text{ K}$ within a single domain. A fully gapped structure with double peaks at $\pm 10\text{ mV}$ and $\pm 15\text{ mV}$ is observed. The gap bottom, with nearly zero tunnelling conduction, is $5\text{ meV}$ wide. We note that a similar gap structure with double peaks at $\pm 9\text{ mV}$ and $\pm 20\text{ mV}$ has been reported in refs 2,10; the difference here could be due to variations in post-annealing condition or substrate preparation. The spatial dependence of the superconducting gap is shown in Fig. 1d. A series of spectra are measured along a line cut, $20\text{ nm}$ in length, across the domain boundary (Fig. 1c). Within one domain, the spectra retain the same structure, although the coherence peaks vary slightly from point to point. At the domain boundaries, the gap retains the same width and the coherence peaks at $\pm 10\text{ mV}$ seem to be enhanced. In most cases, domain boundaries can be treated as non-magnetic line defects (impurities). The retention of a superconducting gap at the domain boundaries is consistent with insensitivity of the superconductivity to non-magnetic impurities, as shown later in the paper.

The superconductivity of the film was further investigated by imaging magnetic vortices. Figure 2a shows a zero-bias conductance (ZBC) mapping of a $70 \times 70\text{ nm}^2$ area, measured at $B = 11\text{ T}$. The emergence of vortices is clearly reflected by the region with high ZBC values. We found that the vortex lattice is disordered, possibly owing to interface defects/disorders. Figure 2b is a closer mapping of a single vortex. It is roughly diamond-shaped, with the diagonal along the surface [100] (Se–Se) direction. This is in contrast to the elongated vortex observed in thick FeSe films, which implies the low-energy states of single-layer FeSe are four-fold symmetric. Figure 2d shows a series of spectra taken along a line cut across a vortex core. At the core centre, a conductance peak with slight asymmetry near zero bias is observed. Such a vortex state is expected for fully gapped superconductors, and implies the film is in the clean regime.

NATURE PHYSICS | VOL 11 | NOVEMBER 2015 | www.nature.com/naturephysics

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Figure 2 | Magnetic vortex states of single-layer FeSe/SrTiO$_3$(001). a, A zero-bias conductance (ZBC) mapping, taken at $B=11$ T ($70 \times 70$ nm$^2$), set point: $V_b=30$ mV, $I=100$ pA, $\Delta V=1$ mV), shows the emergence of the vortex lattice. The total number of vortices in this area is counted 30, close to the expected value of 26 at $B=11$ T. b, A ZBC map around a single vortex. c, Line cuts taken along the [100] and [110] directions in b, together with exponential fittings ($y\propto \exp(-x/\xi)$). d, A series of spectra taken along the red arrow in b (set point: $V_b=30$ mV, $I=60$ pA, $\Delta V=1$ mV).

Figure 3 | QPI mappings of single-layer FeSe/SrTiO$_3$(001). a–f, Fast Fourier transformation (FFT) of real-space $dI/dV$ maps taken at various biases (as labelled). The FFTs are four-fold symmetrized and shown on a logarithmic scale. The positions of scattering vectors ($q_1$, $q_2$, $q_3$) are marked in a. Note that $q_2$ and $q_3$ coincide with the Bragg spots of the top Se lattice and underlying Fe lattice, respectively. The yellow arrow in a indicates the spots of the $2 \times 1$ reconstruction. g, Schematic of the Brillouin zone (BZ) and Fermi surface of single-layer FeSe/SrTiO$_3$(001). The black solid square is the unfolded BZ with a full width of $2\pi/a_{Fe-Fe}$. The dashed square is the folded BZ. The blue solid (dashed) ellipse is the electron (folded) pocket at the M points. Possible scattering vectors ($q_1$, $q_2$, $q_3$) are marked by red arrows. h, Simulated FFT image according to the electronic structure in the unfolded zone, at energies outside the superconducting gap. A band ellipticity of 0.9 is used. i, j, Line cuts extracted from the FFTs along the red and yellow dashed lines shown in b, respectively. The white dashed curves are parabolic fittings of the dispersive scattering rings. The short dashed lines indicate additional features in the range between 5 meV and 15 meV.

circular electron pockets with finite ellipticity at each M point of the folded Brillouin zone (BZ). Because one of them is ‘folded’ from the neighbouring M points by the potential of the Se lattice, it may have a weak spectral weight (shown as dashed ellipses). At energies outside the superconducting gap, possible intra-pocket ($q_1$) and inter-pocket ($q_2$) scattering vectors are illustrated in Fig. 3g. The reciprocal vector ($q_3$) that connects opposite M points is also marked. In Fig. 3h we show a FFT simulated by calculating the joint density of states: $\text{JDOS}(q) = \int \text{I}(k)|\text{I}(k+q)|^2 dq$. Here we used the unfolded BZ and neglected the folded bands. (The JDOS calculated by considering folded bands does not provide a better simulation, see Supplementary Fig. 6.) One can see that most of the basic
features in Fig. 3a–f are reproduced in the simulation. \( q_1 \) and \( q_2 \), coincident with the Bragg spots of the top Se lattice and the underlying Fe lattice, respectively. The centre ring (referred as Ring 1 in the following text) is contributed by intra-pocket scatterings from all the electron pockets, as exemplified by \( q_1 \). The rings centred at \((\pi, \pi)\) (referred as Ring 2) and equivalent points are contributed by inter-pocket scatterings between the nearest-neighbouring electron pockets. The rings centred at \((0, 2\pi)\) (with weak intensity, referred as Ring 3) and equivalent points should have the same properties as Ring 1, as they differ by just a reciprocal vector \( (q_1) \). The anisotropy of Ring 1, with broadening around the \((0, 0)\)–\((0, 2\pi)\) directions, could be due to band ellipticity (which is 0.9 in the simulation). A feature not reproduced in the simulation is that Ring 2 actually consists of arcs. It lacks four-fold symmetry and does not show a similar anisotropy to Ring 1. This may require consideration of the different orbital characters of bands at neighbouring M points (see also Supplementary Fig. 6 and its caption).

In Fig. 3i) we show line cuts extracted from the FFT images (in a colour scale) along the \((0, 0)\)–\((\pi, \pi)\) and \((0, 0)\)–\((0, 2\pi)\) directions, as marked in Fig. 3b. Except for the fully gapped region, the dispersion of Ring 2 is clearly present in Fig. 3i. Fitting with a parabolic form yields a band bottom at \(-60 \text{ mV}\), consistent with the previous ARPES data\(^5\). Ring 1 has basically a similar dispersion along the \((0, 0)\)–\((0, 2\pi)\) direction (Fig. 3)). But we found that in the range between 15 mV and 5 mV there are some additional features besides the parabolic fitting (marked by dashed curves in Fig. 3)). It can also be seen that Ring 1 in Fig. 3c (measured at 9 mV) has a different structure from those in Fig. 3a,b (measured above 15 mV). (A more detailed energy dependence can be found in Supplementary Fig. 4.) Because this energy range is near the superconducting gap edge, these features could be due to some gap anisotropy (as observed in single-layer FeSe with a more stretched lattice\(^6\) and in LiFeAs; ref. 32), and/or related to the double-gap structure of the spectrum, which may prove useful in understanding the superconductivity of the system and requires further study.

Next we focus on an investigation of the gap symmetry. Various pairing scenarios have been previously proposed for iron-based superconductors involving only electron pockets\(^22\)–\(^24\). For plain \( s \) or \( s_\pm \) pairing, the superconducting gap \( \Delta_s \) has the same phase in all the electron pockets (Fig. 3g)\(^14\)–\(^16\). For the ‘nodeless’ \( d \)-wave pairing symmetry\(^21\)–\(^24\) (Supplementary Fig. 6a), in the unfolded BZ, \( \Delta_s \) changes sign between the nearest M points, but is still nodeless. Normally, the finite folding potential will mix Fermi pockets of different signs in the folded BZ and gap nodes will develop. However, it was argued that if the folding potential is not significant\(^7\), a fully gapped spectrum may be observed in this scenario. In addition, various scenarios for \( s_\pm \) pairing have been proposed in the folded BZ (refs 19–21; see Supplementary Fig. 6b and its caption). In these scenarios, \( \Delta_{s\pm} \) changes sign between the inner and outer parts of the two electron pockets at each M point.

QPI can provide information on the gap structure and symmetry, as the scattering is dominated by Bogoliubov quasi-particles when the energy is near or within the superconducting gap edge. In practice, although a thorough understanding of the QPI pattern can be tricky, and often requires detailed calculations, it can still provide some qualitative hints about the pairing symmetry. Owing to the coherence factors in the scattering matrix element\(^27\), in the presence of non-magnetic scattering potentials, which are even under time reversal, scattering that preserves the sign of \( \Delta_s \) will be suppressed, and scattering that changes the sign of \( \Delta_s \) will be enhanced\(^22\)–\(^24\) (Supplementary Fig. 7).

In our case, scatterers that generate the QPI at zero field (Fig. 3a–f and Supplementary Fig. 4) are probably from interface disorder/defects, which are expected to be mostly non-magnetic. Thus, when the energy approaches the superconducting gap edge, the intensities of different scatterings will vary according to the pairing symmetry\(^24\). For example, in the case of \( d \)-wave pairing, as illustrated in Supplementary Fig. 7a, Ring 2 is due to inter-pocket sign-changing scattering and may have an enhanced intensity, whereas the sign-preserving Ring 1 and Ring 3 may have reduced intensity. In Fig. 4b we show the integrated FFT intensities over the three scattering rings, as a function of energy, after excluding regions near \((0, 0)\) and the Bragg spots (see Fig. 4a). All the intensities are normalized at \(-30 \text{ meV}\), where the intensity is much less affected by the coherence factor. We found that the intensities of all the scattering rings actually have similar energy dependences near the gap edge, which are peaked around \(\pm10 \text{ meV}\) and suppressed inside. This uniform energy dependence implies that none of these scattering channels have significant differences, suggesting that the sign of \( \Delta_s \) does not depend on the M point at which it is located. Thus, it is evidence against ‘nodeless’ \( d \)-wave pairing and consistent with the plain \( s \)– or \( s_\pm \)-wave pairing symmetries. Here the \( s_\pm \)-wave pairing cannot be distinguished from the plain \( s \)-wave pairing as the outer and inner parts of the two electron pockets at the M point of the folded BZ are not resolved in the QPI pattern (see Supplementary Figs 6 and 7b,c).

The phase information can also be deduced from the magnetic field dependence of the QPI. Because the vortices will introduce magnetic scattering potentials, which are odd under time reversal, they will enhance the sign-preserving scatterings and suppress the sign-changing scatterings\(^25\)–\(^28\). In Fig. 4c, we show the difference between the QPI patterns at \( B = 1 \text{ T} \) and \( B = 0 \text{ T} \), taken at 10.5 mV (see Supplementary Figs 8 and 9 for further comparisons at other energies). However, an apparent overall suppression is observed for all the scattering rings. We then compared the relative change in intensities of different scattering rings in the field, as a function of energy. As shown in Fig. 4d, one finds that all the scattering rings show similar suppression behaviour. (The greatest suppression is at around \(\pm10 \text{ meV}\).) This uniform behaviour again seems to suggest that the sign structures of \( \Delta_s \) on different M pockets are similar, which is incompatible with \( d \)-wave pairing. However, the discrepancy lies in the overall suppression in a magnetic field, rather than the enhancement that is expected for sign-preserving scatterings\(^27\). We note that vortices not only provide a magnetic scattering potential. It was argued that the surrounding supercurrent could induce a Doppler shift to the quasi-particle energy, which tends to suppress interference from all forms of scatterings\(^25\). Therefore, it is likely that this kind of suppression overwhelmed the expected enhancement of sign-preserving scatterings here.

To further determine the pairing symmetry, we probed impurity-induced effects\(^22\)–\(^24\). It is known that the response of superconductivity to local impurities depends on the pairing symmetry and the characteristics of the impurities\(^22\). For plain \( s \)-wave pairing, the non-magnetic impurities will not suppress superconductivity, according to Anderson’s theorem, whereas magnetic impurities are pair-breakers that can induce quasi-particle bound states within the superconducting gap\(^22\)–\(^23\). For phase-changing pairing symmetries, such as \( d \)-wave or \( s_\pm \)-wave pairing, both magnetic and non-magnetic impurities are pair-breakers, as observed in cuprates with Ni and Zn impurities\(^26\). This is because even scalar scattering will mix quasi-particles with different phases, which tends to eliminate the superconducting gap. For iron-pnictide superconductors, the proposed \( s_\pm \) pairing scenario with a phase change between hole and electron Fermi surfaces is expected to be sensitive to non-magnetic impurities\(^25\)–\(^28\), as is indeed observed in recent STM measurements\(^27\)–\(^28\). Thus, it is both desirable and practical to study the pairing symmetry of single-layer FeSe using impurity effects\(^29\).

The first essential step in studying the impurity effect is to introduce well-defined impurities into the sample and identify whether they are magnetic or non-magnetic. This has been proved to be a non-trivial task\(^32\)–\(^38\). In Fig. 1, we show that domain boundaries, which are most likely non-magnetic impurities,
Figure 4 | QPI intensity analysis for different scattering channels. a, QPI pattern at 16.5 meV, where the masked areas show the integration windows for different scattering rings. b, Integrated intensity (normalized at −30 meV) of the three sets of scattering rings, as functions of the energy. c, Relative difference between the QPI maps at $B=11\,\text{T}$ and $B=0\,\text{T}$, calculated using $(\text{FFT}_{11\,\text{T}} - \text{FFT}_{0\,\text{T}})/(\text{FFT}_{11\,\text{T}} + \text{FFT}_{0\,\text{T}})$. d, Relative difference between the integrated intensity at $B=11\,\text{T}$ and $B=0\,\text{T}$ as a function of the energy for the three set of scattering rings. The data points in the fully gapped region (from −5 meV to 5 meV) are neglected in b and d.

Figure 5 | In-gap states induced by magnetic impurities Cr and Mn. a, b, Topographic images of Cr and Mn single adatoms, respectively ($5 \times 5\,\text{nm}^2$ area, taken at $V_b=40\,\text{mV}, I=10\,\text{pA}$). The black spots represent the position of the surface Se lattice. c, d, Spectra taken along the arrows shown in a and b, respectively (set point: $V_b=30\,\text{mV}, I=120\,\text{pA}, \Delta V=1\,\text{mV}$). The distances from the measuring points to the centre of the atom are marked on the left. e, f, $dI/dV$ mappings taken at 3 mV and −3 mV, respectively, around a Cr atom (map size: $5 \times 5\,\text{nm}^2$, set point: $V_b=30\,\text{mV}, I=80\,\text{pA}, \Delta V=1\,\text{mV}$).

do not induce gap suppression. To perform more deterministic measurements, we developed a more controllable way to introduce impurities, by directly depositing pure metal elements onto the cold sample surface (∼50 K), thus giving impurities in the form of single adatoms. For comparison, two types of magnetic atoms (Cr and Mn) and three types of non-magnetic atoms (Zn, Ag and K) were deposited separately onto the sample. These atoms all appear as point protrusions in the topography image (Figs 5a,b and 6a–c; see also Supplementary Fig. 10 for large-scale images). Their adsorption sites are all identified to be the hollow site of the top Se lattice.
(as marked in the image), which is expected to be the most stable adsorption site. Considering interactions between the underlying FeSe film and low-temperature-adsorbed atoms are possibly weak, we can expect the impurity atoms to retain their magnetic/non-magnetic characteristic after adsorption. In Fig. S5, d, we show the local tunnelling spectra on the magnetic atoms. One can see that on the site of the magnetic impurity Cr, a pair of sharp peaks appears at ±3 mV and the superconducting coherence peaks are greatly suppressed. This is a hallmark of the impurity-induced in-gap states. Moving away from Cr, the impurity states are weakened and the superconducting gap gradually recovers. The spatial distribution of these in-gap states is shown in Fig. 5e (3 mV) and f (−3 mV). They clearly exhibit spatially inverted intensities, which is a characteristic of in-gap Bogoliubov quasi-particles with an anti-phase relation at positive and negative energies. Similar to the Cr case, the spectrum on the Mn impurity site also shows pronounced in-gap states at ±5 mV (Fig. 5d), with the gap recovering about 2.4 nm away from the impurity.

Figure 6d–f shows spectra taken across the non-magnetic impurities Zn, Ag and K. a–c, Topographic images of Zn, Ag and K adatoms (5 × 5 nm^2 size, all taken at V_b = 40 mV, I = 10 pA). Black spots represent the position of the surface Se lattice. d–f, Spectra taken along the arrows shown in a–c, respectively (set point for d: V_b = 40 mV, I = 150 pA, ΔV = 1 mV; set points for e and f: V_b = 30 mV, I = 120 pA, ΔV = 1 mV). The distances from the measuring points to the centre of the atom are marked on the left.

is strong evidence against phase-changing pairing symmetries such as d-wave and s±,wave pairing, and supports the phase-unchanging s- or s+-wave pairing scenarios.

Therefore, by combining the controlled impurity effects and QPI measurements, we show that the pairing symmetry of single-layer FeSe/SrTiO_3 is a plain s-wave pairing. This represents a critical step towards understanding the mechanism behind this remarkable interfacial superconducting system. Scenarios that give a plain s-wave pairing symmetry should be further examined, including the recently proposed phonon-mediated pairing enhancement scenario, orbital fluctuation-mediated pairing, and extended s-wave with a leading \cos(k_x) cos(k_y) pairing.

Note: upon finishing this work, we noticed another independent STM study on single-layer FeSe/SrTiO_3 in ref. 41.

Methods

Methods and any associated references are available in the online version of the paper.

Received 9 April 2015; accepted 22 July 2015; published online 31 August 2015

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Acknowledgements

We thank X.-G. Gong and D.-H. Lee for useful discussions. This work is supported by the National Science Foundation of China, and National Basic Research Program of China (973 Program) under the grant No. 2012CB921402, No. 2011CB801112, and No. 2011CB921802.

Author contributions

The sample growth and STM measurements were performed by Q.F., W.H.Z. and T.Z. The data analysis was performed by Q.F., X.L., J.P.H., T.Z. and D.L.F. T.Z. and D.L.F. coordinated the whole work and wrote the manuscript. All authors have discussed the results and the interpretation.

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 T.Z. or D.L.F.

Competing financial interests

The authors declare no competing financial interests.
Methods
SrTiO$_3$ (001) substrates with 0.5% Nb doping were cleaned by direct heating at 1,250 K in an ultrahigh vacuum. Single-layer FeSe films were grown by co-deposition of high-purity Se (99.999%) and Fe (99.995%) on substrates held at 670 K. The films were post-annealed at 800 K for 2~3 h after growth and then transferred to the STM chamber in situ. Transport measurements of the $T_c$ were not performed on the films studied here. Impurity atoms such as Cr, Mn, Zn, Ag and K were deposited onto the surface separately at low temperatures (~50 K). Conventional PtIr tips were used and cleaned by electron-beam heating before the STM measurements. Topographic images are taken in the constant current mode with a bias voltage ($V_b$) applied to the sample. The tunnelling conductance $dI/dV$ is measured by a standard lock-in method with a modulation frequency of 973 Hz. The typical modulation amplitude ($\Delta V$) is 1 mV.