Nematic transition and nanoscale suppression of superconductivity in Fe(Te,Se)

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The interplay of different electronic phases underlies the physics of unconventional superconductors. One of the most intriguing examples is a high-temperature superconductor, FeTe1−xSe, (refs. 1–11). This superconductor undergoes both a topological transition12, linked to the electronic band inversion, and an electronic nematic phase transition, associated with rotation symmetry breaking, around the same Se composition where the superconducting transition temperature peaks12,13. In this regime, nematic fluctuations and symmetry-breaking strain could be important, but this is yet to be fully explored. Using spectroscopic-imaging scanning tunnelling microscopy, we study the electronic nematic transition in FeTe1−xSe, as a function of composition. Near the critical Se composition, we find electronic nematicity in nanoscale regions. The superconducting coherence peaks are suppressed in areas where static nematic order is the strongest. By analysing atomic displacement in scanning tunnelling microscopy topographs, we find that small anisotropic strain can give rise to these strongly nematic localized regions. Our experiments reveal a tendency of FeTe1−xSe, near x ≈ 0.45, to form puddles hosting static nematic order, suggestive of nematic fluctuations pinned by structural inhomogeneity, and demonstrate the effect of anisotropic strain on superconductivity in this regime.

Fe-based high-temperature superconductors have emerged as one of the leading platforms to study various correlated electron states and electronic phenomena associated with non-trivial topology. A prototypical example in this regard is the superconductor FeTe1−xSe, (Fe(Te,Se))1−x, which has been investigated intensively in recent years, predominantly motivated by the discovery of topological surface states1,2 and Majorana zero modes3,4,5 near the critical composition, x ≈ 0.45. A somewhat overlooked aspect of the intrinsic physics of Fe(Se) near the same composition is that it is also expected to undergo an electronic nematic transition, characterized by a rotation symmetry breaking, where the superconducting transition temperature (Tc) at ambient conditions reaches its peak12,13. In this regime, elastoresistance experiments have uncovered signatures of nematic critical fluctuations and demonstrated an enormous impact of strain14. However, the implications of electronic nematicity and strain on the underlying physics of Fe(Se) have not been fully explored so far.

The experimental signatures of electronic nematicity in Fe-based superconductors include resistivity anisotropy, typically accompanied by a small orthorhombic distortion below the structural transition temperature T0 (refs. 14–16), lifting of the band degeneracy17 and a pronounced C2-symmetric electron scattering18–21. A material can be tuned towards the nematic transition by various parameters, including chemical composition change22–24, strain22,25 and pressure22,25. Although the order parameter is typically considered only in the average crystal structure, it is conceivable that short-range or local order may persist beyond this point. This behaviour could emerge in a system close to the nematic phase transition, such as Fe(Se) at x, which, although not in the orthorhombic phase at low temperature22,23, shows signatures of nematic fluctuations2 that can, in principle, be pinned to become static in localized regions.

In this Letter, we use low-temperature spectroscopic-imaging scanning tunnelling microscopy to study ultrahigh-vacuum (UHV)-cleaved bulk single crystals of Fe(Se) as a function of composition x across the electronic nematic transition (Fig. 1b). Each unit cell of Fe(Se) consists of an Fe layer sandwiched between two Se/Te chalcogen layers (Fig. 1a). STM topographs show a square atomic lattice with lattice constant a0 ≈ 3.8 Å. The bright (dark) atoms in the STM topographs represent Te (Se) atoms in the topmost layer (Fig. 1c), which can be counted to confirm the chemical composition (Supplementary Discussion 1). To gain a comprehensive insight into the evolution of electronic properties with x, we study Fe(Se) samples with three different Se:Te bulk compositions: x ≈ 0.35, x ≈ 0.45 and x ≈ 0.50 (Fig. 1). Characteristic dI/dV spectra for all three compositions show a superconducting gap of comparable size, Δg ≈ 2 meV (insets, Fig. 1d–f), which probably represents a combination of the gaps of the hole pockets at Γ, all with similar magnitudes within ±0.5 meV (refs. 4,28).

In contrast to the relative insensitivity of the gap size on composition x, normalized differential conductance maps LR(x, V) (defined as dI/dV(r, V)/(dIr(r)/dV), where r is the lateral tip position and V is the bias applied to the sample) exhibit a remarkable evolution within the same composition range (Fig. 1d–f). Starting with the highest composition studied (x ≈ 0.50), we find that the LR(x, V) maps show nanometre-scale electronic modulations preferentially oriented along an Fe–Fe direction, everywhere on the sample (Figs. 1f and 2 and Supplementary Fig. 13). As we describe in more detail in subsequent paragraphs, this suggests that Fe(Se) at x ≈ 0.50 is in an electronic nematic state. By contrast, LR(x, V) maps of the lowest composition studied (x ≈ 0.35) show no sign of unidirectional features, indicative of a tetragonal state and the absence of electronic nematicity (Figs. 1d and 2i and Supplementary Fig. 12). Interestingly, at the intermediate composition (x ≈ 0.45), we observe two different types of region in the LR(x, V) maps: one characterized by unidirectional modulations and the other where these modulations are notably absent (Fig. 1e). To illustrate the morphological difference between these areas, we show a domain boundary in Fig. 1e. The transition is atomically smooth, and it does not show...
any obvious structural imperfections or surface buckling. The spatial extent of modulated regions can be as large as several micrometres in size in different \( x \approx 0.45 \) samples (Supplementary Discussion 3).

We note that the modulations are not immediately obvious from STM topographs, which look indistinguishable in regions with or without the modulations, with no apparent change in Se:Te ratio or excess Fe concentration (Fig. 1c and Supplementary Discussion 1).

To characterize the modulated regions, we acquire \( L(\mathbf{r},V) \) maps as a function of energy over a larger field of view (Fig. 2). Our first observation is that the modulation wavelength strongly changes with energy over a few millielectronvolt energy range across the Fermi level. This trend is clear in Fourier transforms of the \( L(\mathbf{r},V) \) maps, which reveal an arc-shaped wavevector oriented along one of the Fe–Fe lattice directions (the \( a \) axis) in momentum space. Notably, we observe almost no intensity along the other Fe–Fe direction (\( b \) axis). The magnitude of this wavevector quickly decreases with increased energy (Fig. 2f–h).

Dispersing electronic modulations in differential conductance maps typically originate due to interference and scattering of electrons at the surface in what is also known as quasiparticle interference (QPI) imaging. For guidance in determining the origin of the dominant wavevector in our data, we refer to the band structure schematic of Fe(Se,Te) near \( x \approx 0.45 \) (the relevant bands are shown in Fig. 2a,b). The Fermi surface of Fe(Se,Te) consists of hole pockets at \( \Gamma \) and electron pockets at the M point\(^{1,29}\). By comparing the magnitude of the scattering vector and its dispersion velocity to the expected band structure from angle-resolved photoemission measurements\(^{1,28,30}\), we can trace it to the scattering between the \( \Gamma \) hole pocket composed of \( d_{x'y'} \) and \( d_{xy} \) orbitals (Fig. 2a,b). Intra-pocket scattering at the M point can be ruled out based on (1) the sign of the dispersion velocity, which is opposite of what we observe, and (2) empirical evidence that the electronic states near the Brillouin zone edge in these systems are difficult to pick up with STM tips\(^{31,22}\). The strongly anisotropic scattering signature is consistent with scattering between \( d_{x'y'} \) orbitals (\( Q_{\alpha} \)), while the scattering between the \( d_{xy} \) orbitals (\( Q_{\beta} \)) is much weaker and cannot be resolved in our measurements. The striking difference in the scattering strengths can be understood in terms of the variation of the spectral weight of different orbitals, giving rise to orbital-selective quasiparticles in the electronic nematic state\(^{30}\). This is also probably accompanied by the elongation of the Fermi surface, creating near-parallel Fermi sheets that enhance scattering along the \( a \) axis (Fig. 2a). In FeSe, it was found that the spectral weight of quasiparticles associated with \( d_{xy} \) orbitals is much larger than that of either \( d_{x'y'} \) or \( d_{xy} \) orbitals\(^{32}\). This picture is consistent with our spectroscopic measurements of modulated electronic regions of Fe(Se,Te), pointing towards the emergence of local electronic nematic order in Fe(Se,Te) at \( x \approx 0.45 \).

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**Fig. 1** | Nematic transition as a function of composition in Fe(Se,Te). a, Schematic of the crystal structure of Fe(Se,Te) with Fe (and Se/Te) denoted as blue (and grey) spheres. An example of an excess interstitial Fe atom (Fe\(_i\)) located between four adjacent Se/Te atoms is circled in black. **b**, Temperature versus Se composition \( x \) phase diagram, portraying the electronic nematic transition. The three different compositions studied in this work are denoted by cyan \( (x \approx 0.35) \), green \( (x \approx 0.45) \) and purple \( (x \approx 0.50) \) circles. **c,e**, STM topograph of a domain boundary (dashed line) between the four-fold symmetric region (bottom half) and a region hosting additional electronic modulations (top half) \( (V) \) maps, \( V \approx 0.45 \) samples (Supplementary Discussion 3). **d, f**, \( L(\mathbf{r},V) \) maps acquired on top of the \( V \approx 0.35 \) (d) and \( x \approx 0.50 \) (f) samples. Lower right insets in d-f show the associated spatially averaged \( \mathrm{d}/\mathrm{d}V(\mathbf{r},V) \) spectra, and upper right insets show two-fold-symmetrized Fourier transforms of the corresponding \( (\mathbf{r},V) \) maps. Lower left inset in e shows a two-fold symmetrized Fourier transform of the bottom half of the \( L(\mathbf{r},V) \) map in e. Excess interstitial Fe atoms seen as bright protrusions in STM topographs are circled in cyan in e. Scale bars in d-f, 10 nm. STM set-up conditions: \( V_{\text{sample}} = -10 \text{ mV}, I_{\text{set}} = 100 \text{ pA}, V_{\text{exc}} = 2 \text{ mV} \) (c,e); inset spectrum, \( V_{\text{sample}} = 10 \text{ mV}, I_{\text{set}} = 60 \text{ pA}, V_{\text{exc}} = 0.3 \text{ mV} \) (e); \( V_{\text{sample}} = 10 \text{ mV}, I_{\text{set}} = 50 \text{ pA}, V_{\text{exc}} = 0.3 \text{ mV} \) (d); \( V_{\text{sample}} = 10 \text{ mV}, I_{\text{set}} = 60 \text{ pA}, V_{\text{exc}} = 0.3 \text{ mV} \) (f).
We observed local electronic nematicity in 10 different $x \approx 0.45$ Fe(Te,Se) single crystals that were grown by three different research groups (Supplementary Table 2), which highlights the ubiquity of the phenomenon and allows us to explore the relationship between local nematicity and superconductivity. We find that electronic nematicity is only present in regions where superconducting coherence is suppressed (Fig. 3f–i) or even completely absent (Fig. 3a–e) at our measurement temperature of 4.5 K. This is in contrast to areas where $C_4$-symmetric electronic modulations associated with electronic nematicity are notably absent, and the superconducting gap is evident at the same temperature (Fig. 3k–o). Although our observations demonstrate that superconductivity and static electronic nematicity can coexist in Fe(Te,Se), they also suggest a direct local competition between the two in this system. We note that QPI dispersions across different electronic nematic regions are comparable, regardless of the presence or absence of superconductivity. The scattering wavevectors at the Fermi level ($q_s \approx 0.2 \text{Å}^{-1}$ in Fig. 3d,i) match well with angle-resolved photoemission spectroscopy measurements of the associated $\Gamma$ pocket$^{40}$. We also note that we are able to find nematic domains oriented along both inequivalent Fe–Fe lattice directions in the same sample (Supplementary Discussion 3), ruling out tip anisotropy as the cause of our observations.

Next, we explore why electronic nematic order may emerge in some regions, but not in others. We rule out the distribution of excess Fe interstitials, which are known to strongly affect the electronic properties of Fe(Te,Se)$^{31–33}$, because their concentration in our samples is minimal and their individual positions are not correlated with electronic nematic regions (Supplementary Discussion 1). We also rule out variations in Se:Te composition by calculating the local composition from the STM topographs (Supplementary Fig. 2 and Supplementary Discussion 1). This leaves the possibility of structural inhomogeneity. Although our samples are attached to sample plates using a standard procedure, and are not intentionally strained (Methods), small strain of a few tenths of a percent may be
imparted on the sample in this geometry due to small differences in thermal contraction coefficients. To investigate this, we used the strain analysis established in our previous work, which can detect local variations in the atomic lattice constant with a fraction of a percent resolution (Supplementary Discussion 2).

To examine the effects of external strain on the Fe(Te,Se) we focus on a region with pronounced topographic variations (Fig. 4). By inspecting different components of the strain tensor, we show the existence of spatially varying strain, with the most pronounced magnitude along the a axis (Supplementary Fig. 3). By subtracting the strain components along the a and b axes, we created a map of relative antisymmetric (anisotropic) strain, which shows spatial variations at the order of 1% (Fig. 4c). We then compare the calculated antisymmetric strain with the local amplitude of electronic modulations over the same region of the sample (Fig. 4d). The two observables exhibit a remarkably high cross-correlation coefficient of ~0.6 (Fig. 4g), thus demonstrating that antisymmetric tensile strain can drive the emergence of local electronic nematic order. Interestingly, superconductivity is also strongly suppressed over the same strained regions (Fig. 4f,h), consistent with our observations in Fig. 3. This can in turn be related to a reduced superfluid density in the same areas. Although small variations in the coherence peak height (dI/dV(r,±Δ)) have been detected directly on top of Se versus Te atoms (Supplementary Fig. 8), a nearly complete suppression of gap edge peaks and filling of the gap observed in average dI/dV spectra in our work clearly go beyond this effect. This is further confirmed by calculating the local chemical composition x, which shows no notable correlation with spatial variations in RCPH(r) (Supplementary Fig. 10). Thus, inhomogeneity in local composition x cannot be the dominant driver behind the spectral gap suppression.

Finally, we compare the effects of strain near the nematic transition at x ≈ 0.45 and away from it. In contrast to our observations at x ≈ 0.45, we find that anisotropic strain in x ≈ 0.35 samples does not give rise to unidirectional scattering in differential conductance maps within our resolution (Supplementary Fig. 9). Moreover, it leads to a substantially smaller suppression of RCPH for a comparable amount of anisotropic strain (Supplementary Fig. 8). This is consistent with the physical picture portrayed by bulk elastotransport measurements of a related superconductor BaFe1−xCoxAs2, where the suppression of superconducting Tc by anisotropic strain was found to be strongly dependent on bulk composition and most pronounced near the nematic critical point. Our experiments

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**Fig. 3** Spectroscopic-imaging STM of critical composition. a–e, STM topograph (a), average dI/dV spectrum (b), linecuts of dI/dV spectra (c) and linecuts in two-fold-symmetrized Fourier transforms of l(r,V) maps along q⊥ (d) and q∥ (e) directions in x ≈ 0.45 sample 3. The insets in d and e portray the directions along which the linecuts were taken in reciprocal space. f–j, k–o, Equivalent panels corresponding to a–e for x ≈ 0.45 sample 4 (f–j) and sample 5 (k–o). The green lines in d and f are visual guides showing the dispersion of Qa. Dashed lines in e, j, n and o denote the absence of scattering vectors expected at these positions. Each linecut was averaged by seven consecutive pixels along the transverse direction. STM set-up conditions for a–e: topograph, Vsample = 400 mV, Iset = 60 pA; spectrum and dispersion, Vsample = 10 mV, Iset = 60 pA, Vref = 0.3 mV. STM set-up conditions for f–j: topograph, Vsample = 10 mV, Iset = 60 pA; spectrum and dispersion, Vsample = 5 mV, Iset = 30 pA, Vref = 0.2 mV. STM set-up conditions for k–o: topograph, Vsample = 2 mV, Iset = 40 pA; spectrum and dispersion, Vsample = –10 mV, Iset = 100 pA, Vref = 0.2 mV.

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**Table 1** Superconductivity

| Sample | Tc (K) | Δ (meV) | x | Composition |
|--------|--------|---------|---|-------------|
| 3      | 3.5    | 0.2     | 0.45 | Fe(0.35)Te(0.65)Se |
| 4      | 3.7    | 0.3     | 0.45 | Fe(0.35)Te(0.65)Se |
| 5      | 3.8    | 0.4     | 0.45 | Fe(0.35)Te(0.65)Se |
provide a complementary insight by further demonstrating that this suppression is accompanied by strengthening of static electronic nematicity. The emergence of microscopic nematic regions with strongly suppressed superconductivity around $x = 0.45$ is seemingly at odds with the global picture of bulk superconducting $T_c$ that peaks at the same composition (Supplementary Fig. 16). However, this could be explained by the presence of an underlying nematic quantum critical point in Fe(Se,Te). In this scenario, the bulk $T_c$ would be enhanced\(^{15}\), while the system would at the same time become more susceptible to the formation of electronic nematic puddles. The observation of quantum critical fluctuations associated with a divergent nematic susceptibility in the same material\(^{14}\) provides additional support for the potential existence of an underlying nematic quantum critical point in Fe(Se,Te) at zero temperature. Local static nematicity observed at $x = 0.45$ could be a reflection of nematic critical fluctuations that are pinned to become static in local regions.

Recently, suppressed superconducting coherence and substantial zero-energy spectral weight have been reported along topographic ribbons in Fe(Se,Te); this was attributed to a one-dimensional Majorana mode\(^{1}\). By applying our strain analysis to the data from ref. \(^7\), we find anisotropic local strain as high as 3–5\% in these regions (Supplementary Discussion 6). This is much larger than that in our data, where we already observe a notable suppression of superconducting coherence peaks and an increase in in-gap conductance. This strain analysis, in combination with our experiments, provides strong evidence that strain can be responsible for suppression of the superconducting coherence and gap filling observed in these regions. It remains to be seen to what extent any additional spectral weight due to a Majorana mode can exist within the same regions.

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Methods
FeTe$_{1-x}$Se$_x$ bulk single crystals were grown using the self-flux method and post-annealed to remove excess Fe impurities. The Se:Te ratio estimated from STM topographs (Supplementary Discussion 1) is comparable to the expected value from energy-dispersive spectroscopy measurements. The samples were attached to the STM sample plate (Titanium) using H20E silver epoxy (EPO-TEK) and heated to ~100–150 °C to cure the epoxy. An aluminium cleave bar was attached to the top of the sample using the same type of epoxy and cured at the same temperature. The samples were cleaved in UHV (pressure of 10$^{-10}$ torr) to expose a clean surface free of contaminants, and immediately inserted into the STM. The cleave temperature used was either ~300 K or 80 K, and there was no noticeable difference in the quality of the surface between the two. We note that 10 Fe(Te,Se) samples with $x \approx 0.45$ were measured in this work, and we show representative data from eight samples in the main text and Supplementary Information. For each composition studied, samples were labelled sequentially starting with number 1 (that is, $x \approx 0.45$ (samples 1–8) and $x \approx 0.35$ (samples 1–2)). The chemical composition reported for each sample is the bulk value determined by energy-dispersive X-ray spectroscopy, and is comparable to the composition determined by counting individual atoms in STM topographs (Supplementary Table 1 and Supplementary Discussion 1). Representative magnetization measurements for each composition studied are shown in Supplementary Fig. 16.

STM data were acquired using a Unisoku USM1300 STM at the base temperature of 4.5 K. Spectroscopic measurements were made using a standard lock-in technique at a frequency of 915 Hz, with bias excitation as detailed in the figure captions. The STM tips used were home-made chemically etched tungsten tips, and were annealed in UHV to a bright orange colour before STM imaging. We used normalized conductance $I(r,V)$ maps (defined as $dI/dr(V)/I(r,V)/V$) in our analysis to remove the effect of the STM tip set-up condition$^{20,22}$.

Data availability
Data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Code availability
The computer code used for data analysis is available upon request from the corresponding author.

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Author contributions
STM experiments were carried out by H.Z. and H.L. L.D., B.X., J.S. and R.Z. grew the Fe(Te,Se) single crystals, supervised by M.F., G.G., J.H. and S.D.W. H.Z. and H.L. analysed the STM data with guidance from I.Z. Z.W. provided theoretical input on the interpretation of STM data. I.Z., Z.W., H.Z. and S.D.W. wrote the manuscript with input from all the authors. I.Z. supervised the project.

Competing interests
The authors declare no competing interests.

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