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Atomic-scale strain manipulation of a charge density wave


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A charge density wave (CDW) is one of the fundamental instabilities of the Fermi surface occurring in a wide range of quantum materials. In dimensions higher than one, where Fermi surface nesting can play only a limited role, the selection of the particular wavevector and geometry of an emerging CDW should in principle be susceptible to controllable manipulation. In this work, we implement a simple method for straining materials compatible with low-temperature scanning tunneling microscopy (STM/S), and use it to strain-engineer CDWs in 2H-NbSe2. Our STM/S measurements, combined with theory, reveal how small strain-induced changes in the electronic band structure and phonon dispersion lead to dramatic changes in the CDW ordering wavevector and geometry. Our work unveils the microscopic mechanism of a CDW formation in this system, and can serve as a general tool compatible with a range of spectroscopic techniques to engineer electronic states in any material where local strain or lattice symmetry breaking plays a role.

Significance

Charge density waves (CDWs) are simple periodic reorganizations of charge in a crystal, and yet they are still poorly understood and continue to bear surprises. External perturbations, such as strain or pressure, can in principle push a CDW phase into a different ordering geometry. However, engineering this type of quantum criticality has been experimentally challenging. Here, we implement a simple method for straining bulk materials. By applying it to 2H-NbSe2, a prototypical CDW system studied for decades, we discover two dramatic strain-induced CDW phase transitions. Our atomic-scale spectroscopic imaging measurements, combined with theory, reveal the distinct roles of electrons and phonons in forming these emergent states, thus opening a window into the rich phenomenology of CDWs.


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(30) CDW ordering of ~3a₀ period (CDW-3a₀) below 33 K (10, 21, 28). In our strained samples of 2H-NbSe₂, in addition to detecting the well-known CDW-3a₀ in small patches (Fig. 1B), we reveal two additional types of charge ordering in other large regions of the sample—unidirectional “stripe” (1Q) ordering with 4a₀ period (CDW-4a₀) and a triangular (3Q) ordering with a 2a₀ period (CDW-2a₀) (Fig. 2 C and D). The wavevectors of all observed CDWs are found to be oriented along the Γ-M directions, based on the Fourier transforms of STM topographs where each CDW peak lies exactly along the atomic Bragg wavevector $\mathbf{Q}_{\text{Bragg}}$ (Fig. 1 E–G). We have observed the same CDW wavevectors on multiple NbSe₂ single crystals attached to substrates with mismatched TECs (Methods). Interestingly, all of the CDW wavevectors measured are commensurate with the lattice, in contrast to the recently observed incommensurate 1Q CDW phase with an ~3.5a₀ period, which was found in accidentally formed nanometer-scale “ribbons,” and which could possibly be attributed to strain (21, 29). The magnitudes of the wavevectors identified in our experiments also do not change as a function of energy (SI Appendix, section I), which eliminates a dispersive quasiparticle interference (QPI) signal (10) as the cause of our observations.

The presence of multiple distinct CDWs in different regions of the same strained single crystal suggests that these phases may be associated with strain of locally varying magnitude and/or direction. Although in an ideal homogeneous sample attached to a substrate under elastic deformation the strain is expected to remain laterally uniform as it is transmitted to the surface, this is unlikely to be the case in real materials that are inevitably inhomogeneous. In our NbSe₂ sample glued to a silica substrate by epoxy, inhomogeneous transmission of strain could arise due to the weak van der Waals interlayer bonding that makes the material prone to warping (4) or inhomogeneous glue distribution at the interface. To shed light on what type of strain, if any, might play a role in the formation of each observed CDW, it is necessary to quantify strain at the atomic length scales. We start with an STM topograph $T(\mathbf{r})$ to which we apply the transformation $\mathbf{r} \rightarrow \mathbf{r} - \mathbf{u}(\mathbf{r})$ [where $\mathbf{u}(\mathbf{r})$ is the total displacement field obtained from the Lawler–Fujita algorithm (30)], such that the resulting topograph $T(\mathbf{r} - \mathbf{u}(\mathbf{r}))$ contains a perfect hexagonal lattice. We disentangle the experimental artifacts (piezo and thermal drift) from structural strain in $\mathbf{u}(\mathbf{r})$ by fitting and subtracting a polynomial background to create the strain field $s(\mathbf{r})$. The directional derivatives of $s(\mathbf{r})$ form a strain tensor $s_{ij}(\mathbf{r}) \equiv \partial s_{ij}(\mathbf{r})/\partial r_l$ (where $i, j = x, y$), and their linear combinations provide information on the strain type and magnitude (31–33) (SI Appendix, section II). For example, we can extract biaxial (isotropic) strain as $(s_{xx} + s_{yy})/2$ (Fig. 2 C and D). Although this algorithm cannot provide us with the absolute value of the applied strain, it can extract the relative local strain variations between different regions within a single STM topograph. Applying this procedure to the occasionally encountered boundaries between the CDW-3a₀ and the newly observed CDW-2a₀ and CDW-4a₀ phases (Fig. 2 A and B), we find that regions hosting CDW-2a₀ and CDW-4a₀ are both under biaxial tensile strain (Fig. 2 C and D) with a prominent uniaxial strain component relative to the CDW-3a₀ phase (SI Appendix, section II). This
direct proof that in-plane tensile strain plays an important role in driving the observed charge ordering transitions. To gain insight into the effects of strain on local electronic band structure in each region of the sample, we use QPI imaging, a method that applies 2D Fourier transforms (FTs) to the STM $dI/dV$ maps to extract the electronic band dispersion. First, we focus on a large region of the sample hosting exclusively CDW-4a$_0$, in which the FTs of the $dI/dV$ maps show a circular QPI morphology (Fig. 3 A–C) with the strongest intensity along the $\Gamma$–M direction. Higher momentum-space resolution of our data compared with previous experiments on NbSe$_2$ hosting a CDW-3a$_0$ (10) allows us to disentangle two distinct QPI peaks Q$_1$ and Q$_2$ (Fig. 3B), which arise from backscattering within the two Fermi surface pockets concentric around $\Gamma$ (Fig. 3B, Inset and SI Appendix, section III). By measuring the positions of these peaks as a function of energy, we can map the two bands crossing the Fermi level along the $\Gamma$–M direction (Fig. 3D). Interestingly, the electronic band structure is only slightly different compared with that of the well-characterized unstrained material (10) (SI Appendix, section IV), despite the dramatic changes in both the observed CDW wavelength and its geometry.

In the CDW-2a$_0$ region, we observe only the Q$_1$ vector, while Q$_2$ is notably absent in our measurable momentum range, in contrast to the CDW-4a$_0$ area (Fig. 3 E–G). This suggests a more prominent change in the band structure. Our strain measurements in Fig. 2 reveal that this region of the sample is under tensile strain, which would lead to a larger momentum-space separation of the pockets around $\Gamma$ (Fig. 3F, Inset), owing to
the concomitant increase in the interlayer tunneling (as the interlayer orbital overlaps increase). Our OPI measurements however have been unable to detect any scattering vectors larger than $Q_{Bragg}/2$ in either CDW-2$a_{0}$ or CDW-4$a_{0}$ regions at any energy (SI Appendix, section V), and we therefore cannot directly observe the shift of $Q_{0}$ to higher momenta. A possible explanation for the lack of signal at higher momenta may be canting of the orbital texture toward more in-plane orientations (34), making them likely to be detected by the STM tip. Nevertheless, our measurements reveal that a larger distortion to the Fermi surface accompanies the formation of a CDW-2$a_{0}$.

**Discussion**

Having quantified the changes in the structural and electronic properties of regions hosting CDW-2$a_{0}$ and CDW-4$a_{0}$, we turn to the fundamental question of what drives and stabilizes a particular CDW wavevector and geometry in this quasi-2D system. Taking into account the exactly commensurate nature of all observed CDWs, Fermi surface nesting is even more unlikely to play a role for the observed CDW phases. To provide further insight, we construct a simple model that captures the strain effects on both the electronic structure and phonon dispersion. We start with a tight-binding fit to the angle-resolved photoemission spectroscopy (ARPES) data (26, 35), including the in-plane strain by modifying the hopping integrals, and employ the Random Phase Approximation to calculate the resulting full electronic susceptibility $D_{j}(q)$ (Methods and SI Appendix, section VI). We separately introduce the effect of the uniaxial strain on the phonons by shifting their bare energies differently in lattice-equivalent directions (29). Within this model’s description, the CDW ordering vector can be identified as the first wavevector for which the calculated susceptibility $D_{2}(q)$ exceeds the bare phonon energy $\Omega(q)$ identified in resonant inelastic X-ray scattering experiments (20, 36).

In our model, we consider the effects of both uniaxial and biaxial in-plane strain, each modeled by a relative change in the nearest-neighbor overlap integrals; $\sigma$ associated with the uniaxial strain and $\tau$ associated with the biaxial strain (for more details, see Methods and SI Appendix, section VI). For simplicity, we explore the effects of the two types of strain separately. We find that biaxial strain by itself has very little effect on the shape of $D_{2}(q)$, while the uniaxial strain can lead to a significant change in $D_{2}(q)$ and induce different types of CDW ordering (Fig. 4). Specifically, we find that $\sigma = 0.1$ (stretching along $\Gamma$-M and compressing along the perpendicular $\Gamma$-K direction) stabilizes the CDW-4$a_{0}$ order, with a peak in $D_{2}(q)$ forming near 0.25$Q_{Bragg}$ and 0.28$Q_{Bragg}$ (modeled by $\sigma = 0.1$) resulting in a 1Q CDW-4$a_{0}$ with wavevector $-0.25Q_{Bragg}$. The thick dashed line represents $D_{2}(q)$ for uniaxial strain in the perpendicular direction (modeled by $\sigma = -0.3$) resulting in a peak at $-0.4Q_{Bragg}$. In practice, this will most likely result in looking into a commensurate CDW-2$a_{0}$ with 0.5$Q_{Bragg}$ wavevector when lattice-interaction effects are included (37). Red (blue) symbols indicate the first point to order into a 3Q (1Q) CDW geometry. Following the generic considerations of ref. 38, the predicted relative changes in orbital overlap may be expected to be roughly five times the relative strain defined in the experimental analysis, as explained in SI Appendix, section VI.

![Fig. 4. Theoretical modeling](image)

**Fig. 4.** Theoretical modeling. The dispersion $\Omega_{2}$ of the longitudinal acoustic phonons extracted from experimental resonant inelastic X-ray scattering data (20) (thick solid gray line). All other curves and symbols represent results from our theoretical simulation, which computes the electronic susceptibility $D_{2}(q)$ as a function of strain. Following ref. 35: $D_{2}(q)$ is defined in millelectron volts, so that the charge order is expected to develop whenever $D_{2}(q)$ exceeds $\Omega_{2}$. The thin solid black line represents $D_{2}(q)$ for the unstrained case with 3Q order and wavevector $-0.33Q_{Bragg}$, in agreement with the observed value (41). The dotted line represents $D_{2}(q)$ for a uniaxial stretch along $\Gamma$-M (modeled by $\sigma = 0.1$) resulting in a 1Q CDW-4$a_{0}$ with wavevector $-0.25Q_{Bragg}$. The thick dashed line represents $D_{2}(q)$ for uniaxial strain in the perpendicular direction (modeled by $\sigma = -0.3$) resulting in a peak at $-0.4Q_{Bragg}$. In practice, this will most likely result in looking into a commensurate CDW-2$a_{0}$ with 0.5$Q_{Bragg}$ wavevector when lattice-interaction effects are included (37). Red (blue) symbols indicate the first point to order into a 3Q (1Q) CDW geometry. Following the generic considerations of ref. 38, the predicted relative changes in orbital overlap may be expected to be roughly five times the relative strain defined in the experimental analysis, as explained in SI Appendix, section VI.
technique can be applied to a range of other materials. For example, \( \text{IT-TiSe}_2 \) could be strained to induce superconductivity (39) or novel CDW wavevectors and geometries in analogy to what we observe in \( 2\text{H-NbSe}_2 \). Similarly, Fe-based superconductors could be strained, potentially using substrates with a TEC along a preferred direction (3), to create a rich playground to study the interplay of nematic order and superconductivity (40) within a single material using SI-STM.

**Methods**

Single crystals of \( 2\text{H-NbSe}_2 \) were grown using vapor transport growth technique with iodine (I\(_2\)) as the transport agent, and exhibit superconducting transition temperature \( T_c \approx 7 \text{ K} \) based on the onset of diamagnetic signal due to the Meissner effect in magnetization measurements (SI Appendix, section IX). Superconducting transition temperature remained approximately the same with \( T_c \approx 7 \text{ K} \) after the samples were strained and remeasured. Typical size of the single crystals used was \(-2 \text{ mm} \times 2 \text{ mm} \), with \(-0.1 \text{ mm} \) thickness before cleaving and \(-0.01 \text{ mm} \) to \(-0.1 \text{ mm} \) thickness postcleaving. Instead of attaching the \( 2\text{H-NbSe}_2 \) crystals directly to a metallic holder with TEC comparable to that of \( \text{NbSe}_2 \), as typically used in most STM experiments, we use conducting epoxy (EPO-TEK H20E) to glue the bottom of \( \text{NbSe}_2 \) to silica (SiO\(_2\)), a material with a vastly different TEC (Fig. 1A). Then, the sample structure is attached to the STM sample holder and cooled down to \(-4.5 \text{ K} \) (more information in SI Appendix, section IX). Based on the difference between TECs of NbSe\(_2\) and silica, NbSe\(_2\) is expected to stretch isotopically in-plane by \(-0.15\%\). As we demonstrate from STM topographs, the actual induced strain in the sample surface can be spatially inhomogeneous. To create a clean surface necessary for STM measurements, the samples were cleaved in ultra-high vacuum (UHV), and inserted into the STM head within minutes. We studied four different \( \text{NbSe}_2 \) crystals glued on silica (five different surfaces as one sample was recleaved for the second measurement). For each of these five, we approached the tip on several different points on the sample, which are typically tens of micrometers away from one another, and searched for different types of CDWs. We observed: all three CDWs on two surfaces, just CDW-2a and CDW-4a on two other surfaces, and just CDW-3a on one surface. STM data were acquired using a Uniosko USM1300 STM at the base temperature of \(-4.5 \text{ K} \). All spectroscopic measurements have been taken using a standard lock-in technique at \( 915 \text{ Hz} \) frequency and varying bias excitation as detailed in the figure legends. The STM tips used were home-made, chemically etched W tips annealed to bright-orange color in UHV. Tip quality has been evaluated on the surface of single-crystal Cu(111) before performing the measurements presented in this paper. The Cu(111) surface was cleaned by repeated cycles of heating and argon sputtering in UHV before it was inserted into the STM head.

To construct a model which captures experimental observations, we employ a tight-binding fit to the ARPS data for the two bands crossing the Fermi level (described in detail in refs. 26 and 35). The model assumes the two bands to be bonding and antibonding combinations of the two \( \text{Nb}-d_{3z^2-r^2} \) orbitals. We include both biaxial and uniaxial in-plane strain by modifying the hopping integrals based on the assumption that overlap integrals are linearly dependent on displacement, with an equal prefactor for all overlap terms. In modeling uniaxial strain, we assume that a tensile strain in one direction leads to a compressive strain in the perpendicular in-plane direction, conserving the volume of the unit cell. Then, we employ the Random Phase Approximation to calculate the phonon softening as seen in resonant inelastic X-ray scattering (20, 36). The CDW wavevector is identified as the first wavevector to soften to zero. By including nonlinear terms in a Landau free-energy expression we are able to reveal whether the CDW geometry consists of stripes (1Q) or triangles (3Q) (see SI Appendix, section VI for more details).

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