Observation of charge density waves in free-standing 1T-TaSe$_2$ monolayers by transmission electron microscopy


This paper was selected as an Editor's Pick

ARTICLES YOU MAY BE INTERESTED IN

Tunneling anomalous Hall effect in a ferroelectric tunnel junction
Applied Physics Letters 113, 172405 (2018); https://doi.org/10.1063/1.5051629

How to measure the thickness of a lubrication film in a pancake bubble with a single snapshot?
Applied Physics Letters 113, 173701 (2018); https://doi.org/10.1063/1.5051057

Study of spin-orbit torque induced magnetization switching in synthetic antiferromagnet with ultrathin Ta spacer layer
Applied Physics Letters 113, 162402 (2018); https://doi.org/10.1063/1.5045850
Observation of charge density waves in free-standing 1T-TaSe$_2$ monolayers by transmission electron microscopy

P. C. Börner,$^1$ M. K. Kinyanjui,$^1$ T. Björkman,$^2$ T. Lehnert,$^1$ A. V. Krasheninnikov,$^{3,4}$ and U. Kaiser$^{1,4(a)}$

$^1$Central Facility of Electron Microscopy, Ulm University, Albert Einstein Allee 11, 89069 Ulm, Germany
$^2$Physics/Department of Natural Sciences, Åbo Akademi, FI-20500 Turku, Finland
$^3$Institute of Ion Beam Physics and Materials Research, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
$^4$Department of Applied Physics, Aalto University, PO Box 14100, 00076 Aalto, Finland

(Received 21 August 2018; accepted 10 October 2018; published online 25 October 2018)

While bulk 1T-TaSe$_2$ is characterized by a commensurate charge density wave (CCDW) state below 473 K, the stability of the CCDW state in a 1T-TaSe$_2$ monolayer, although theoretically predicted, has not been experimentally confirmed so far. As charge density waves and periodic lattice distortions (PLDs) always come together, we evaluate the PLD in a 1T-TaSe$_2$ monolayer from low-voltage aberration-corrected high-resolution transmission electron microscopy experiments. To prevent fast degradation of 1T-TaSe$_2$ during exposure to the electron-beam, a 1T-TaSe$_2$/graphene heterostructure was prepared. We also perform the image simulations based on atom coordinates obtained using density functional theory calculations. From the agreement between the experimental and simulated images, we confirm the stability of the CCDW/PLD in a monolayer 1T-TaSe$_2$/graphene heterostructure at room temperature in the form of a $\sqrt{13} \times \sqrt{13}$ superstructure. At the same time, we find that in comparison to multi-layer structures, the superstructure is less pronounced. Published by AIP Publishing. https://doi.org/10.1063/1.5052722

Materials with reduced dimensionality are nowadays an enormously increasing field of research, involving fundamental physics, materials science, and quantum technology. It has been predicted for instance that in graphene the quantum Hall effect can be reliably measured even at room temperature.\(^1\) Likewise, high temperature superconductivity at interfaces and in single-layers were reported.\(^2,3\) Moreover, some of the bulk layered materials exhibit many-body quantum state features, associated with charge density wave (CDW) ordering and gap in the electronic spectrum.\(^1,4,6\)

CDWs are periodic modulations of the electron charge density observed preferably in low-dimensional metals, which depend on temperature, dimensionality, doping, and pressure. They often arise due to instabilities at the Fermi surface and give rise to metal-insulator transitions due to the opening of a bandgap.\(^7,8\) Due to electron-phonon coupling, the CDW state is always accompanied by a periodic lattice distortion (PLD) which is characterized by a periodic modulation of the atomic positions.\(^9\) Thus, CDW and PLD always come together, and we will call them CDW/PLD throughout the paper. The CDW/PLD structure can be either commensurate or incommensurate with respect to the undistorted lattice, depending on the transition temperature and the dimensionality of the system.\(^4\)

Bulk transition metal dichalcogenides (TMDs) are layered materials (either semiconductors or metals) with MX$_2$ as the common structural formula, where M stands for transition metals and X for chalcogens S, Se, and Te. The layers are coupled by van der Waals forces.\(^10\) Thus, bulk TMDs are mechanically and electrically extremely anisotropic.\(^11\) The possibility of obtaining single-layers from layered bulk structures\(^12,13\) has raised great attention as many possibilities are envisaged for potential technological applications\(^14–16\) and for understanding solid state quantum phenomena.\(^4–6,10\)

Bulk TMDs such as TaSe$_2$, TaS$_2$, and NbSe$_2$ are metals that exhibit a strong CDW/PLD.\(^3,5\) Obtaining defect-free single-layers from bulk CDW/PLD TMD materials and understanding their characteristics are active fields of research. Due to confinement effects, interesting properties are already predicted for the CDW/PLD state, e.g., for single-layer 1T-TaS$_2$ which obtains a triclinic stripe order or for single-layer 2H-NbSe$_2$ which shows an enhanced transition temperature.\(^17,18\) So far, there are different qualitative models for the CDW phase transition, e.g., the Fermi surface nesting.\(^5,19,20\) Peierls distortion,\(^7,\) and giant Kohn anomaly,\(^4\) but a “coherent and realistic microscopic theory has not yet emerged.”\(^5\)

For 1T-TaSe$_2$, thickness- and temperature-dependent properties have already been reported in the commensurate charge density wave CCDW/PLD state: It is metallic in the bulk structure but insulating in a single-layer,\(^21,22\) and the transition temperature to the commensurate (C)CDW/PLD phase in the bulk structure is 437 K, which is reduced with the decreasing thickness.\(^23,24\) However, no experimental evidence has been given for the formation of the CCDW/PLD state in freestanding monolayer 1T-TaSe$_2$ at room temperature.

In this paper, we investigate the CCDW/PLD structure of free-standing single-layer 1T-TaSe$_2$ using an 80 kV aberration-corrected high-resolution transmission electron microscopy (AC-HRTEM) at room temperature. The knock-on damage threshold for TaSe$_2$ is considerably higher, about (190–200) kV, calculated using the displacement threshold energy for Se atoms obtained within the framework of density functional theory (DFT)-based molecular dynamics for TaSe$_2$.\(^25\) However, previous AC-HRTEM investigations of...
single-layer TMDs have shown that electron beam-induced damage can lead to rapid generation of structural defects through other mechanisms, which include electronic excitations, especially for insulating materials, and beam-induced chemical etching.\(^\text{26,27}\) The effects of electron beam-induced damage can be reduced by protecting the single-layer TMD with one graphene layer or sandwiching it between two graphene layers.\(^\text{26–29}\) Here, we investigate the single-layer 1T-TaSe\(_2\)/graphene heterostructure. Furthermore, we assume that heating of a few-layer thick sample by the electron beam at 80 kV can be neglected, as experiments and theory indicate.\(^\text{26,30,31}\)

The atomic structure of the CCDW/PLD in single-layer 1T-TaSe\(_2\) is shown in Fig. 1 with Ta atoms colored blue and Se atoms orange. The Ta atoms show a 13-atom star-of-David-like pattern with a \(\sqrt{13} a_0 \times \sqrt{13} a_0\) unit cell (marked in green), rotated by about 13.9° to the undistorted lattice. The superstructure lattice vectors are \(a_{\text{CDW}}\) and \(b_{\text{CDW}}\) with a length of \(|a_{\text{CDW}}| = |b_{\text{CDW}}| = \sqrt{13} a_0\). The main distortion of the atoms is governed by the Ta atoms with the largest displacement of Ta being about 0.33 Å (in-plane).\(^\text{5}\) The red arrows indicate the direction of the in-plane atom displacements. Se atoms are displaced mainly out of plane.\(^\text{5}\) In the incommensurate (I)CDW/PLD case, the rotation angle is between 0° and 13.9°, depending on the incommensurability, and a domain-like structure is formed.\(^\text{5}\)

Single-layers of 1T-TaSe\(_2\) were mechanically exfoliated from the bulk material using the Scotch tape method (for more details, see supplementary material).\(^\text{32,33}\) The exact thicknesses of the 1T-TaSe\(_2\) flakes were determined by the contrast measurement with an optical microscope.\(^\text{32,33}\) In Fig. 2(a), an optical microscopy image of a 1T-TaSe\(_2\) flake on a SiO\(_2\) substrate is shown. The flake is marked with a black solid line, and the monolayer area is marked with a dashed black line. A green channel image of the same flake is shown in Fig. 2(b) as green light is used for the contrast calculation of a 1T-TaSe\(_2\) monolayer.

A line scan from A to B for the thickness determination is also indicated with a red line. The profile of the line scan is depicted in Fig. 2(c). The average values for the minimum and maximum are drawn as horizontal lines in the graph. The measured contrast is \(C = 18\%\). This experimental value was compared to the calculated contrast for a 1T-TaSe\(_2\) monolayer on SiO\(_2\), which was conducted analogously to contrast calculations for monolayers of graphene or TMDs.\(^\text{32,33}\) The calculated contrast \(C\) for a single 1T-TaSe\(_2\) monolayer on this Si/SiO\(_2\) wafer was \(C = 0.19(5)\) (values for calculation, see supplementary material). The confidence interval (brackets) was calculated from the propagation of the uncertainties of the physical quantities. Thus, we conclude that the layer marked with a dashed line in Fig. 2(a) is a monolayer. For HRTEM investigations, this 1T-TaSe\(_2\) flake was transferred to a gold sputtered Quantifoil grid on which a graphene flake has already been transferred [see Fig. 2(d)]. The Au sputtered grids show better heat conductivity during cooling experiments, but they have the disadvantage of a very low contrast for monolayers in the optical microscope. A 1T-TaSe\(_2\)/graphene heterostructure was prepared to reduce electron beam-induced damages of the 1T-TaSe\(_2\) layer\(^\text{27–29}\) during the HRTEM investigations. Furthermore, graphene acts as a support material for the few micrometer wide monolayers.

The experimental HRTEM image of the 1T-TaSe\(_2\)/graphene heterostructure is presented in Fig. 3(a). Due to the low contrast of graphene, the contrast is dominated by the 1T-TaSe\(_2\) structure. We chose Scherzer defocus imaging conditions, and Ta (180.95 u) atoms have a higher contrast than Se (78.96 u) atoms due to their higher atomic mass. In the upper right corner of Fig. 3(a), the graphene lattice is shown. The experimental HRTEM image of the 1T-TaSe\(_2\)/graphene heterostructure is presented in Fig. 3(a). Due to the low contrast of graphene, the contrast is dominated by the 1T-TaSe\(_2\) structure. We chose Scherzer defocus imaging conditions, and Ta (180.95 u) atoms have a higher contrast than Se (78.96 u) atoms due to their higher atomic mass. In the upper right corner of Fig. 3(a), the graphene lattice is

![FIG. 1. Atomic structure of the CCDW/PLD in single-layer 1T-TaSe\(_2\) with Ta atoms colored blue and Se atoms colored orange. The Ta atoms show a star-of-David-like superstructure consisting of 13 Ta atoms. The outer 12 Ta atoms are displaced towards the center atom, indicated by red arrows. The unit cell of the commensurate superstructure is marked with the lattice vectors \(a_{\text{CDW}}\) and \(b_{\text{CDW}}\) to show the \(\sqrt{13} a_0 \times \sqrt{13} a_0\) superstructure. The superstructure is rotated about 13.9° against the undistorted 1T structure.](Image 1)

![FIG. 2. Optical microscopy image of a 1T-TaSe\(_2\) flake on a Si/SiO\(_2\) wafer (a). The monolayer is marked with a dashed line. The thickness of this monolayer is determined using a line scan (red) from the green-channel image (b). The profile of the line scan reveals a Weber contrast \(C\) of 18% which identifies the layer as a monolayer. For HRTEM investigations, the flake is transferred on a gold sputtered Quantifoil TEM grid with a graphene monolayer on it (d).](Image 2)
The pattern of the HRTEM image is depicted in Fig. 3(d), which further illustrates it in the reciprocal space. The Fourier transformation of the experimentally found superstructure is the expected 1T-TaSe$_2$ reflections, marked in blue, satellite spots due to the √13-superstructure, marked in green, and graphene reflections, marked in red. Reflections originating from a convolution between the graphene and the 1T-TaSe$_2$ structure are marked in pink. As can be seen, the satellite spots are rotated about 13.9° against the 100 1T-TaSe$_2$ reflections, identifying the structure as commensurate. In the SAED pattern of the 1T-TaSe$_2$ monolayer on graphene, satellite spots of the CCDW/PLD are visible. (f) Simulated kinematic electron diffraction pattern originating from a larger sample area shows the main reflections of the 1T-structure and satellite spots of the √13-superstructure [see Fig. 3(e)]. Reflections of the graphene lattice are not visible as they have a much smaller intensity than the 1T-TaSe$_2$ reflections. For the sake of completeness, a simulated kinematic electron diffraction pattern is shown in Fig. 3(f), showing the reflections of the 1T-TaSe$_2$ structure and satellite spots due to the √13-superstructure. In the enlarged area, the reciprocal lattice vectors of the superstructure $a_{CDW}$ and $b_{CDW}$ are shown which have the length of $|a_{CDW}| = |b_{CDW}| = 1/\sqrt{13} \, a_0$. The angle between the satellite spots and the main 100 reflections is 13.9°. The positions of the 1T-TaSe$_2$ reflections and satellite spots in the experimental Fourier transformation and the SAED pattern are the same as in the simulated diffraction pattern. This all identifies the superstructure in the single-layer 1T-TaSe$_2$ sample as the expected √13-superstructure; however, the experimental HRTEM image shows a less pronounced star-of-David-like contrast modulation. This structure is formed at about room temperature which confirms the assumed temperature behavior from bulk crystals down to monolayers.23
The stability of the CCDW/PLD in a single-layer of 1T-TaSe₂ is predicted by density functional theory (DFT) relaxations, which shows the same superstructure for a single-layer 1T-TaSe₂ as known for bulk 1T-TaSe₂. To see whether the graphene substrate has an influence on the 1T-TaSe₂ layer, we performed calculations of the CCDW/PLD phase on graphene, as described in detail below. In the alignment of Fermi levels of the systems, the graphene substrate will donate electrons to the 1T-TaSe₂ sheet, as shown in Fig. 4(a), but this does not result in any noticeable alterations of the CCDW/PLD structure. Although charge transfer between the 1T-TaSe₂ and the graphene layer does not completely destabilize the CCDW/PLD phase, it might affect its formation energy. To investigate this, we carried out a series of calculations with account for doping of the CCDW/PLD and the undistorted phase with a series of different fractional electron charges, computing the CCDW/PLD formation energy per formula unit as \( E_f = E(\text{Pristine}) - \frac{E(\text{CCDW/PLD})}{13} \), and thus defined as the positive energy gained by the structure upon distortion. The results, for a range of large but possibly realizable surface electron charges, are shown in Fig. 4(b). The CCDW/PLD is further stabilized by electron doping (increasing formation energy), whereas hole doping tends to decrease the formation energy, although—at realistic doping concentrations—not enough to stabilize the undistorted phase. The sudden downturn of the formation energy curve in Fig. 4(b) around \( 7.5 \times 10^{13} \) electrons/cm² results from the complete filling of one additional, isolated empty band in the CCDW/PLD structure.

To sum up, we have unambiguously proven that the CCDW/PLD is stable in a monolayer of 1T-TaSe₂ at room temperature. We have shown that the expected commensurate \( \sqrt{13} \)-superstructure has been formed as we investigated not only the monolayer of 1T-TaSe₂ but also the heterostructure consisting of two monolayers (1T-TaSe₂ and graphene). We conclude that the underlying graphene has no influence on the commensurate \( \sqrt{13} \) PLD in a monolayer of 1T-TaSe₂.

See supplementary material for experimental details.

The authors acknowledge the financial support from the German research foundation (DFG) and the Ministry of Science, Research and the Arts (MKW) of Baden-Württemberg in the frame of the “SALVE” (Sub Angstrom Low-Voltage Electron microscopy) project and project KR 4866 and from the EU in the frame of the Graphene Flagship. A.V.K. also thanks the Academy of Finland for the support under Project No. 286279. We thank CSC Finland and PRACE (HLRS, Stuttgart, Germany) for generous grants of CPU time.

35 M. M. Benamer, B. Radisavljevic, J. S. Heron, S. Sahoo, H. Berger, and A. Kis, Nanotechnology 22, 125706 (2011).