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Topotactic Growth of Edge-Terminated MoS₂ from MoO₂ Nanocrystals

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Abstract.

Layered transition metal dichalcogenides have distinct physicochemical properties at their edge-terminations. The production of an abundant density of edge structures is, however, impeded by

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3 the excess surface energy of edges compared to basal planes and would benefit from insight into
4 the atomic growth mechanisms. Here, we show that edge-terminated MoS₂ nanostructures can
5 form during sulfidation of MoO₂ nanocrystals by using *in situ* transmission electron microscopy
6 (TEM). Time-resolved TEM image series reveal that the MoO₂ surface can sulfide by inward
7 progression of MoO₂(20-2):MoS₂(002) interfaces resulting in upright-oriented and edge-
8 exposing MoS₂ sheets. This topotactic growth is rationalized in interplay with density functional
9 theory calculations by successive O-S exchange and Mo sublattice restructuring steps. The
10 analysis shows that *e*-MoS₂ formation is energetically favorable at MoO₂(110) surfaces and
11 provides a necessary requirement for the propensity of a specific MoO₂ surface termination to
12 form edge-terminated MoS₂. Thus, the present findings should benefit the rational development
13 of transition metal dichalcogenide nanomaterials with abundant edge-terminations.
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31 Progress in the synthesis of layered transition metal dichalcogenides (TMDCs) has led to a
32 variety of nanoscale structures including fullerenes, tubes/wires and platelets, each with distinct
33 physicochemical properties.¹ These TMDC structures are derived from layers of hexagonally
34 arranged transition metal atoms (*e.g.* Mo and W) in which each metal atom is coordinated by six
35 chalcogenide atoms usually in a trigonal prismatic geometry. Such TMDC sheets are terminated
36 by extended basal planes with a regular atomic arrangement and by atomically thin edges. Due to
37 the reduced atomic coordination, the edges expose structures that markedly differ from those of
38 the basal plane and, in turn, offer distinct electronic,^{2,3} optical,⁴ magnetic⁵ and chemical^{6,7}
39 properties. In particular, the edges of MoS₂ sheets have long received interest as catalysts for
40 mineral oil refining,^{8,9} hydrogen evolution,^{10,11} CO₂ reduction¹² and photo-oxidation¹³ reactions,
41 whereas the unperturbed MoS₂ basal plane is regarded as essentially inert. These catalytic
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3 processes would therefore benefit from edges that are more abundantly available. In addition,
4 exposed edges are also beneficial for reducing steric hindrance in adsorption of *e.g.* heavy sulfur-
5 containing organic compounds, which is a prime target in improving catalysts for oil refining
6 processes.¹⁴
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12 The availability of edge sites depends on the size, shape and orientation of the TMDC
13 sheets. As the edge terminations are associated with a considerably higher surface energy than
14 the basal plane, the formation of edge sites is suppressed compared to the growth of basal planes.
15 Hence, TMDC sheets are expected to form with extended basal plane exposed to the
16 surroundings and oriented parallel with a supporting surface. In contrast, the sulfidation or
17 thermolysis of molybdenum precursors dispersed on a support material have empirically been
18 found to also produce upright-oriented and thereby edge-exposing MoS₂ sheets.^{12,13,15-26}
19 Common for the majority of these edge-favoring synthesis procedures is the employment of a
20 dense molybdenum precursor in the form of nanoparticles or thin films.^{12,13,15,18-23} The
21 appearance of the upright orientation has been attributed to a strong bonding of the MoS₂ edge to
22 the supporting material to counteract the thermodynamic drive towards a parallel
23 orientation.^{16,27,28} However, an elaborate understanding of the atomic mechanisms governing the
24 formation of the edge-terminated MoS₂ is still lacking and bottom-up strategies have therefore
25 not been available for synthesizing edge-terminated materials with superior catalytic and other
26 functionalities.
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47 With recent advances in transmission electron microscopy (TEM), dynamic
48 transformations of solid materials can now be monitored *in situ* at high spatial resolution during
49 exposure to reactive gas or liquid environments. By acquiring time-lapsed series of TEM images,
50 it has become possible to gain insight into the mechanisms and kinetics involved in the formation
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3 of different types of nanometer-sized structures.²⁹⁻³¹ Here, we employ this TEM approach to
4 monitor the growth of MoS₂ nanostructures from molybdenum(IV) oxide (MoO₂) nanocrystals *in*
5 *situ* during exposure to a reactive H₂S/H₂ atmosphere. The time-resolved TEM image series
6
7 reveal that the oxide nanocrystal surfaces can form domains of upright-oriented MoS₂ sheets by
8 the progression of the MoO₂(20-2):MoS₂(002) interface from the MoO₂ surface toward its bulk,
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10 in addition to domains of parallel-oriented MoS₂ sheets (Figure 1a). This topotactical reaction is
11 explained in interplay with density functional theory (DFT) modelling by repeated steps of O-S
12 exchange and Mo sublattice restructuring. Specifically, these reaction steps exhibit a marked
13 dependency of the MoO₂ surface structure in the way that energetically favors formation of edge-
14 terminated MoS₂ sheets at the MoO₂(110) surface. The implication of these findings is therefore
15 that (110)-terminated MoO₂ precursors can produce abundantly available MoS₂ edge sites and
16 that the reaction steps offer descriptors for surface topotaxy, which should, in general, facilitate
17 the design of TMDC nanomaterials with superior edge functionalities.
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35 **Results/Discussion**

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37 The electron microscope experiments used MoO₂ nanoparticles as precursor because (1)
38 previous studies suggested that molybdenum-dense precursors favor formation of upright-
39 oriented MoS₂ sheets, (2) nanoparticles enable surface-profile imaging by electron microscopy
40 and (3) reduced MoO₃, such as MoO₂ and MoO_{3-x}, has been considered as intermediate in
41 sulfidation by H₂S/H₂ into inorganic fullerene structures.^{32,33} The molybdenum(IV) oxide
42 precursor was formed by heating ammonium heptamolybdate tetrahydrate
43 ((NH₄)₆[Mo₇O₂₄]·4H₂O) to 450°C at the base vacuum of ca. 5×10⁻⁶ mbar (Methods). The
44 procedure resulted in nanoparticles with projected diameters in the range of 5 to 20 nm and with
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3 the monoclinic MoO₂ crystal structure^{34,35} (Figures S1 and S2 in the Supporting Information).
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5 The MoO₂ nanocrystals exposed predominantly low-indexed facets such as *e.g.* (100), (010) and
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7 (110) (Figure S2 in the Supporting Information). Subsequently, the as-prepared MoO₂
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9 nanocrystals were exposed to a gas mixture of 10% H₂S in H₂ at a total pressure of 1 mbar and
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11 heated to a nominal temperature of 250-300°C for 240-300 min inside the electron microscope
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13 (Methods). Such low temperatures have previously been associated with the synthesis of upright-
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15 oriented MoS₂ sheets.^{16,17} During the present treatment, structures emerged that are attributed to
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17 molybdenum sulfide because they were absent in similar experiments without H₂S in the reaction
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19 gas (Figure S3 in the Supporting Information). The molybdenum sulfide structures appeared with
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21 two distinctly different orientations relative to the surface of the MoO₂ nanocrystals.
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26 The first structure, denoted *e*-MoS₂, represents our main finding and surprisingly consists
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28 of sheets oriented upright with respect to the projected nanocrystal surface (Figure 1a). The
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30 sheets represent lattice fringes with spacing of ca. 0.62 nm, corresponding to the MoS₂ (002)
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32 lattice planes (Figure 1b). Domains of *e*-MoS₂ extend from the projected periphery towards the
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34 bulk of the nanocrystal and typically consist of 3-8 MoS₂ sheets with length of 1 - 5 nm (Figure
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36 1b and Figures S4-S6 in the Supporting Information). Thus, *e*-MoS₂ exposes predominantly edge
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38 sites to the surroundings. Due to the projection geometry, it is possible that the *e*-MoS₂ only
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40 partly covers the corresponding surface termination oriented along the electron beam direction
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42 (Figure 2) and that the remaining MoO_x sites eventually sulfide to cover the nanocrystal surface
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44 by *p*-MoS₂. Moreover, the anisotropy of MoS₂ sheets implies that the corresponding TEM image
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46 contrast depends strongly on their orientation. MoS₂ sheets oriented with their (002) basal plane
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48 along the electron beam direction obtain strong phase contrast in high-resolution TEM images,
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50 whereas MoS₂ sheets having the (002) planes tilted more than ca. 9° off the electron beam
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3 direction appear with a markedly diminished contrast due to the reduced number of atoms
4 contributing to the projected electrostatic potential.^{36,37} Therefore, domains of *e*-MoS₂ may be
5 present in other parts of the MoO₂ nanocrystal and remain unresolved in the TEM images due to
6 their orientation. It is therefore not surprising that the *e*-MoS₂ structure was observed in only
7 about 13% of all nanocrystals (Note in the Supporting Information). However, the low
8 abundance of *e*-MoS₂ could also reflect that only certain surface facets of the parent MoO₂
9 nanocrystal promote growth of the edge-terminated MoS₂.
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19 The second structure, denoted *p*-MoS₂, consists of sheets contouring the surface of most
20 of the MoO₂ nanocrystals (Figure 1a, note in the Supporting Information). Occasionally, these
21 sheets stack with an interlayer spacing of ca. 0.63 nm, corresponding to the MoS₂(002) lattice
22 planes, and reveal internal lattice fringes with spacing of 0.27 nm, corresponding to (100) lattice
23 planes (Figure 1b and 1c). The *p*-MoS₂ sheets extend along the projected MoO₂ surface parallel
24 to the electron beam. In addition, the sheets are likely also contouring those parts of the MoO₂
25 nanocrystal surface that is *not* parallel with the electron beam direction (within $\sim\pm 9^\circ$) and *p*-
26 MoS₂ therefore remain undetectable in such regions of the TEM images due to their orientation
27 and overlaid contrast from the projected bulk MoO₂ nanocrystal. Thus, the *p*-MoS₂ structure
28 consists of MoS₂ sheets that are confined to the surface region of the MoO₂ nanocrystal and
29 expose predominantly the MoS₂(002) basal plane, similarly to previous findings for fullerene
30 MoS₂ structures.^{32,33,38}
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47 To address the growth mode of the edge-terminated MoS₂, *e*-MoS₂, an analysis is first
48 presented of time-resolved series of TEM images that were acquired of individual MoO₂
49 nanocrystals as the sulfidation reaction progressed. Figure 2 shows an image sequence (extracted
50 from Video S1 in the Supporting Information) revealing the dynamic transformation of the
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3 surface on a MoO₂ nanocrystal during sulfidation. The images show that the MoS₂ sheets
4 nucleate directly in the exposed MoO₂ surface without any additional surface layers. Adjacent
5 MoS₂ sheets form simultaneously and establish a domain of *e*-MoS₂. Subsequently, the MoS₂
6 sheets grow in length from the original surface toward the bulk of the MoO₂ nanocrystal,
7 reaching a final length of ca. 2.8 nm. Figure S7 in the Supporting Information shows that the
8 MoS₂ sheets grow initially fast and that the growth stagnates at longer sulfidation times. The
9 decay of the growth rate may be due to the slower mass transport through the bulk of the
10 nanoparticle. Similar dynamic behavior is revealed in the formation of shorter *e*-MoS₂ structures
11 albeit at a corresponding lower signal-to-noise ratio (Figure S5 in the Supporting Information).
12 On average, *e*-MoS₂ sheets observed *in situ* grew to a final average projected length of 1.7 nm
13 (with a standard deviation of 0.6 nm) and sheets observed *post mortem* had grown to an average
14 projected length of 1.8 nm (with a standard deviation of 0.7 nm) (Figure S8 in the Supporting
15 Information). This conformity demonstrates that alterations of the growth process induced by the
16 electron illumination were insignificant with the applied low dose-rate imaging protocol and that
17 the observed MoS₂ formation is inherent to the sulfidation reaction as such (Methods). Thus, the
18 time-resolved observations indicate that growth of *e*-MoS₂ proceeded by an O-S exchange
19 reaction and by an inward progression of the MoO₂:MoS₂ interface from the surface of the MoO₂
20 nanocrystal upon continued exposure to the sulfur-rich gas.
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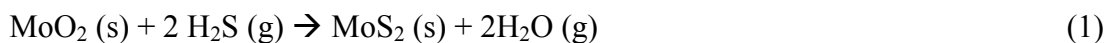
44 To address the relation between the *e*-MoS₂ and MoO₂ host nanocrystal structures, their
45 interface is examined at the atomic-scale. Figure 3 shows a close-up TEM image of the interface,
46 which reveals a threefold periodicity with three MoO₂(20-2) lattice planes matching one single
47 MoS₂(002) lattice plane. The lattice matching at the interface influenced the MoS₂ interlayer
48 spacing in such a way that the spacing varied with the distance from the MoO₂:MoS₂ interface to
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3 the nanocrystal surface. Specifically, the MoS₂(002) lattice spacing was larger closer to the
4 interface, corresponding to $3a_{\text{MoO}_2[20-2]} = 0.73$ nm, and smaller near the nanocrystal surface,
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6 corresponding to $a_{\text{MoS}_2[002]} = 0.62$ nm (Figure 3). Consistently, shorter *e*-MoS₂ slabs were
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8 separated by ca. 0.73 nm (Figures S4 and S6 in the Supporting Information). The larger
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10 MoS₂(002) lattice spacing near the interface constitutes a geometric strain of +17%, which is
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12 energetically feasible due to the weak van der Waals interaction between the MoS₂ sheets. A
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14 similar analysis of the crystal lattice planes in high-resolution TEM images of nine additional
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16 MoO₂ nanocrystals also characterized the interface as MoO₂(20-2):MoS₂(002) (Figure S4 in the
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18 Supporting Information). This interfacial relation of the two crystal lattices shows that the *e*-
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20 MoS₂ sheets formed as the result of a topotactic transformation of the MoO₂ surface region.³⁹
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22 Moreover, as the MoS₂ sheets are oriented upright with respect to the projected MoO₂ surface, *e*-
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24 MoS₂ must nucleate at surface facets inclined from the MoO₂(20-2) lattice planes, including the
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26 more abundant low-indexed surface terminations, such as (110), (010) and (100).
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33 Furthermore, the conversion of MoO₂ into MoS₂ by anion exchange also entails a
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35 restructuring of the Mo sublattice due to different Mo atom densities. MoO₂ is a monoclinic
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37 structure with a density of 30.4 Mo atoms/nm³, and MoS₂ is a hexagonal structure with a density
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39 of 18.8 Mo atoms/nm³. The corresponding volume expansion of 62% per Mo atom implies that
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41 Mo atoms were expelled from the bulk MoO₂ during formation of *e*-MoS₂. These Mo atoms
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43 possibly contributed to *p*-MoS₂, because *p*-MoS₂ and *e*-MoS₂ formed simultaneously (Figure 2)
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45 and *p*-MoS₂ formed at the exterior surface of the MoO₂ nanocrystals, causing an apparent
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47 increase in the projected size of the nanocrystals (Figure S9 in the Supporting Information).
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51 The present observations of topotactic growth of edge-terminated MoS₂ sheets from
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53 MoO₂ can be rationalized by the atomistic mechanism proposed in Figure 4. The consistency of
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3 this mechanism is examined by means of DFT calculations, combined with a thermodynamic
4 extrapolation to the present sulfidation conditions (Methods). First, the conversion of bulk MoO₂
5 to MoS₂ is addressed by the reaction:
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11 For this reaction, a calculation shows a Gibbs free energy change of -1.00 eV, corresponding to
12 an average gain of -0.50 eV/S atom, with 0.9 mbar H₂ and 0.1 mbar H₂S at 250 °C. The
13 sulfidation described by eq. (1) initiates at the MoO₂ surface.^{40,41} The surface sulfidation by H₂S
14 is modelled at the low-indexed (110), (010) or (100) facets of MoO₂, consistent with the TEM
15 observations. This process is associated with a free energy change of -0.01 eV/S atom, -0.29
16 eV/S atom and +0.09 eV/S atom for the MoO₂ (110), (010) and (100) surfaces, respectively, at
17 the same conditions. Thus, only the (110) and (010) surface terminations tend to sulfide (Figure
18 S10 in the Supporting Information), whereas the (100) surface remains oxidic under the present
19 reaction conditions.
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33 Following the initial sulfidation, the MoO₂ surface is envisioned to develop by successive
34 steps of Mo sublattice reconstruction and O-S exchange to accommodate the upright oriented
35 MoS₂ sheets. At the sulfided MoO₂(110) surface, every second topmost [-11-1]-row contains half
36 the number of Mo atoms (row 1 and 3 in Figure 4a) compared to the [-11-1]-rows in the bulk
37 MoO₂ structure (row 4 and 5 in Figure 4a). A stepwise displacement of these topmost [-11-1]-
38 rows toward each other, by $1a_{[20-2]}$ as outlined for row 1 (a → b in Figure 4) and row 3 (b → c in
39 Figure 4), results in a sulfided row of Mo atoms with a density similar to MoS₂[100] (note in the
40 Supporting Information). Moreover, the repetition of the displacements along the MoO₂ surface
41 develops a threefold periodicity of MoO₂(20-2):MoS₂(002) interface, in agreement with the TEM
42 images. The [-11-1]-row displacements uncover underlying oxide [-11-1]-rows (row 2, 4 and 5
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3 in Figure 4) comparable to the pristine oxide surface. As the exposure to the sulfiding
4 environment is continuous in the experiments, these oxide rows likewise undergo O-S exchange
5 as well. A two-row high MoS_2 sheet therefore emerges extending one row in and out from the
6 initial surface (row 1+3 and 2 in Figure 4c). Moreover, the deeper-lying MoO_2 [-11-1]-rows also
7 partly sulfide upon exposure to the reaction environment (row 4 and 5), and these rows may
8 subsequently transform in a similar way as the outermost rows (row 1 and 3). That is, half of the
9 sulfided Mo atoms in the [-11-1]-rows (row 4 and 5) are displaced into an additional sheet that
10 extends the *e*- MoS_2 sheet outwards. The remaining half-filled Mo [-11-1]-rows (row 4 and 5)
11 mimic the initial state of the sulfided surface (Figure 4a) and therefore undergo the same
12 transformations, resulting in a four-row *e*- MoS_2 sheet (Figure 4d). As a result, the mechanism
13 outlined in Figure 4 a-d becomes cyclic and, in turn, develops an *e*- MoS_2 structure with a
14 $\text{MoO}_2(20-2):\text{MoS}_2(002)$ interface and a threefold periodicity, consistent with the experimental
15 observations. To corroborate this mechanism, the O-S exchange and Mo [-11-1]-row
16 displacement steps were examined by DFT calculations to evaluate the Gibbs free energy for
17 each state (Methods). Figure 4e shows a successive lowering of the Gibbs free energy per unit
18 cell as the sulfidation reaction progressed, demonstrating that the proposed mechanism for the
19 topotactic growth of *e*- MoS_2 at the $\text{MoO}_2(110)$ surface is plausible.
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42 The mechanism in Figure 4 implies that the *e*- MoS_2 sheets grow to the same extent
43 inward and outward from the original MoO_2 surface. In contrast, the MoS_2 sheets are observed to
44 progress mainly inward and only modestly outward from the original MoO_2 surface in the
45 experiment (Figure 2). The asymmetric growth of the *e*- MoS_2 sheets possibly occurs under the
46 experimental conditions, because the Mo atoms expelled from the MoO_2 bulk are free to migrate
47 to sites on the MoO_2 surface where incorporation into *p*- MoS_2 can occur. In contrast, in the DFT
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3 modelling the same Mo atoms are added as an outward extension of the MoS₂ layer, due to the
4 geometrical constraint of the employed unit cell. The difference may reflect that, in the
5 experimental situation, the outward growth is kinetically limited or the emergence of the basal
6 plane of *p*-MoS₂ is energetically favored over *e*-MoS₂ sheets protruding outward from the
7 original the MoO₂ surface.
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12 To address the surface dependency of the topotactic reaction, the sulfidation mechanism
13 is compared on the MoO₂ (110) and (010) surfaces (Figure 4 and Figure S11 in the Supporting
14 Information). For both surfaces, the energy gain upon sulfidation is lower than the limit set by
15 equation (1) for growth of bulk MoS₂ from MoO₂ (0.50 eV/S atom). Specifically, for the MoO₂
16 (110) and (010) surface, the corresponding Gibbs free energy difference from the surface to bulk
17 sulfidation is -0.49 eV/S-atom (-0.50 eV/S atom minus -0.01 eV/S atom) and -0.21 eV/S atom (-
18 0.50 eV/S atom minus -0.29 eV/S atom), respectively, under the present conditions. Thus, S
19 atoms are less stable on the (110) than the (010) surface with respect to the *e*-MoS₂ structure. In
20 addition, the Mo sublattice restructuring also exhibits a surface-dependency. Whereas
21 displacement of the [-11-1] rows is spontaneous on the MoO₂(110) surface (a → b in Figure 4e),
22 the displacement of [101]-rows on the MoO₂(010) surface into a one-row high MoS₂ sheet (a →
23 b in Figure S11 in the Supporting Information) is associated with a Gibbs free energy change of
24 +2.74 eV/unit-cell (Figure 4e). This energy change results from the higher Mo atom density in
25 the (010) surface (note in the Supporting Information) and adds a barrier for restructuring the Mo
26 sublattice that suppresses growth of *e*-MoS₂. Thus, the calculations show that growth of *e*-MoS₂
27 is favored on MoO₂(110) due to the large energy gain for transferring surface S atoms into bulk
28 MoS₂ and the spontaneous and facile restructuring the Mo sublattice, whereas formation of *e*-
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3 MoS₂ is hindered on MoO₂(010) due to the smaller energy gain in the S transfer and the larger
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5 barrier for Mo sublattice restructuring.
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11 12 13 **Conclusion**

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16 The present study demonstrates the O-S exchange energy and the Mo sublattice
17 reconstruction energy as descriptors for the propensity of a specific MoO₂ surface to form *e*-
18 MoS₂, and the analysis provides a necessary requirement for a MoO₂ surface to facilitate a
19 spontaneous topotactic transformation into edge-terminated MoS₂. This insight may help
20 understanding previous reports on oriented nucleation and growth of MoS₂ sheets based on the
21 surface properties of the molybdenum oxide precursors.¹⁶⁻¹⁸ Moreover, the present findings
22 suggest that the *e*-MoS₂ growth is energetically favored at (110) surfaces of a MoO₂
23 nanomaterials under the present growth conditions. In the future, developing shape-selective
24 synthesis procedures of MoO₂ nanomaterials with an enhanced abundance of (110) surface
25 terminations therefore seems as one viable route for optimizing the abundance of *e*-MoS₂. The *e*-
26 MoS₂ formation could be kinetically limited by adsorption or diffusion processes not considered
27 in the present analysis. Such limitations can be addressed by detailed characterization using
28 oxygen adsorption of the MoS₂ edge sites⁴² and a shape-determination of the MoO₂ nanomaterial
29 using electron microscopy or X-ray diffraction.⁴³ Conceptually, the present descriptors of surface
30 topotaxy may be generally applicable in guiding bottom-up synthesis procedures of TMDC
31 nanomaterials towards enhanced edge-functionalities.
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Methods/Experimental

Sample preparation and sulfidation. Ammonium heptamolybdate tetrahydrate, $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$ (Merck, 1180336, minimum 99% nominal purity) was used as molybdenum precursor. The precursor granulate was ground to a fine powder and dispersed in its dry state onto plasma-cleaned Protochips Aduro E-chips or FEI Company NanoEx chips. Precursor particles were approximately 2-5 μm wide and overhung the membrane holes near the center of the chip membrane. Heating of the chips to 450°C in the microscope base vacuum transformed the precursor into MoO_2 nanoparticles ranging from 5 to 20 nm in width. For the Aduro E-chips, MoO_2 nanoparticles protruding from holes in the second innermost quadrant of 7x7 hole arrangement were examined in the electron microscope to ensure temperature uniformity⁴⁴ and to minimize the image contrast contribution from the chip membranes. The NanoEx chips have a uniform temperature across the perforated membrane,⁴⁵ and particles protruding from any hole were imaged by TEM.

To initiate the sulfidation reaction, the temperature of the chip was lowered to 300°C or 250°C, and subsequently a premixed gas with 10% H_2S in H_2 (Air Liquide, nominal purity 98% for H_2S and 99.999% for H_2) was introduced into the electron microscope at time = 0 min. The gas composition was continuously monitored using a quadrupole mass spectrometer (Balzers Prisma QMS 200) positioned at the microscope second differential pumping step for masses 2, 16, 18, 32, 33 and 34 AMU corresponding to signals from H_2 , O_2 , H_2O , S, HS, and H_2S . This showed that a constant gas composition was obtained after 5 min at constant gas pressure (Figure S12 in the Supporting Information). The ion currents were sampled at a total acquisition time of 11 sec.

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3 **Transmission electron microscopy (TEM).** The growth of MoS₂ was examined by means of a
4 Philips CM300 FEG-ST transmission electron microscope, which is equipped with a differential
5 pumping system and heating stages to enable the exposure of solid specimens to reactive gasses
6 and elevated temperatures.^{37,46} Specifically, this microscope is dedicated to experiments
7 including corrosive sulfur-containing gases.³⁷ The microscope was operated at a primary electron
8 energy of 300 keV and with an electron dose-rate of 150 e⁻/(Å²s) for *in situ* observations with
9 10% H₂S in H₂ at 1 mbar total pressure in the sample region and of 200 e⁻/(Å²s) for *post mortem*
10 observations under a high vacuum of better than 5x10⁻⁶ mbar in the sample region. The applied
11 gas environment reduced the electron transmittance by only ca. 3% relative to vacuum.
12 Therefore, electron doses and dose-rates are quoted with reference to measurements in the
13 evacuated microscope. Moreover, the microscope projection system was set at a magnification
14 corresponding to an effective pixel size ranging from 0.03 nm to 0.07 nm of the charged coupled
15 device (CCD) camera (Tietz F114) during TEM image acquisition. These magnification settings
16 are sufficient to resolve the MoS₂ (100) lattice planes of spacing 0.27 nm and the MoO₂ (20-2)
17 lattice planes of spacing 0.24 nm, as the shortest lattice spacings. Moreover, imaging was done at
18 focus settings close to the Scherzer defocus value of $f = -64$ nm to ensure a large contrast
19 information transfer for the MoS₂ (002) and (100) lattice planes and the MoO₂ (20-2) lattice
20 planes. The CCD illumination time was 0.5 - 1 s per image.
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44 The experiments were conducted using micro-electro-mechanical heaters as sample
45 support. A part of the experiments employed the Protochips Aduro system, which consists of
46 silicon chips supporting silicon carbide membranes perforated with 7x7 holes near the center.⁴⁷
47 Prior to sample loading, chips were exposed to Ar/O₂ plasma for cleaning. In the experiment,
48 sample dispersed on the membranes was heated by resistively passing an electrical current
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3 through the membrane. The membrane current-temperature characteristic was calibrated using
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5 pyrometry at a pressure of 1.3×10^{-2} mbar by the manufacturer (Protochips). During gas exposure
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7 in the microscope, additional heat dissipation to the gas phase was accounted for by operating the
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9 membrane in a constant resistance mode.³⁷ The other part of the experiments employed the FEI
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11 Company NanoEx system, which consists of silicon chips with a silicon nitride membrane
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13 perforated with 22 holes near its center and a conductive thin film with four electrodes for
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15 resistive heating and on-board temperature sensing.⁴⁵ Prior to sample loading, chips were also
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17 exposed to Ar/O₂ plasma for cleaning. The temperature-resistance characteristic of the chips was
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19 provided by the manufacturer (FEI Company).
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24 During a sulfidation experiment, 3-4 sample regions were monitored. The regions were
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26 located at distances larger than the width of the electron beam, so that the regions were
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28 monitored separately. As sulfidation of the sample progressed, each region was imaged every
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30 approximately 15 min. and each imaging step lasted for a maximum of 60 s for positioning,
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32 focusing and image acquisition. The total experiment duration was 240-300 min, corresponding
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34 to a total of up to 21 electron beam exposures of each region. The maximal total accumulated
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36 electron dose incident on a region in the *in situ* experiments was therefore $189 \times 10^3 \text{ e}^-/\text{\AA}^2$, using
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38 an electron dose rate of $150 \text{ e}^-/(\text{\AA}^2\text{s})$. At each position and time step, an image series of 5 or 10
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40 sequential images was acquired. These images were post-aligned using cross-correlation and
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42 summed to the final displayed images with improved signal-to-noise-ratio. Immediately after an
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44 imaging step, the electron beam was moved to the next sample position. This imaging strategy
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46 was applied to minimize the total dose rate while maintaining a detectable image signal.⁴⁸
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51 Additional images series were obtained after termination of the sulfidation reaction at positions
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3 without prior exposure to the electron beam (*post mortem*). These *post mortem* images were
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5 acquired at a base vacuum below 5×10^{-6} mbar and 120°C.
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8 The magnification of the TEM images was calibrated relative to a standard Au/C
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10 calibration grid. The images are represented as a direct representation of the summed CCD
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12 current outputs in a monochromatic green color scale with only a linear adjustment of the image
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14 contrast and brightness.
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17 **Image simulation.** High-resolution TEM images of MoO₂ were simulated using the multi-slice
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19 approach as implemented in the MacTempasX software.⁴⁹ To describe the Philips CM300
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21 microscope, the simulations employed an incident electron beam energy of 300 keV, spherical
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23 aberration coefficient of $C_s = 1.4$ mm, a convergence angle of 0.3 mrad, a defocus spread of 8.3
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25 nm, an outer objective aperture of 0.14 nm, and a mechanical vibration amplitude in the imaging
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27 plane of 0.07 nm. The MoO₂ nanoparticles were described by a monoclinic MoO₂ crystal
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29 structure³² belonging to the P2₁/c space group.
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33 **Theoretical calculations.** The GPAW^{50,51} density functional theory code was employed in finite
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35 difference mode using a grid spacing of 0.18 Å to obtain total energies. The exchange and
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37 correlation was described by the revised Perdew-Burke-Ernzerhof (RPBE) functional. All atomic
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39 positions in the systems involving MoO₂ and MoS₂ structures were relaxed until the largest
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41 interatomic force was smaller than or equal to 0.05 eV/Å and the molecules were relaxed to a
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43 value less than 0.01 eV/Å. The DFT electronic energies of H₂S and H₂O were corrected with
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45 zero-point energies and entropic contributions. The zero-point energy corrections were obtained
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47 by performing vibrational analysis calculations in GPAW using the harmonic approximation.⁵²
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49 The remaining thermodynamic corrections were obtained from thermochemical tables.⁵³ The
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51 calculations employed reaction conditions at 250°C with 0.1 mbar H₂S and 0.9 mbar H₂,
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3 matching the experimental sulfidation conditions. The calculations used an estimated H₂O
4 pressure of 10⁻³ mbar to reflect an upper limit of the residual gas phase in the electron
5 microscope.
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10 The bulk structure of monoclinic MoO₂ was modeled using a unit cell consisting of 4 Mo
11 and 8 O atoms periodic in the x, y and z directions, respectively. Bulk MoS₂ was modeled as
12 infinite layers periodic in the x [110] and y [1-10] directions, separated by vacuum in the z [002]
13 direction and with 2 Mo and 4 S atoms in the unit cell. The Brillouin zone was sampled with
14 8,8,8 k-points in the x, y and z directions, respectively, both for bulk MoO₂ and MoS₂. The
15 surfaces were modeled as symmetric layers of six (010) or (110) MoO₂ layers periodic in the x
16 [20-2] and y [101] or [-11-1] lattice directions and separated by 13 Å of vacuum in the z [010] or
17 [110] direction to prevent the surfaces from interacting due to the periodic boundary conditions.
18 The DFT calculations of the MoO₂ surface employed a periodicity of 4 along the [20-2]
19 direction. Importantly, the unit cell dimension of 4x a_[20-2] is longer than the observed periodicity
20 of 3x a_[20-2] at the MoO₂:MoS₂ interface (Figure 3). The longer periodicity employed in the DFT
21 calculations ensured that periodic boundaries could be invoked and kept the computational time
22 low. Moreover, the periodicity in the DFT calculations is a pure geometric effect, because
23 identical exchange and Mo sublattice restructuring occurs locally in the larger cell and the extra
24 surface energy is canceled out by the reference (Figure 4a). Therefore, the present calculations
25 still capture the energetics in the transformation of three MoO₂ planes into one MoS₂ sheet.
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46 The Brillouin zone of the MoO₂ for the (010) and (110) surface slabs were sampled with
47 4, 4, 1 k-points in the x [20-2], y [101] or [-11-1] and z [010] or [110] directions, respectively.
48 The energies for the surface sulfidation were obtained by replacing all directly gas exposed O
49 atoms with S atoms and using gas phase H₂O and H₂S as references. For the calculations
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3 regarding the reconstructive growth mechanism of MoS₂ the unit cell had to be repeated once in
4 the x direction for the MoO₂ (010) and in the y direction for the MoO₂ (110) surface in order to
5 prevent the formed MoS₂ sheets from overlapping. The Brillouin zone was thus sampled with 4,
6 2, 1 k-points for the (010) system and 2, 4, 1 k-points for the (110) system in the x [20-2], y
7 [101] or [-11-1] and z [010] or [110] directions, respectively. Details regarding calculation of the
8 data points in Figure 4e are given in Supplementary methods in the Supporting Information.
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35 **Supporting Information.**

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37 Note, Supplementary methods and Figures S1-S12 (PDF)

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40 Video S1 accompanies Figure 2 and shows a MoO₂ nanocrystal during the exposure to 1 mbar of
41 10% H₂S in H₂ at 250°C. The images are recorded with 15 min intervals, with the first image
42 equivalent to 45 min of gas exposure. The movie is displayed with 2 frames per second. Each
43 frame corresponds to an image series of 5 exposures, which are post-aligned using cross-
44 correlation and summed to improve the image signal-to-noise ratio. description (AVI)
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References

- 1 Tenne, R. Inorganic Nanotubes and Fullerene-like Nanoparticles. *Nat. Nanotechnol.* **2006**, 1, 103-111.
- 2 Xu, H.; Liu, S.; Ding, Z.; Tan, S. J. R.; Yam, K. M.; Bao, Y.; Nai, C. T.; Ng, M.-F.; Lu, J.; Zhang, C Loh, K. P. Oscillating Edge States in One-Dimensional MoS₂ Nanowires. *Nat. Commun.* **2016**, 7, 12904.
- 3 Bollinger, M. V.; Lauritsen, J. V.; Jacobsen, K. W.; Nørskov, J. K.; Helveg, S.; Besenbacher, F. One-Dimensional Metallic Edge States in MoS₂. *Phys. Rev. Lett.* **2001**, 87, 196803.
- 4 Yin, X.; Ye, Z.; Chenet, D. A.; Ye, Y.; O'Brien, K.; Hone, J. C.; Zhang, X. Edge Nonlinear Optics on a MoS₂ Atomic Monolayer. *Science* **2014**, 344, 488-490.
- 5 Vojvodic, A.; Hinnemann, B.; Nørskov, J. K. Magnetic Edge States in MoS₂ Characterized by Density-Functional Theory. *Phys. Rev. B* **2009**, 80, 125416.
- 6 Chhowalla, M.; Shin, H. S.; Eda, G.; Li, L.-J.; Loh, K. P.; Zhang, H. The Chemistry of Two-Dimensional Layered Transition Metal Dichalcogenide Nanosheets. *Nat. Chem.* **2013**, 5, 263-275.
- 7 Deng, D.; Novoselov, K. S.; Fu, Q.; Zheng, N.; Tian, Z.; Bao, X. Catalysis with Two-Dimensional Materials and their Heterostructures. *Nat. Nanotechnol.* **2016**, 11, 218-230.
- 8 Prins, R. Energy-Related Catalysis: Hydrotreating Reactions: Hydrodesulfurization, Hydrodenitrogenation, Hydrodeoxygenation and Hydrodechlorination in *Handbook of Heterogeneous Catalysis* (eds. Ertl, G., Knözinger, H. & Weitkamp, J.), Wiley-VCH Verlag GmbH, 2008.
- 9 Besenbacher, F.; Brorson, M.; Clausen, B.S.; Helveg, S.; Hinnemann, B.; Kibsgaard, J.; Lauritsen, J.V.; Moses, P.G.; Nørskov, J.K.; Topsøe, H. Recent STM, DFT and HAADF-STEM Studies of Sulfide-Based Hydrotreating Catalysts: Insight into Mechanistic, Structural and Particle Size Effects. *Catal. Today* **2008**, 130, 86-96.

- 1
2
3 10 Jaramillo, T.F.; Jørgensen, K.P.; Bonde, J.; Nielsen, J.H.; Horch, S.; Chorkendorff, I.
4 identification of Active Edge Sites for Electrochemical H₂ Evolution from MoS₂
5 Nanocatalysts. *Science* **2007**, 317, 100-102.
6
7
8 11 Hou, Y.; Abrams, B. L.; Vesborg, P. C. K.; Björketun, M. E.; Herbst, K.; Bech, L.; Setti,
9 A. M.; Damsgaard, C. D.; Pedersen, T.; Hansen, O.; Rossmeisl, J.; Dahl, S.; Nørskov, J.
10 K.; Chorkendorff, I. Bioinspired Molecular Co-Catalysts Bonded to a Silicon
11 Photocathode for Solar Hydrogen Evolution. *Nat. Mater.* **2011**, 10, 434-438.
12
13 12 Asadi, M.; Kumar, B.; Behranginia, A.; Rosen, B. A.; Baskin, A.; Repnin, N.; Pisasale,
14 D.; Phillips, P.; Zhu, W.; Haasch, R.; Klie, R. F.; Král, P.; Abiade, J.; Salehi-Khojin, A.
15 Robust Carbon Dioxide Reduction on Molybdenum Disulphide Edges. *Nat Commun.*
16 **2014**, 5, 4470.
17
18 13 Liu, C.; Kong, D.; Hsu, P.-C.; Yuan, H.; Lee, H.-W.; Liu, Y.; Wang, H.; Wang, S.; Yan,
19 K.; Lin, D.; Maraccini, P. A.; Parker, K. M.; Boehm, A. B.; Cui, Y. Rapid Water
20 Disinfection using Vertically Aligned MoS₂ Nanofilms and Visible Light. *Nat.*
21 *Nanotechnol.* **2016**, 11, 1098-1104.
22
23 14 Tuxen, A. K.; Füchtbauer, H. G.; Temel, B.; Hinnemann, B.; Topsøe, H.; Knudsen, K.
24 G.; Besenbacher, F.; Lauritsen, J. V. Atomic-Scale Insight into Adsorption of Sterically
25 Hindered Dibenzothiophenes on MoS₂ and Co–Mo–S Hydrotreating Catalysts. *J. Catal.*
26 **2012**, 295, 146-154.
27
28 15 Hayden, T. F.; Dumesic, J. A. Studies of the Structure of Molybdenum Oxide and Sulfide
29 Supported on Thin Films of Alumina. *J. Catal.* **1987**, 103, 366-384.
30
31 16 Sakashita, Y.; Araki, Y.; Honna, K.; Shimada, H. Orientation and Morphology of
32 Molybdenum Sulfide Catalysts Supported on Titania Particles, Observed by using High-
33 Resolution Electron Microscopy. *Appl. Catal., A* **2000**, 197, 247-253.
34
35 17 Shimada, H. Morphology and Orientation of MoS₂ Clusters on Al₂O₃ and TiO₂ Supports
36 and their Effect on Catalytic Performance. *Catal. Today* **2003**, 86, 17-29.
37
38 18 Kibsgaard, J.; Chen, Z. B.; Reinecke, B. N.; Jaramillo, T. F. Engineering the Surface
39 Structure of MoS₂ to Preferentially Expose Active Edge Sites for Electrocatalysis. *Nat.*
40 *Mater.* **2012**, 11, 963-969.
41
42 19 Kong, D.; Wang, H.; Cha, J. J.; Pasta, M.; Koski, K. J.; Yao, J.; Cui, Y. Synthesis of
43 MoS₂ and MoSe₂ Films with Vertically Aligned Layers. *Nano Lett.* **2013**, 13, 1341-1347.
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 20 Wang, H.; Kong, D.; Johanes, P.; Cha, J. J.; Zheng, G.; Yan, K.; LiU, N.; Cui, Y. MoSe₂
4 and WSe₂ Nanofilms with Vertically Aligned Molecular Layers on Curved and Rough
5 Surfaces. *Nano Lett.* **2013**, 13, 3426-3433.
6
7
8 21 Jung, Y.; Shen, J.; Liu, Y.; Woods, J. M.; Sun, Y.; Cha, J. J. Metal Seed Layer
9 Thickness-Induced Transition from Vertical to Horizontal Growth of MoS₂ and WS₂.
10 *Nano Lett.* **2014**, 14, 6842-6849.
11
12
13 22 Wang, H.; Tsai, C.; Kong, D.; Chan, K.; Abild-Pedersen, F.; Nørskov, J. K.; Cui, Y.
14 Transition-Metal Doped Edge Sites in Vertically Aligned MoS₂ Catalysts for Enhanced
15 Hydrogen Evolution. *Nano Res.* **2015**, 8, 566-575.
16
17
18 23 Fei, L.; Lei, S.; Zhang, W.-B.; Lu, W.; Lin, Z.; Lam, C. H.; Chai, Y.; Wang, Y. Direct
19 TEM Observations of Growth Mechanisms of Two-Dimensional MoS₂ Flakes. *Nat.*
20 *Commun.* **2016**, 7, 12206.
21
22
23 24 Deng, Z. H.; Li, L.; Ding, W.; Xiong, K.; Wei, Z. D. Synthesized Ultrathin MoS₂
24 Nanosheets Perpendicular to Graphene for Catalysis of Hydrogen Evolution Reaction.
25 *ChemComm* **2015**, 51, 1893-1896.
26
27
28 25 Lan, F.; Lai, Z.; Xu, Y.; Cheng, H.; Wang, Z.; Qi, C.; Chen, J.; Zhang, S. Synthesis of
29 Vertically Standing MoS₂ Triangles on SiC. *Sci. Rep.* **2016**, 6, 31980.
30
31
32 26 Li, S.; Wang, S.; Salamone, M. M.; Robertson, A. W.; Nayak, S.; Kim, H.; Tsang, S. C.
33 E.; Pasta, M.; Warner, J. H. Edge-Enriched 2D MoS₂ Thin Films Grown by Chemical
34 Vapor Deposition for Enhanced Catalytic Performance. *ACS Catal.* **2017**, 7, 877-886.
35
36
37 27 Arrouvel, C.; Breysse, M.; Toulhoat, H.; Raybaud, P. A Density Functional Theory
38 Comparison of Anatase (TiO₂)- and γ -Al₂O₃-Supported MoS₂ Catalysts. *J. Catal.* **2005**,
39 232, 161-178.
40
41
42 28 Costa, D.; Arrouvel, C.; Breysse, M.; Toulhoat, H.; Raybaud, P. Edge Wetting Effects of
43 γ -Al₂O₃ and Anatase-TiO₂ Supports by MoS₂ and CoMoS Active Phases: A DFT Study.
44 *J. Catal.* **2007**, 246, 325-343.
45
46
47 29 Helveg, S. An Industrial Perspective of the Impact of Haldor Topsøe on (*In Situ*) Electron
48 Microscopy in Catalysis. *J. Catal.* **2015**, 328, 102-110.
49
50
51 30 Tao, F.; Crozier, P. A. Atomic-Scale Observations of Catalyst Structures under Reaction
52 Conditions and during Catalysis. *Chem. Rev.* **2016**, 116, 3487-3539.
53
54
55
56
57
58
59
60

- 1
2
3 31 Ross, F. M. Opportunities and Challenges in Liquid Cell Electron Microscopy. *Science*
4 **2015**, 350, aaa9886.
5
6 32 Feldman, Y.; Wasserman, E.; Srolovitz, D. J.; Tenne, R. High-Rate, Gas-Phase Growth
7 of MoS₂ Nested Inorganic Fullerenes and Nanotubes. *Science* **1995**, 267, 222-225.
8
9 33 Feldman, Y.; Frey, G. L.; Homyonfer, M.; Lyakhovitskaya, V.; Margulis, L.; Cohen, H.;
10 Hodes, G.; Hutchison, J. L.; Tenne, R. Bulk Synthesis of Inorganic Fullerene-Like MS₂
11 (M = Mo, W) from the Respective Trioxides and the Reaction Mechanism. *J. Am. Chem.*
12 *Soc.* **1996**, 118, 5362–5367.
13
14 34 Brandt, B. G.; Skapski, A. C. A Refinement of the Crystal Structure of Molybdenum
15 Dioxide. *Acta Chem. Scand.* **1967**, 21, 661-672.
16
17 35 Wienold, J.; Jentoft, R. E.; Ressler, T. Structural Investigation of the Thermal
18 Decomposition of Ammonium Heptamolybdate by *In Situ* XAFS and XRD. *Eur. J.*
19 *Inorg. Chem.* **2003**, 2003, 1058-1071.
20
21 36 Stockmann, R. M.; Zandbergen, H. V.; Langeveld, A. D. v.; Moulijn, J. A. Investigation
22 of MoS₂ on γ -Al₂O₃ by HREM with Atomic Resolution. *J. Mol. Catal. A: Chem.* **1995**,
23 102, 147–161.
24
25 37 Hansen, L. P.; Johnson, E.; Brorson, M.; Helveg, S. Growth Mechanism for Single- and
26 Multi-Layer MoS₂ Nanocrystals. *J. Phys. Chem. C* **2014**, 118, 22768-22773.
27
28 38 Margulis, L.; Salitra, G.; Tenne, R.; Talianker, M. Nested Fullerene-Like Structures.
29 *Nature* **1993**, 365, 113-114.
30
31 39 Shannon, R. D.; Rossi, R. C. Definition of Topotaxy. *Nature* **1964**, 202, 1000-1001.
32
33 40 Muijsers, J. C.; Weber, T.; Vanhardeveld, R. M.; Zandbergen, H. W.; Niemantsverdriet,
34 J. W. Sulfidation Study of Molybdenum Oxide Using MoO₃/SiO₂/Si(100) Model
35 Catalysts and Mo-^{IV}₃-Sulfur Cluster Compounds. *J. Catal.* **1995**, 157, 698-705.
36
37 41 Weber, T.; Muijsers, J. C.; van Wolput, J. H. M. C. ; Verhagen, C. P. J.;
38 Niemantsverdriet, J. W. Basic Reaction Steps in the Sulfidation of Crystalline MoO₃ to
39 MoS₂, As Studied by X-ray Photoelectron and Infrared Emission Spectroscopy. *J. Phys.*
40 *Chem.* **1996**, 100, 14144–14150.
41
42 42 Tauster, S. J.; Pecoraro, T. A.; Chianelli, R. R. Structure and Properties of Molybdenum
43 Sulfide: Correlation of O₂ Chemisorption with Hydrodesulfurization Activity, *J. Catal.*
44 **1980**, 63, 515-519.
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 43 Shi, Q.; Li, Y.; Zhou, Y.; Miao, S.; Ta, N.; Zhan, E.; Liu, J.; Shen, W. The Shape Effect
4 of TiO₂ in Vox/TiO₂ Catalysts for Selective Reduction of NO by NH₃. *J. Mater. Chem. A*
5 **2015**, 27, 14409-14415.
6
7
8 44 Picher, M.; Mazzucco, S.; Blankenship, S.; Sharma, R. Vibrational and Optical
9 Spectroscopies Integrated with Environmental Transmission Electron Microscopy.
10 *Ultramicroscopy* **2015**, 150, 10-15.
11
12
13 45 Mele, L.; Konings, S.; Dona, P.; Evertz, F.; Mitterbauer, C.; Faber, P.; Schampers, R.;
14 Jinschek, J. R. MEMS-Based Heating Holder for the Direct Imaging of Simultaneous *In*
15 *Situ* Heating and Biasing Experiments in Scanning/Transmission Electron Microscopes.
16 *Microsc. Res. Tech.* **2016**, 79, 239-250.
17
18
19
20 46 Hansen, P. L.; Helveg, S.; Datye, A. K. Atomic-Scale Imaging of Supported Metal
21 Nanocluster Catalysts in the Working State. *Adv. Catal.* **2006**, 50, 77-95.
22
23
24 47 Allard, L. F.; Bigelow, W. C.; Jose-Yacamán, M.; Nackashi, D. P.; Damiano, J.; Mick, S.
25 E. New MEMS-Based System for Ultra-High-Resolution Imaging at Elevated
26 Temperatures. *Microsc. Res. Tech.* **2009**, 79, 208-215.
27
28
29 48 Helveg, S.; Kisielowski, C. F.; Jinschek, J. R.; Specht, P.; Yuan, G.; Frei, H. Observing
30 Gas-Catalyst Dynamics at Atomic Resolution and Single-Atom Sensitivity. *Micron* **2015**,
31 68, 176-185.
32
33
34 49 Kilaas, R. *Total Resolution LLC: Software for High Resolution Electron Microscopy*,
35 <<http://www.totalresolution.com>> (2016).
36
37
38 50 Mortensen, J. J.; Hansen, L. B.; Jacobsen, K. W. Real-Space Grid Implementation of the
39 Projector Augmented Wave Method. *Phys. Rev. B* **2005**, 71, 035109.
40
41 51 Enkovaara, J.; Rostgaard, C.; Mortensen, J. J.; Chen, J.; Dulak, M.; Ferrighi, L.; Gavnholt,
42 J.; Glinsvad, C.; Haikola, V.; Hansen, H. A. *et al.* Electronic Structure Calculations with
43 GPAW: A Real-Space Implementation of the Projector Augmented-Wave Method. *J.*
44 *Phys.: Condens. Matter* **2010**, 22, 253202.
45
46
47
48 52 Bahn, S. R.; Jacobsen, K. W. An Object-Oriented Scripting Interface to a Legacy
49 Electronic Structure Code. *Comput. Sci. Eng.* **2002**, 4, 56-66.
50
51 53 Chase, M. W. *NIST-JANAF Thermochemical Tables*. 4 edn, (American Chemical
52 Society, 1998).
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7 **Figure 1.** Surface sulfidation of MoO₂ nanocrystals. **a** An illustration of a MoO₂ nanocrystal
8 before and after partial sulfidation by heating in H₂S/H₂. In the sulfided state, a partial coverage
9 of co-existing *e*-MoS₂ and *p*-MoS₂ phases is illustrated by the MoS₂ sheets (yellow) orientated
10 perpendicular to and along the MoO₂ crystal facets (blue), respectively. **b, c** TEM images of
11 MoO₂ nanocrystals after exposure to 10% H₂S in H₂ *in situ* at (b) 250°C for 300 min and (c)
12 300°C for 240 min. The images are acquired in the microscope base vacuum (5×10^{-6} mbar) at
13 120°C. A distinct lattice constant with the MoS₂ (002) lattice spacing of 0.62nm and the MoS₂
14 (100) lattice spacing of 0.27 nm are resolved at the surface of the MoO₂ nanocrystals in b and c.
15 Crystal lattice planes with spacing corresponding to MoO₂ are resolved in the bulk of the
16 nanoparticles.
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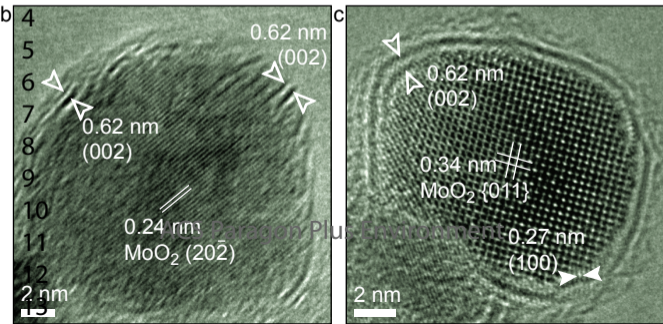
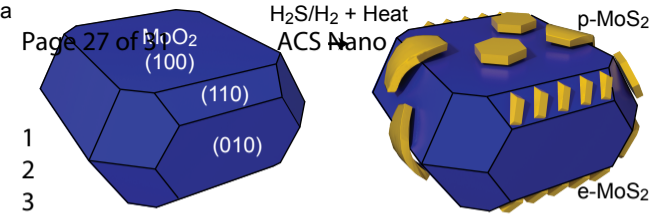
33 **Figure 2.** Time-resolved TEM imaging of a MoO₂ nanocrystal *in situ* during sulfidation. **a-f**
34 Time-resolved TEM of a MoO₂ nanocrystal during the exposure to 1 mbar of 10% H₂S in H₂ at
35 250°C. The images are extracted from Video S1 in the Supporting Information at times [and
36 accumulated electron dose] of (a) 45 min [9×10^3 e⁻/Å²], (b) 65 min [27×10^3 e⁻/Å²], (c) 85 min
37 [45×10^3 e⁻/Å²], (d) 160 min [81×10^3 e⁻/Å²], (e) 220 min [126×10^3 e⁻/Å²] and (f) 280 min
38 [153×10^3 e⁻/Å²]. The time of 0 min corresponds to the time of gas introduction in the experiment.
39 The inserts show Fast Fourier Transforms of the corresponding images. The open arrowhead
40 indicates the location of *e*-MoS₂. First the MoO₂ (01-1) and later the (20-2) lattice planes are
41 visible in the MoO₂ bulk due to slight rotation of the nanocrystal with time. All TEM images
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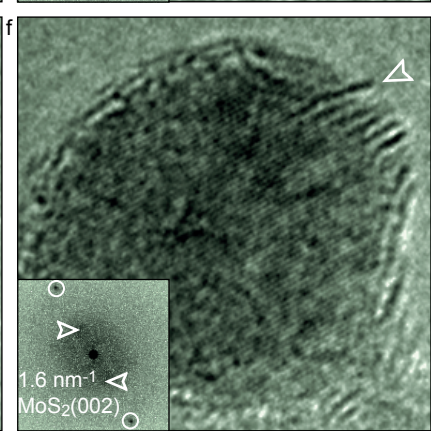
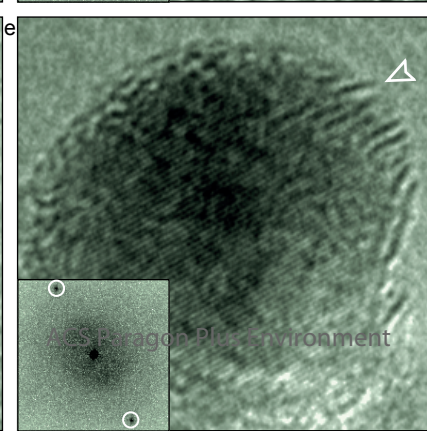
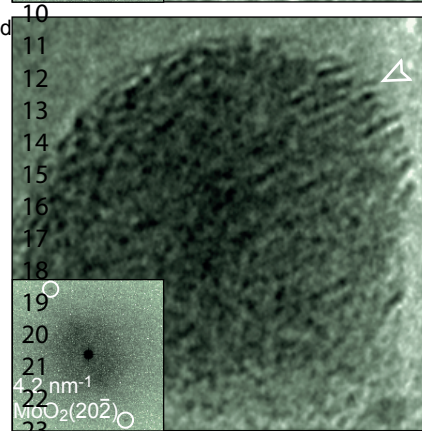
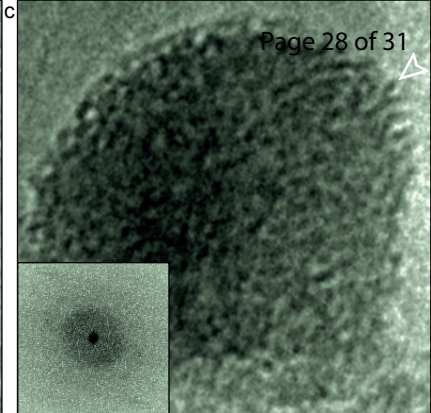
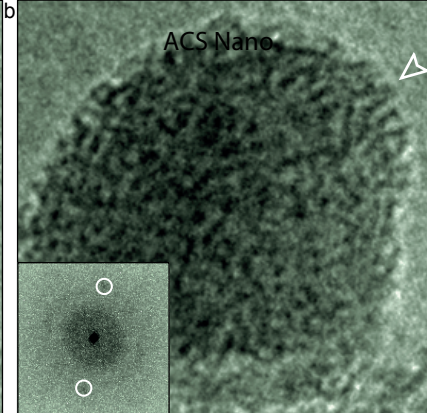
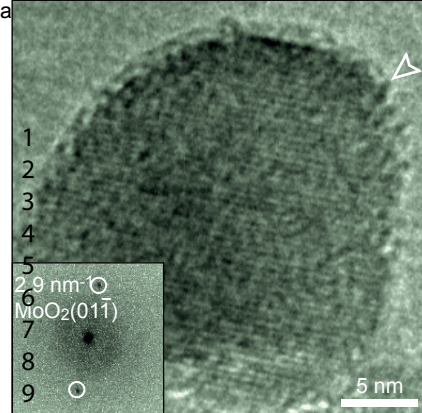
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8 **Figure 3.** Interface between *e*-MoS₂ and MoO₂. **a** Close-up high resolution TEM image of the
9 nanocrystal in Figure 2, acquired *post mortem* after sulfidation for 300 min exposure to 1 mbar
10 10% H₂S in H₂ at 250°C. The superimposed crystal lattice vectors and zone axis (Z.A.)
11 correspond to MoO₂. **b** FFT image revealing the MoO₂ (20-2), MoO₂ (11-1) and MoS₂ (002)
12 lattice planes, corresponding to a zone axis (Z.A.) view of the MoO₂ nanocrystal in the [101]
13 direction. **c** Image intensity line-scans in MoO₂ and *e*-MoS₂ obtained along MoO₂[20-2] and
14 averaged over 10 pixels corresponding to the blue (MoO₂), orange (*e*-MoS₂) and yellow (*e*-
15 MoS₂) boxes in (a).
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28 **Figure 4.** Atomic mechanism for topotaxy of *e*-MoS₂ at the MoO₂(110) surface. **a-d** The
29 topotactic transformation is illustrated by ball models of the atomic structures at an inclined
30 projection (left) and by sketches of the [-11-1] oriented atomic rows with Mo in the center and
31 the anionic content as the rim (right). The colors coding is dark blue for Mo in [-11-1] rows with
32 the bulk density (full row), light blue for Mo in [-11-1] rows with half the bulk density (half
33 row), red for O and yellow for S. Crystal directions are quoted with reference to the MoO₂
34 lattice. The atomic row numbering is equivalent in the ball models and sketches. All surface
35 structures are obtained by DFT calculations. **a** Initial state for the sulfided MoO₂(110) surface
36 (indicated by the dashed line). **b** The sulfided MoO₂(110) surface after displacement of row 1. **c**
37 The sulfided MoO₂(110) surface in (b) after displacement of row 3 and surface O-S exchange of
38 the exposed oxide surface in rows 2, 4 and 5, resulting in a two-row *e*-MoS₂ sheet. **d** The
39 sulfided MoO₂(110) surface in (c) after displacement row 4 and 5 and O-S exchange in the
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3 exposed oxide surface, resulting in a four-row *e*-MoS₂ sheet aligned with the MoO₂(20-2) planes.
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5 **e** Calculated Gibbs free energies per unit cell for (a-d) for both the MoO₂(110) and (010)
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7 surfaces (Methods).
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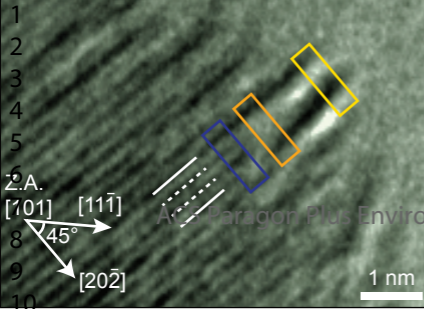




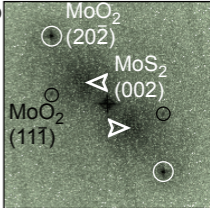
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