Nanometer-sized particles of MoS₂ were synthesized on (100), (001), and (110) surfaces of rutile TiO₂. Molybdenum oxide was deposited on the TiO₂ substrates and then sulfided to simulate the preparation of industrial catalysts. The nanoparticles which appeared on the sulfided surfaces were assigned to MoS₂ particles. The topography of the nanoparticles was observed by atomic force microscopy (AFM) and by transmission electron microscopy (TEM). The number density of the nanoparticles was related to the surface energy of the substrates through the population of nucleation centers. On the TiO₂(110) surface, AFM and TEM images assignable to MoS₂ crystals edge-bonded to the substrate were observed. The coincidental lattice spacings of MoS₂ and this particular surface were related to the observed edge-bonded growth. [DOI: 10.1380/ejssnt.2004.32]

Keywords: Atomic force microscopy; Transmission electron microscopy; MoS₂; TiO₂; Nano structure chemistry, processing and fabrication

I. INTRODUCTION

MoS₂-based catalysts have been intensely investigated for the hydrodesulfurization (HDS) reaction of petroleum [1]. It has been claimed that the aspect ratio (height vs. width) of MoS₂ nanoparticles supported on a substrate controls the selectivity of the reaction, i.e., the HDS or hydrogenation [2,3]. MoS₂/Al₃O₃ catalysts promoted with cobalt additives present more advanced catalytic performances. It also has been pointed out that on Co-promoted catalysts, the CoMoS-II phase cluster of a multilayered structure is more active than the CoMoS-I phase of a single-layer structure [4,5]. In addition, the role of MoS₂ crystals edge-bonded to the substrates has been debated [6-8]. Recently, edge-bonded particles have been found on γ-Al₂O₃ [9,10] and anatase TiO₂ [11,12] substrates by transmission electron microscopy (TEM). These edge-bonded particles showed improved activity for hydrogenation [12]. Therefore, a method for making various figures of MoS₂ clusters is needed to control catalytic reactions. It is important to understand the 3-D topography of supported MoS₂ nanoparticles. Handling real catalysts is one of the advantages of TEM, while information on the cluster height is limited. Scanning probe microscopy (SPM) is a powerful method to deduce the 3-D topography of nanoparticles supported on a flat substrate. Macroscopic crystals of MoS₂ have been frequently observed by scanning tunneling microscopy (STM) as a substrate of compound semiconductors [13-17], as a conductive support of metal clusters [18], and as a model catalyst for the HDS reaction [19,20]. MoS₂ nanoparticles have been observed by STM on graphite [21,22] and on gold [23-25] substrates. Atomic-scale topography of triangular-shaped MoS₂ was resolved on the latter substrate. In the present study, we chose rutile TiO₂ as the substrate to construct a more realistic model of industrial MoS₂ catalysts supported on metal oxides. Nanoparticles of MoS₂ were synthesized on (100), (001), and (110) single-crystalline surfaces of rutile TiO₂ and observed by atomic force microscopy (AFM) and by TEM, as an extension of our earlier works [9,26]. Molybdenum oxide was deposited on the TiO₂ substrates and then sulfided to simulate the preparation of industrial catalysts.

II. EXPERIMENTAL

One-side polished single-crystalline substrates of rutile TiO₂ (Shinkosha, 10 × 10 × 0.5 mm³) were used as substrates. The preparation method of the MoS₂ model catalyst on these substrates was described elsewhere [9,26]. Molybdenum oxide was vacuum evaporated from a Knudsen cell at 783 K to the substrate which was maintained at room temperature. The thickness of the deposited film was controlled to be 0.3 nm by referring to a quartz oscillator. The deposited samples were oxidized with O₂ gas (1.3 × 10⁻³ Pa) at 673 K for 30 min and then sulfided with H₂-balanced 5%-H₂S gas (1.0 × 10⁵ Pa) at 673 K for 30 min.

The topography of the sulfided samples was observed with an AFM (Jeol, JSPM-4200) under a vacuum (5 × 10⁻⁴ Pa) at room temperature using a Si₃N₄ cantilever (Olympus, OMCL-TR400PSA-1). The 3-D scale of the microscope was calibrated on HOPG (Advanced Ceramics, STM-1) and MoS₂ wafers. Constant force topography determined in a contact mode is presented in a gray scale.
FIG. 1: Constant force topography of the model catalyst prepared on a TiO$_2$(100) surface. (a): a surface before the MoO$_x$ deposition, (b): the surface of (a) following the MoO$_x$ deposition and oxidation at 673 K, (c) the surface of (b) sulfided at 673 K. Image size: 500 × 500 nm$^2$. The cross sections determined on the lines in (a), (b), and (c) are presented in (d), (e), and (f).

TEM (Topcon EM-002B) observation was performed at 200 kV with a point resolution of 0.19 nm on the substrates, which were prepared by using a combination of punching, grinding, and ion-milling techniques [27].

III. RESULTS AND DISCUSSION

A. AFM observation

Figure 1 shows 500-nm-square AFM images of the TiO$_2$(100) sample following the fabrication steps. The surface as received (washed by supersonic wave in acetone before use) (a) was flat with vertical corrugations less than 0.6 nm as shown in cross section (d). Molybdenum oxide was thermally deposited on the surface of (a) and oxidized at 673 K. The topography (b) and cross section (e) of the oxidized surface remained flat, indicating the TiO$_2$ substrate was homogeneously coated with molybdenum oxide. Similarly, a flat topography of the MoO$_x$ layers was observed on TiO$_2$(001) and (110) substrates (not shown). This is consistent with the epitaxial growth of MoO$_2$ found on these TiO$_2$ substrates [26]. The O/Mo atom ratio of the oxide-covered samples was determined to be 2 by Auger electron spectroscopy (AES). MoO$_2$ of a distorted rutile structure was proposed to epitaxially crystallize with Mo-O-Ti linkages along the following orientations,

MoO$_2$(010) // TiO$_2$(100),
MoO$_2$(101) // TiO$_2$(001),
MoO$_2$(11T) // TiO$_2$(110),
on the basis of reflection high-energy electron diffraction (RHEED) [26]. Nanometer-sized particles appeared when the oxide-covered (100), (001), and (110) surfaces were sulfided. The topography of the sulfided (100) surface is shown in (c). These particles should have been assigned to the MoS$_2$ nanoparticles of composition, because the S/Mo atom ratio was determined at 1.9 on a similarly treated TiO$_2$(100) substrate [26]. The size and number density of the MoS$_2$ nanoparticles were examined on wide-area scans and are described in the next paragraph. Corrugations on the flat plane other than the nanoparticles remained less than 0.6 nm. The amount of deposited
Mo (equivalent to an oxide thickness of 0.3-nm) was involved much more in the clusters as excess MoS$_2$ than the nanoparticles of MoS$_2$ composition. We thus assumed that the excess MoS$_2$ yielded clusters of sub-nanometer sizes and were spread over the plane among the nanoparticles. Those sub-nanometer clusters which directly interfaced with the TiO$_2$ particles were spread over the plane among the nanoparticles. Those sub-nanometer clusters which directly interfaced with the TiO$_2$ substrate may have been incompletely sulfided [26]. Incompletely sulfided clusters which were anchored to TiO$_2$ substrates via Mo-O-Ti linkages were also observed by EXAFS [28] and XPS [29].

Figures 2(a), (b), and (c) show 1-µm-square AFM images of the MoS$_2$ nanoparticles which were synthesized on the (100), (001), and (110) substrates. The population and topographic height of the particles were sensitive to the orientation of the substrates. The number density of the MoS$_2$ nanoparticles was statistically determined based on a number of observations with values of $2.8 \times 10^{-5}$, $6.8 \times 10^{-6}$ and $1.4 \times 10^{-6} \text{nm}^{-2}$, respectively (Table 1). The height of the particles was measured on cross sections, a fraction of which are presented in (d)-(f). The distribution of the particle height is summarized in the bar-graph of Fig. 3. On the (001) substrate more than 80% of the particles fall in the 2-nm segment. The average height is listed in Table 1.

The number density of the nanoparticles is related to the surface energy of the substrates. A substrate with a larger surface energy yields more particles. The particles should be nucleated on singularities (steps, vacancies, etc.) of the single crystalline substrates. It is expected that the creation of those singularities is enhanced on a surface of large surface energy. When the total MoS$_2$ quantity available for the particle formation is the same on the three substrates, the maximum particle size should be found on the surface with the least number of particles. This was the case on the (110) substrate in Table 1.

On the other hand, the sub-nanometer clusters assumed in the interpretation of Fig. 1 may remain as Mo-O-Ti linkages to the substrates and may be restricted in surface mobility. The S/Mo ratio determined by our AES analysis [26] exhibits the lowest number, 1.5, on the (110) substrate. This suggests the Mo-O-Ti linkages on TiO$_2$(110) in particular resist being sulfided. The stability of the MoO$_2$/TiO$_2$ interface is possibly sensitive to the atomicistic structure of the linkages rather than to the surface energy of the uncovered surface.

Indeed a characteristic feature of the nanoparticles synthesized on the (110) substrate was observed; oval and elongated shapes as shown in the zoomed-up topography of Fig. 4. The elongated axis of each nanoparticle was parallel to the [001], [110], or [112] direction of the substrate. How the nanoparticles were aligned on the (110) substrates was examined by TEM.

### B. TEM observation

Figure 5 shows the TEM image of model catalysts prepared on (110) and (100) substrates sulfided at 773 K. Short, dark rows were observed on the (110) substrate in (a), whereas only a few were recognized on the (100) substrate in (b). Most particles were fully sulfided on TiO$_2$(100) surface (Table 1). Basal-bonded MoS$_2$ clusters should be grown on TiO$_2$(100) during the sulfidation. However, it is difficult to image basal-bonded clusters by TEM [8]. Typical examples of the rows are pointed by white arrows in (a). Similar dark rows have been observed on MoS$_2$ supported on γ-Al$_2$O$_3$ [7-9, 27] and anatase TiO$_2$ powders [11] and assigned to the side-viewed Mo planes of MoS$_2$ crystals edge-bonded to the substrates. As shown in the zoomed images of (c), (d), and (e), the crystal plane of the edge-bonded clusters was oriented parallel to the [001], [110], and [112] directions. The preferred directions observed by AFM (Fig. 4) and TEM (Fig. 5) were consistent. The length and layer-thickness of the edge-bonded cluster ranged from 1-3 nm and 1-3 layers in the TEM images, whereas its height ranged from 4-6 nm as shown in the AFM results.

On the basis of the atomically resolved TEM images of Fig. 5, Fig. 6 illustrates possible alignments of the edge-bonded MoS$_2$ clusters on the single crystal thin film [9, 27] and...
TABLE I: Statistics of MoS$_2$ nanoparticles synthesized on rutile surfaces. $^a$: from [30]. $^b$: determined by AES [26].

<table>
<thead>
<tr>
<th>Orientation</th>
<th>TiO$_2$(100)</th>
<th>TiO$_2$(001)</th>
<th>TiO$_2$(110)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number density (nm$^{-2}$)</td>
<td>$2.8 \times 10^{-5}$</td>
<td>$6.8 \times 10^{-6}$</td>
<td>$1.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>Topographic height (nm)</td>
<td>3.0</td>
<td>2.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Surface energy (Jm$^{-2}$) $^a$</td>
<td>2.08</td>
<td>2.40</td>
<td>1.78</td>
</tr>
<tr>
<td>S/Mo atom ratio$^b$</td>
<td>1.9</td>
<td>1.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

MoS$_2$/anatase TiO$_2$ nano-crystal [11] systems. The distance between the two Mo planes was fixed at 615 pm. A MoS$_2$ crystal truncated normal to its [10$ar{1}$0] direction (316 pm of inline Mo-Mo distance) was interfaced to the TiO$_2$ surface. These structures contained lattice mismatches less than 9%, which are summarized in Table 2. The mismatches likely induced some edge-bonded crystals in Fig. 5 which caused them to bend. The results suggest that the edge-bonded MoS$_2$ cluster can be synthesized using lattice matching of the interface where the incomplete sulfided Mo-O-Ti bond is situated. We have reported evidence of an edge-bonded MoS$_2$ cluster on $\gamma$-Al$_2$O$_3$ and anatase TiO$_2$ by a TEM study. The present study of the rutile TiO$_2$ surfaces suggests that the edge-bonded MoS$_2$ generally grew as the result of the lattice matching between a cluster and a substrate.

**IV. CONCLUSIONS**

MoS$_2$ nanoparticles were synthesized on rutile (100), (001), and (110) surfaces via the deposition of molybdenum oxide and subsequent sulfidation to simulate the preparation of industrial catalysts. The number density of the sulfide nanoparticles was related to the surface energy of the substrates through the population of nucleation centers. Edge-bonded MoS$_2$ crystals were yielded on the (110) surface. The coincident lattice spacings of the deposit and the particular substrate allows effective linkage of Mo-O-Ti at the interface and results in the edge-
FIG. 6: Possible arrangements of MoS$_2$ crystals edge-bonded to the TiO$_2$(110) substrate. MoS$_2$ crystals were placed on the TiO$_2$(110) surface as a mismatch of period between Mo and Ti atoms was made into the minimum. The Mo planes are parallel to the (a) [001], (b) [110], and (c) [112] direction of the substrate.

TABLE II: Comparison of lattice mismatches between MoS$_2$ crystal and rutile TiO$_2$(110) surface

<table>
<thead>
<tr>
<th>Alignments of MoS$_2$</th>
<th>[001]</th>
<th>[110]</th>
<th>[112]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inline Mo-Mo (316 pm)</td>
<td>+6.8%</td>
<td>-2.8%</td>
<td>+8.5%</td>
</tr>
<tr>
<td>Mo planes (615 pm)</td>
<td>-5.4%</td>
<td>+3.9%</td>
<td>-6.3%</td>
</tr>
</tbody>
</table>

bonded growth.