Reactivity and Stability of Ultrathin VO\textsubscript{x} Films on Pt(111) in Catalytic Methanol Oxidation

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Abstract
The growth of ultrathin layers of VO\textsubscript{x} (<12 monolayers) on Pt(111) and the activity of these layers in catalytic methanol oxidation at 10\textsuperscript{−4} mbar have been studied with low-energy electron diffraction, Auger electron spectroscopy, rate measurements, and with photoemission electron microscopy. Reactive deposition of V in O\textsubscript{2} at 670 K obeys a Stranski–Krastanov growth mode with a (√3 × √3)R30° structure representing the limiting case for epitaxial growth of 3D-VO\textsubscript{x}. The activity of VO\textsubscript{x}/Pt(111) in catalytic methanol oxidation is very low and no redistribution dynamics is observed lifting the initial spatial homogeneity of the VO\textsubscript{x} layer. Under reaction conditions, part of the surface vanadium diffuses into the Pt subsurface region. Exposure to O\textsubscript{2} causes part of the V to diffuse back to the surface, but only up to one monolayer of VO\textsubscript{x} can be stabilized in this way at 10\textsuperscript{−4} mbar.

Keywords vanadium oxide catalysts · Pt(111) · Supported catalyst · Methanol oxidation · Stranski–Krastanow growth

1 Introduction
Vanadium oxides belong to the most important catalysts in chemical industry, finding applications for example in sulfuric acid production and in many partial oxidation reactions [1]. Typically the V-oxides are supported on oxidic materials like SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, ZrO\textsubscript{2} or TiO\textsubscript{2} with the most active form being isolated VO\textsubscript{2}-clusters or VO\textsubscript{x}-films of monolayer thickness [2, 3]. Quantum chemical calculations and surface science experiments were able to clarify the reaction mechanism in catalytic methanol oxidation and the influence of the support material [4–8]. In the surface science approach [9], first single crystals of the bulk oxides were studied [10, 11], followed by planar model systems in which ultrathin V-oxide layers were deposited on single crystal oxide surfaces like α-Al\textsubscript{2}O\textsubscript{3}(0001), CeO\textsubscript{2}(111) or TiO\textsubscript{2}(110) [12–15] and on the fcc(111) und fcc(100) surfaces of the metals Pt, Rh, Pd, Cu, and Au [16–20]. In the past three decades the synthesis and characterization of ultrathin metal oxide films on metal surfaces has evolved into an own research field [21, 22].

A particularly well studied system are ultrathin V-oxide layers on a Rh(111) surface with the V coverage being in the monolayer and submonolayer range [20, 23, 24]. The dynamics of catalytic reactions on VO\textsubscript{x}/Rh(111) have been studied with spatially resolving methods focusing on catalytic methanol oxidation. A very rich redistribution dynamics of the VO\textsubscript{x} layer on Rh(111) was found with breathing VO\textsubscript{x} islands in the 10\textsuperscript{−4} mbar range, turbulent dynamics at 10\textsuperscript{−2} mbar and, remarkably, with reaction-induced coalescence of macroscopic VO\textsubscript{x} islands in the 10\textsuperscript{−4} mbar range [25, 26]. A natural question was how general the phenomenon of a reaction-induced island coalescence is, i.e., whether such ripening processes can also be observed in other reactions [27], with different support materials [28–30], and with other oxidic catalysts. It turned out that a number of oxidation reactions showed qualitatively the same behavior on VO\textsubscript{x}/Rh(111) as long as O\textsubscript{2} is used as oxidizing agent [31].

Pt(111) is a fcc(111) noble metal surface similar to Rh(111), and therefore one should expect to find quite similar behavior on VO\textsubscript{x}/Pt(111) as on VO\textsubscript{x}/Rh(111). Different
from the system VO\textsubscript{x}/Rh(111), which has thoroughly been characterized in the past two decades [20, 23, 24], only few experimental studies on the growth and reactivity of VO\textsubscript{x} films on Pt(111) are reported in the literature [19, 32–34]. Here we report on the growth behavior of VO\textsubscript{x} on Pt(111) and we investigate the catalytic activity and the dynamics of such a VO\textsubscript{x} layer during catalytic methanol oxidation.

The concept of depositing oxides onto a metal support instead of having small metal particles sitting on an oxidic support, as it is the case for the supported catalysts used in industry, has been termed inverse model catalyst approach [22, 35–38]. Besides practical advantages such as avoiding electrical charging of the sample, this concept has been used to study processes at the metal/oxide interface, and to investigate a group of phenomena summarized under the term strong metal support interaction (SMSI). Historically, the term SMSI was introduced by Tauster who observed a change in the H\textsubscript{2} and CO adsorption properties after high temperature reduction of dispersed platln group metals (PGM) on metal oxide supports [39–41]. Transmission electron microscopy unambiguously showed the encapsulation of supported PGM catalysts by their metal oxide support [42–45]. Besides partial wetting or complete encapsulation of metallic nanoparticles by the oxidic support, also the formation of intermetallic compounds or alloys has been observed, especially at very high temperature under reducing conditions [46, 47].

In the present case, the inverse catalyst concept seems not to be adequate for VO\textsubscript{x}/Pt(111) since V-oxide is not used as a support material for Pt particles. Nevertheless, the concept still appears to be useful to explore the interface VO\textsubscript{x}/Pt and to compare the properties of ultrathin V-oxide layers on different noble metal surfaces. Surprisingly the system VO\textsubscript{x}/Pt(111) displays quite different properties than the system VO\textsubscript{x}/Rh(111) with respect to the structure as well as with respect to the catalytic activity, stability and dynamic behavior in catalytic methanol oxidation. The differences can be traced back to different properties of the VO\textsubscript{x} film on Pt(111), and to a low oxygen adsorption energy and slow O\textsubscript{2} adsorption kinetics on Pt(111) [48–52].

## 2 Experimental

The experiments are performed in a standard ultrahigh-vacuum (UHV) vessel equipped with a photoemission electron microscope (PEEM), a low-energy electron diffraction (LEED) optics, a cylindrical mirror analyzer for Auger electron spectroscopy (AES), and a differentially pumped quadrupole mass spectrometer (QMS) for temperature programmed reaction (TPR) measurements. The Pt(111) single crystal (8 mm diameter, 1 mm thick) is spot-welded to two Ta wires. Heating the surface is either possible via passing current through the Ta wires (up to ~1100 K) or by electron bombardment from the sample backside. The temperature is measured with a K-type thermocouple spot-welded to the backside of the Pt crystal. Surface cleaning is performed by repeated cycles of Ar\textsuperscript{+} ion sputtering (1 keV, 300 K, 2–5 µA, 20 min) and oxygen treatment at 1 × 10\textsuperscript{-6} mbar and 820–1020 K. Each cleaning cycle is finished by a final flash annealing to 1100 K prior to experiments. The presence of impurities is checked by AES. Vanadium oxide films are deposited by reactive evaporation [23], a process in which V is evaporated by electron beam bombardment from a high purity V rod (Goodfellow) in an oxygen atmosphere at elevated substrate temperature. VO\textsubscript{x} is deposited at 670 K in an oxygen atmosphere of 2 × 10\textsuperscript{-7} mbar.

Under reaction conditions oxygen and methanol are dosed through high precision leak valves ensuring constant partial gas pressures via a feedback controlled gas inlet system. The pressure is measured with a Bayard-Alpert ionization gauge, (uncorrected pressure). To perform TPR measurements, the sample is positioned directly in front of a cone of 6 mm opening that connects the main UHV chamber to a differentially pumped QMS. In this way, all detected molecules have hit the sample surface prior to detection. To convert the ion currents measured in the QMS into pressure units, tabulated gas correction factors have been taken into account, as well as molecule fragmentation patterns. Ex situ sample characterization is carried out by AES and LEED prior and after exposure to methanol oxidation.

## 3 Results

### 3.1 Growth of VO\textsubscript{x} on Pt(111)

The rate of VO\textsubscript{x} deposition during reactive evaporation onto the Pt(111) substrate is followed by a combined AES and LEED analysis. VO\textsubscript{x} is successively deposited, first in 30 s steps up to a total deposition time of 5.5 min, afterwards the deposition is continued in larger steps ranging between one and 10 min. Before and after each deposition step, the sample is kept for 10 min at evaporation conditions, i.e. at 670 K in 2 × 10\textsuperscript{-7} mbar oxygen. The growth of VO\textsubscript{x} is monitored by AES and LEED after the sample has been cooled down to room temperature in the oxygen atmosphere. The AES deposition rate and a series of LEED images recorded throughout the deposition process are shown in Figs. 1 and 2, respectively.

The plot of the V, O, and Pt Auger intensities as a function of deposition time in Fig. 1 shows a steep, linear increase of the V and O signals during the first 2.5 min of VO\textsubscript{x} deposition, accompanied by a sharp decrease of the Pt signal (for details please refer to the Online Resource 1). After 2.5 min the V and O signals continue to increase, but
at a considerably lower rate. A similar change in slope can also be seen in the Pt signal, which decreases at a slower rate starting from 2.5 min. We interpret the initial linear increase followed by a pronounced change in the slope of the V and O signals as completion of the first oxide monolayer, followed by the growth of three-dimensional VOₓ crystallites on top of the initial layer. Following arguments provided in the next two paragraphs, we conclude that during reactive evaporation VOₓ grows in the Stranski–Krastanow mode [53, 54].

According to the AES calibration curve in Fig. 1, 2.5 min deposition time are required to deposit 1 ML of VOₓ. The coverage of 1 ML refers to a closed VOₓ film, i.e. we are using relative coverages. Since no structure model for the V-oxide film exists, the number of V atoms present on the surface is not known. Accordingly, VOₓ coverages cannot be expressed in monolayer equivalents (MLE), as customary in studies on the growth of ultrathin oxide films.

The interpretation of the AES data as a Stranski–Krastanow growth mode of VOₓ on Pt(111) is further corroborated by the LEED images shown in Fig. 2. Initially, a diffuse Moiré-type LEED pattern is observed for coverages below 1 ML. As the first oxide layer is completed, additional weak spots of a (√3 x √3)R30° structure appear superimposed onto the Moiré pattern. Starting at around 1.4 ML, spots belonging to a (2 x 2) are added to the (√3 x √3)R30° and the vanishing Moiré LEED spots. After the deposition of ~2 ML VOₓ only the (√3 x √3)R30° and (2 x 2) remain. Further VOₓ dosage results in an intensity decrease of the (2 x 2) diffraction pattern, until at roughly 12 ML the (√3 x √3)R30° diffraction pattern dominates and only very faint spots of the (2 x 2) remain visible in LEED.

We interpret the sequence of LEED patterns, in terms of a Stranski–Krastanow growth mode, as follows: For coverages up to 1 ML vanadium oxide grows as a poorly ordered 2D-oxide until the first monolayer is completed. Further VOₓ dosage results in the nucleation and growth of small 3D-crystallites that exhibit a (√3 x √3)R30° structure as topmost plane. The reason to assign the (√3 x √3)R30° structure to 3D-crystallites is that the same (√3 x √3)R30° structure is observed after the growth of a many monolayers thick VOₓ film. The appearance of a (2 x 2) in LEED that follows is apparently due to a transformation of the 1st monolayer exhibiting a Moiré type pattern. This can either be
caused by an ordering of the first oxide layer with increasing VO\textsubscript{x} coverage, resulting from an incorporation of V atoms into the initial oxide layer as observed in the system VO\textsubscript{x}/Rh(111) [23], or, alternatively, by opening up a second VO\textsubscript{x} layer on areas not covered by the (√3 × √3)R30° crystallites. The growth mode would in that case no longer be pure Stranski–Krastanow. Finally, after deposition of a large amount of VO\textsubscript{x}, only the (√3 × √3)R30° phase is present on the surface. From the Auger data we estimate an O/V ratio of roughly 1.4 for several layers thick VO\textsubscript{x} films, in agreement with the composition of a V\textsubscript{2}O\textsubscript{3} phase (for details please refer to the Online Resource 1).

### 3.2 Reaction Rate Measurements During Methanol Oxidation

For TPR measurements, the bare Pt(111) surface as well as VO\textsubscript{x}/Pt(111) surfaces with different VO\textsubscript{x} coverages (0.6 and 4 ML) are placed directly in front of a cone that connects the main chamber to a differentially pumped QMS. The reaction rate curves for Pt(111) and VO\textsubscript{x}/Pt(111) during a heating/cooling cycle are shown in Figs. 3a and b, respectively. On the uncovered Pt(111) surface pronounced production peaks appear in the CO\textsubscript{2} and H\textsubscript{2}O signals at 470 K (heating branch) and 440 K (cooling branch). Besides the product of total oxidation, CO\textsubscript{2}, also traces of the partial oxidation product formaldehyde are found on the uncovered Pt(111) surface in a very broad production peak around 500 K. Only

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**Fig. 3** TPR measurements (0.2 K/s) on Pt(111) a and 0.6 ML VO\textsubscript{x} on Pt(111) b during catalytic methanol oxidation in the 10\textsuperscript{−4} mbar range. Shown are the methanol (right axis) and water, carbon dioxide and methanol (left axis) QMS signals as a function of temperature. Gas phase composition: 1 × 10\textsuperscript{−4} mbar oxygen and 1 × 10\textsuperscript{−5} mbar methanol. Adapted with permission from [62].
negligible catalytic activity is seen above $\approx 600$ K. The low product formation at high temperature is probably caused by the low initial sticking coefficient of oxygen on Pt(111) of 0.05 at 300 K [55], which decreases with increasing temperature. Moreover, the surface residence time of adsorbates decreases with rising temperature. Interestingly, no CO signal can be found, i.e. it is below the detection limit of the mass spectrometer.

The deposition of larger quantities of VO$_x$ onto Pt(111) inhibits almost all catalytic activity, as evidenced by rate measurements with 0.6 and 4 ML VO$_x$. The data in Fig. 3b show reaction rates that are more than one order of magnitude lower than on the uncovered Pt(111) surface. The increase in the rate signals at lower temperature are probably caused by a slightly unstable gas flow and by accumulation of H$_2$O in the UHV chamber. Thermal decomposition of methanol at hot filaments causes some background signal. This low activity does not change if the gas phase composition is modified to more reducing conditions with $p$(CH$_3$OH) being $5 \times 10^{-5}$ mbar and $1 \times 10^{-4}$ mbar, respectively, while keeping $p$(O$_2$) constant at $1 \times 10^{-4}$ mbar. Evidently, the deposition of thin VO$_x$ films passivates the Pt(111) surface with respect to methanol oxidation.

LEED and AES data acquired before and after exposure to reaction conditions are shown in Fig. 4 for 0.6 and 4 ML thick VO$_x$ films. Auger spectra are recorded before and after a heating/cooling cycle in a gas atmosphere of oxygen and methanol. One notices a clearly detectable loss in V intensity as a consequence of the high temperature treatment. The V loss shows some dependence on the methanol to oxygen partial pressure ratio but the signal decrease varies strongly with the initial VO$_x$ coverage. Whereas the loss in V$_{437}$ intensity only amounts to 20–30% for the 0.6 ML films, more than 70% of the initial V intensity are lost after a 4 ML VO$_x$ film was exposed to methanol oxidation. For the thin 0.6 ML films, the highest V loss is observed in a reducing gas atmosphere, i.e. with $1 \times 10^{-4}$ mbar methanol and $1 \times 10^{-4}$ mbar oxygen. The loss of V intensity is an indication for a migration of V atoms into the surface or subsurface region of the Pt crystal. Since such a formation of a subsurface V/Pt

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**Fig. 4** Auger spectra and LEED images recorded before and after freshly deposited VO$_x$ films on Pt(111) were exposed to catalytic methanol oxidation with varying CH$_3$OH to O$_2$ ratios. Reaction conditions are in the $10^{-4}$ mbar range. For methanol oxidation, the samples are heated with 0.2 K/s from 300 to 1020 K and back to room temperature in an atmosphere consisting of $1 \times 10^{-4}$ mbar oxygen and methanol pressures of $1 \times 10^{-5}$, $5 \times 10^{-5}$ and $1 \times 10^{-4}$ mbar, respectively. **a** Auger spectra recorded before (black solid line) and after (red dashed line) the reaction. The spectra were recorded with 3 keV primary electron energy. **b–c** LEED images (65 eV) recorded after 0.6 ML VO$_x$ on Pt(111) were exposed to $1 \times 10^{-4}$ mbar oxygen and either $5 \times 10^{-5}$ mbar b or $1 \times 10^{-3}$ mbar methanol c. In c a (2 x 2) superimposed with a (1 x n) pattern (n=8) with three rotational domains is visible. Adapted with permission from [62].

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alloy requires metallic V, a reduction of VO\textsubscript{x} is a necessary
prerequisite for this process.

LEED shows an intense (2 x 2) after methanol oxidation on a 0.6 ML VO\textsubscript{x} film with a 1:2 ratio of methanol and oxygen in the gas phase. A (2 x 2) is also obtained with a 1:10 methanol to oxygen ratio. Under more oxidizing conditions, however, additional spots of a (1 x n) structure (n=8) appear in LEED, as shown in Fig. 4c. As shown below, a (2 x 2) also develops after several ML thick VO\textsubscript{x} films are exposed to reducing conditions. The formation of a (2 x 2) accordingly depends on the gas phase composition, but to a minor degree on the initial VO\textsubscript{x} coverage.

### 3.3 Segregation Behavior of VO\textsubscript{x}/Pt(111)

Quite general, elevated temperatures favor the formation of alloys between the supporting metal and metal from the deposited metal oxide film. This is particularly true if no miscibility gaps exist in the phase diagram of the two metals, as it is the case for Pt/V [56]. In order to determine up to which temperature VO\textsubscript{x} is stable as an oxide on the Pt(111) surface, a roughly 1.5 ML thick vanadium oxide film on Pt(111) is heated up to 1000 K in vacuum, while monitoring the surface composition with AES. Prior to this alloying experiment, the initially 5 ML thick VO\textsubscript{x}/Pt(111) sample has been exposed to methanol oxidation and heated in 1 x 10\textsuperscript{-4} mbar oxygen at 870 K for 40 min. The resulting V, O and Pt signal vs. temperature curves recorded during heating the sample up in vacuum are shown in Fig. 5.

Below 770 K the V and O Auger signals are constant, as can be seen in Fig. 5. A pronounced decrease in the V and O signals occurs beyond 770–870 K, accompanied by a growth of the Pt peak. We interpret the V and O intensity decrease as a reduction of VO\textsubscript{x} followed by diffusion of V into the subsurface region of the Pt crystal (for details please refer to the Online Resource 1). The increase in the Pt signal that already starts beyond 400 K might be due to ordering processes in the VO\textsubscript{x} layer. At 1020 K the V intensity has decreased by a factor of two compared to the initial V signal. After annealing the VO\textsubscript{x}/Pt(111) sample for another 20 min at 1020 K, the V signal has only about 20% of the initial intensity at room temperature. The high temperature of 1020 K that is required to generate such a loss indicates a slow diffusion of V into the Pt crystal.

An alternative explanation for the decreasing V Auger signals under reducing conditions could also be an agglomeration of the initially homogeneously distributed VO\textsubscript{x} into three-dimensional clusters. A similar behavior, the aggregation of a thin Ni/NiO layer into small, three-dimensional NiO clusters under oxidizing conditions has recently been observed in the H\textsubscript{2} + O\textsubscript{2} reaction over Ni/Rh(111) [57, 58]. However, if such a mechanism would operate in the VO\textsubscript{x}/Pt(111) system, a V signal decrease would occur under oxidizing conditions and not under reducing conditions as observed here.

### 3.4 Stability of Submonolayer VO\textsubscript{x} Films During Catalytic Methanol Oxidation

The reaction-induced redistribution dynamics of 0.4 and 5 ML VO\textsubscript{x} supported on the Pt(111) surface are studied in the 10\textsuperscript{-3} mbar range with PEEM. A 0.4 ML VO\textsubscript{x} film is heated in 1 x 10\textsuperscript{-4} mbar oxygen to 870 K within a few minutes, followed by introducing methanol into the vacuum chamber. As p(CH\textsubscript{3}OH) is varied in a wide pressure range between 1 x 10\textsuperscript{-5} and 1 x 10\textsuperscript{-4} mbar, no V-oxide redistribution is observed and the surface remains homogeneous in PEEM. Only gradual and homogeneous brightness changes are seen, reflecting a change in the work function. The observed brightness variations are indirectly linked to the adsorption of methanol and oxygen from the gas phase, which cause a reduction/oxidation of the VO\textsubscript{x} overlayer.

A higher amount of methanol in the gas phase results in an increased brightness due to the lower work function of adsorbed carbon containing species and of a reduced VO\textsubscript{x} layer. With a lower methanol content in the gas phase, the VO\textsubscript{x} film gets re-oxidized again, and C containing species desorb/react off, resulting in a higher work function and low PEEM intensity.
This result is in strong contrast to the systems VO\textsubscript{x}/Rh(111) and VO\textsubscript{x}/Rh(110), where a dynamic response and different redistribution patterns were observed [25, 28]. In order to systematically probe the accessible parameter range, linear heating/cooling ramps between 300 and 1020 K (0.2 K/s) are applied to 0.4 and 5 ML VO\textsubscript{x} films on Pt(111). The composition of the atmosphere is varied between a 1:10 and a 1:1 ratio of p(MeOH)/p(O\textsubscript{2}), with p(O\textsubscript{2}) being kept fixed at 1 × 10\textsuperscript{-4} mbar. In these experiments no V-oxide island formation or other reaction dynamics are seen in PEEM.

3.5 Stability of Multilayer VO\textsubscript{x} Films During Catalytic Methanol Oxidation

Since a diffusion of V into the Pt bulk only takes place under reducing conditions, the question is whether this process can be reverted by changing the oxygen coverage. This problem we address in the following with LEED and AES exposing VO\textsubscript{x} films of different coverage to methanol oxidation in the 10\textsuperscript{-4} mbar range.

Figure 6 shows Auger spectra after a 5 ML VO\textsubscript{x} film on Pt(111) has been exposed to methanol oxidation in the 10\textsuperscript{-4} mbar range with a p(MeOH)/p(O\textsubscript{2}) ratio of 1:10. AES data are also taken after a subsequent oxygen treatment at 870 K and p(O\textsubscript{2}) = 1 × 10\textsuperscript{-4} mbar. The resulting Auger ratio V\textsubscript{437}/Pt\textsubscript{237} is reproduced in Fig. 6b. Initially, after reactive evaporation of 5 ML VO\textsubscript{x}, LEED displays a diffuse (√3 × √3)R30° pattern shown in Fig. 6c. The corresponding Auger spectrum is dominated by V and O Auger transitions. After the sample has been exposed to catalytic methanol oxidation for roughly 40 min, the (√3 × √3)R30° structure has vanished and LEED displays a sharp (2 × 2) as demonstrated by Fig. 6d. In AES the V and O intensities are significantly decreased while the Pt related transitions grew in intensity. Evidently, even with oxygen being in large excess and with an oxygen pressure of 1 × 10\textsuperscript{-3} mbar, the oxygen coverage does not suffice to stabilize a 5 ML thick VO\textsubscript{x} film during methanol oxidation.

In order to check for the reversibility of V bulk diffusion the VO\textsubscript{x}/Pt(111) surface is, after the reaction treatment, exposed to 1 × 10\textsuperscript{-4} mbar oxygen at 870 K for 40 min. This results in a (1 × 1) with strong background intensity and streaky features around the integral order diffraction spots. In AES only a small part of the initial V and O intensity is restored, as shown in Fig. 6b. Apparently only a small amount of V atoms in subsurface sites can migrate back to the surface despite an elevated temperature and high oxygen partial pressure.

We obtain more insight as we systematically study the reversibility of V bulk diffusion for different V coverages. We subject four VO\textsubscript{x} films with V coverages between 2 and 10 ML to a similar procedure of exposure to reaction conditions followed by oxygen treatment as described above. The reactions were carried out with varying methanol partial pressures, the oxidation step was always carried out at 870 K in 1 × 10\textsuperscript{-4} mbar oxygen. Surprisingly, the 40 min oxygen treatment at 870 K restores more or less the same V\textsubscript{437}/Pt\textsubscript{237}
intensity ratio for all four films, irrespective of the initially deposited VO₃ coverage. We compare these data with V₄37/Pt₂37 Auger intensity ratios of the calibration curve of Fig. 1. For the four thick films exposed to reducing reaction conditions the values only vary within a small range; the average V₄37/Pt₂37 intensity ratio is 1.6 ± 0.3. This value lies between the V₄37/Pt₂37 intensity ratios of 0.8 and 1.2 ML films in Fig. 1, which are 1.2 ± 0.1 and 2.2 ± 0.1, respectively. A simple assumption to explain these findings is that only a certain amount of V dissolved in the Pt bulk can segregate back to the surface under oxidizing conditions until a closed oxide monolayer has been formed.

4 Discussion

4.1 VO₃ Growth on Pt(111)

VO₃ on Rh(111) [20, 23, 24] and on Pd(111) [17, 59–61] are systems where the structures developing in the submonolayer and monolayer range have been particularly well studied and understood. They represent two-dimensional VO₃ network structures formed from VO₃ polyhedra (n = 3–6) that are connected by sharing oxygen corner atoms [20]. In the multilayer range most of the structures that form on metal single crystal surfaces can be described as epitaxial growth of known bulk oxides of vanadium; VO(111) on Cu(100) and Ni(110) [62], V₂O₃(0001) on W(110) and Au(111) [63] and V₂O₅(001) on Au(111) [64, 65]. In the latter case an oxygen partial pressure of 50 mbar was applied to stabilize V in a +5 oxidation state. Typically, the growth of ultrathin transition metal oxide films on noble metal surfaces is kinetically controlled, and the preparation procedure has a decisive influence on the oxide phases that are formed [22].

The growth of VO₃ on Pt(111) has only been investigated by few groups [19, 32–34]. With vibrational spectroscopy and LEED as main methods, Tang et al. studied the deposition of VO₃ onto Pt(111) up to a thickness of three monolayers. Their results differ significantly from ours, but the differences can be attributed to the different preparation procedures used in both cases. Tang et al. deposited V at room temperature in vacuum and post-oxidized the surface at 623 K in 1 × 10⁻⁷ mbar O₂, whereas we deposited V by reactive evaporation at 670 K in an oxygen atmosphere of 2 × 10⁻⁷ mbar. In their calibration curve of VO₃ deposition they observed two break points in the slope and concluded layer-by-layer growth up to three ML. A (2 × 2) developed only beyond 0.5 ML, for coverages > 2 ML, a (3√3 × 6) was present. In particular the (√3 × √3)R30° that was the dominant structure in our experiments beyond 2 ML, here, was not seen at all.

A (2 × 2) structure was seen after deposition of submonolayer VO₃ films on Pd(111); it was described there as a VO wetting layer also denoted as s-V₂O₅ [17]. Based on their vibrational data Tang et al. followed the interpretation of the (2 × 2) as a surface V₂O₃ layer. Different from the results reported by Tang et al. we observed a (2 × 2) only in coexistence with a (√3 × √3)R30° structure after deposition of more than 1 ML (step-wise deposition) during VO₃ growth. Furthermore we observed the (2 × 2) after methanol oxidation has been carried out on VO₃ films of an initial thickness varying between 0.6 and several ML. From AES we estimate the VO₃ coverage of the (2 × 2) obtained after reaction conditions were applied to thick VO₃ films to be roughly 1 ML.

A (√3 × √3)R30° structure reported for thick VO₃ layers (≥1 MLE VO₃) on Rh(111) and Pd(111) was assigned to the (0001) oriented surface of corundum V₂O₃ [17, 23]. Accordingly, we attribute the (√3 × √3)R30° structure observed here to three-dimensional crystallites of V₂O₃ with (0001) orientation. Interestingly, no such corundum V₂O₃ phase has been reported by Tang et al. for VO₃/Pt(111). Although some weak (√3 × √3)R30° diffraction spots were visible after deposition of 2.5 ML VO₃ on Pt(111) (Fig. 3f in [32]) they were not discussed further. For V coverages between 1 and 2 ML, a (3√3 × 6) pattern was observed by Tang et al. who interpreted this pattern as a bilayer structure.

To conclude, compared with the results of Tang et al., we find differences in the growth mode—Stranski–Kranstorff vs. layer-by-layer—as well in the structures at higher V coverage. Since different preparation procedures have been used the results are not in contradiction to each other. One could speculate whether the structures seen here are closer to thermodynamic equilibrium since reactive evaporation at high temperature was applied instead of post-oxidation. This, however, needs to be verified by future analyses.

4.2 Catalytic Activity of VO₃/Pt(111)

In catalytic methanol oxidation the system VO₃/Rh(111) exhibited a high catalytic activity and displayed remarkable dynamic behavior [25, 31], whereas VO₃/Pt(111) showed negligible catalytic activity and practically no dynamics at all. In this comparison we refer to submonolayer coverages of VO₃ and reaction conditions in the 10⁻⁴ mbar range. If we take the picture of VO₃ islands acting as catalytic microreactors on Rh(111), then we can explain the lower activity of VO₃/Pt(111) in two ways: (i) the VO₃ islands are less active on Pt(111) and/or (ii) the surrounding metal surface, which in the case of Rh(111) provides the oxygen for the reaction, is less active in O₂ adsorption.

Starting with point (ii), Rh(111) has a high oxygen sticking coefficient as evidenced by a value of 0.3 at 300 K [49]. On Pt(111) where oxygen sticking reportedly is controlled by the step density, values around 0.06 are found for 300 K in the literature [48]. Evidently oxygen adsorption is much slower on Pt(111) as compared to Rh(111). Accordingly,
a considerable stationary O$_x$ coverage around 0.2 ML on the Rh surface has been measured with XPS, even at high temperature during methanol oxidation [25]. On Pt(111) the stationary oxygen coverage is expected to be very low under reaction conditions, even with a ten times excess of oxygen in the gas phase. Therefore under conditions where the supply of oxygen is rate-limiting, the rate of catalytic methanol oxidation will be small on VO$_x$/Pt(111).

Besides the low oxygen sticking coefficient on Pt(111), also the adsorption energies of oxygen on Pt(111) and Rh(111) differ considerably. The adsorption energy of atomic oxygen on Pt(111), as determined from thermal desorption spectroscopy (TDS), gives a value of 2.21 eV per O$_2$ molecule [48, 50]; with microcalorimetry a substantially larger energy of 3.16 eV was obtained [51]. DFT calculations for O/Pt(111) yield 2.68 eV for the adsorption energy at low O coverages ($\theta_O \leq 0.25$ ML) [52], surface vibrational gas-phase enthalpy corrections reduce this value to 2.46 eV, which is close to the experimental TDS adsorption energy. In contrary, DFT calculations for O/Rh(111) yield with 4.48 eV [66] and 4.88 eV [67] adsorption energies that are considerably above those for O/Pt(111).

Apparently, for an oxygen atom bonded to vanadium, it should be easier to change to a Rh site than to a Pt site because the energetic difference is smaller. Therefore, besides the kinetic factor given by different oxygen sticking coefficients, also a thermodynamic factor exists favoring oxygen exchange between VO$_x$ and a Rh(111) surface as compared to VO$_x$ and a Pt(111) surface. Oxidation reactions over VO$_x$ catalysts proceed via a Mars-van Krevelen mechanism [68, 69], but the catalytic studies are typically conducted at high pressure (mbar to bar). At low pressure, reoxidation of VO$_x$ by direct adsorption from the gas phase is presumably too slow to be efficient, and the effect of the supporting noble metal surface becomes important [25].

For V-oxide to be highly active in catalytic methanol oxidation, vanadyl groups should be present on the oxide surface [5, 6, 70–72]. Although Tang et al. demonstrated the existence of vanadyl containing V-oxide clusters on Pt(111) for coverages below 0.5 ML, these clusters condense into the (2 × 2) s-V$_2$O$_x$ structure already upon CO adsorption at room temperature [32]. The formation of vanadyl containing vanadium oxide on Pt(111) requires oxygen partial pressure in the mbar range [32]. This is confirmed by an infrared reflection absorption spectroscopy (IRAS) study of propane oxidation over VO$_x$/Pt(111) where the high activity in the mbar range was linked to the presence of vanadyl groups [34]. Given that no vanadyl groups are present on VO$_x$/Pt(111) in the 10$^{-4}$ mbar range, the VO$_x$ should exhibit only a small activity in catalytic methanol oxidation.

The island movement on VO$_x$/Rh(111) proceeds via a polymerization/depolymerization (PD) mechanism in which V$_n$O$_m$ clusters are detached from the VO$_x$ island in regions of high oxygen coverage and are reattached to the island in areas of low oxygen coverage [25]. With a low oxygen coverage and with no or only very shallow oxygen gradients that can evolve due to a negligible catalytic activity on VO$_x$/Pt(111), the PD mechanism cannot be effective on VO$_x$/Pt(111). A high oxygen sticking coefficient and adsorption energy of the metal surface alone, is not the only criterion to observe coalescence of VO$_x$ islands. On Rh(110) the oxygen sticking coefficient is even larger than on Rh(111), but no island coalescence on VO$_x$/Rh(110) has been observed under reaction conditions [28, 29, 73]. However, the rate of formaldehyde production on VO$_x$/Rh(110) in catalytic methanol oxidation has been very low likewise, and one can speculate whether it is the absence of vanadyl groups also in this case that is responsible for the low activity of VO$_x$ on Rh(110). In contrast to VO$_x$/Pt(111), however, a very rich dynamics was observed in catalytic methanol oxidation on VO$_x$/Rh(110): chemical wave patterns [30] and also VO$_x$ island formation [28] were seen but no VO$_x$ island coalescence.

### 4.3 Segregation Behavior of VO$_x$/Pt(111)

Under reaction conditions in the 10$^{-4}$ mbar range, part of the vanadium on the surface starts to diffuse into the Pt bulk at temperatures above 770–870 K. Apparently, as a consequence of the low oxygen sticking coefficient and the low adsorption energy of oxygen on Pt(111), the oxygen coverage is not high enough to stabilize V as a surface oxide under reaction conditions. If the surface is then exposed to 1 × 10$^{-4}$ mbar oxygen at 870 K for prolonged time, part of the V dissolved in the Pt bulk segregates back to the surface, forming (2 × 2) structure. However, the amount of V which can segregate back to the Pt surface is limited to approximately one monolayer of VO$_x$. A similar behavior has also been observed in the system VO$_x$/Rh(110), in which only a certain amount of VO$_x$ could be stabilized by oxygen, while excess V diffused into the Rh bulk [74]. For comparison, on Rh(111) already oxygen pressures in the 10$^{-7}$ mbar range suffice to stabilize VO$_x$ on the surface up to 1000 K [24].

The high stability of VO$_x$/Rh(111) against reduction, and the diffusion of V into Pt subsurface sites even in the presence of oxygen at high temperature might be explained by thermodynamics. We have found that oxidizing conditions can stabilize ≈1 ML VO$_x$ on Pt(111). This indicates that the Pt substrate is not able to supply enough oxygen to form strong Pt-O-V bonds, probably due a lower O-Pt bond strength as compared to Rh-O. This conclusion is supported by the observation that Rh-O-V bonds are a common structural motif in the system VO$_x$/Rh(111).

After adsorbed oxygen attracted V from the Pt bulk or from the subsurface region, a (2 × 2) structure is visible in LEED. The same pattern is seen if methanol oxidation is carried out under reducing conditions. We have assigned
this (2 × 2) to a V$_2$O$_3$ surface oxide known from the system VO$_x$/Pd(111) [75]. In the s-V$_2$O$_3$ structure V is directly bound to the Pd substrate. The oxygen binding energy on Pd(111) is ~1.5 eV, as calculated with DFT, and therefore much lower than for O/Rh(111) [76]. The low O binding energies on Pt and Pd might be the reason for the formation of M–V bonds (M = substrate metal), rather than M–O–V bonds as it is the case for VO$_x$/Rh(111).

With a metal oxide being reduced and being alloyed with the support metal, this process can be summarized under SMSI. However, one has to be aware that the system VO$_x$/Pt(111) represents an inverse model catalyst and not the actual supported catalyst used in industrial catalysis. Since the concept of inverse supported catalysts has also been applied to design novel type of catalysts, knowledge of the processes encountered here with VO$_x$/Pt(111) might be useful for constructing such catalysts [38].

5 Conclusions
We studied the growth and the catalytic activity of ultrathin layers of V-oxide on Pt(111) with coverages in the sub-monolayer and multilayer range (<12 ML). We interpret the LEED/AES data during reactive V deposition as Stranski–Krastanow growth with the (√3 × √3)R30° structure as limiting case for thick films. The (√3 × √3)R30° structure presumably represents the (0001) plane of epitaxially grown 3D-crystallites of “corundum” V$_2$O$_3$. Significant differences to reports in the literature indicate that the growth mode as well as the resulting structures depend strongly on the preparation procedure. The activity of VO$_x$/Pt(111) is very low in catalytic methanol oxidation, what can be attributed to (i) a low O$_2$ sticking coefficient and a low oxygen adsorption energy of Pt(111) and (ii) to the absence of vanadyl groups in the VO$_x$ layer in the 10$^{-4}$ mbar range. No redistribution dynamics in the VO$_x$ layer was detected during methanol oxidation in the 10$^{-4}$ mbar range. Multilayer V-oxide coverages cannot be stabilized on the Pt(111) surface under reaction conditions in the 10$^{-4}$ mbar range as part of the V, after being reduced, diffuses into the Pt bulk. Exposure to O$_2$, reverses the bulk diffusion, but only up to 1 ML of VO$_x$ can be stabilized on the surface at 10$^{-4}$ mbar.

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Compliance with Ethical Standards
Conflict of interest The authors declare no competing financial interest.

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