Molecular Design of Supported MoO_x Catalysts with Surface TaO_x Promotion for Olefin Metathesis

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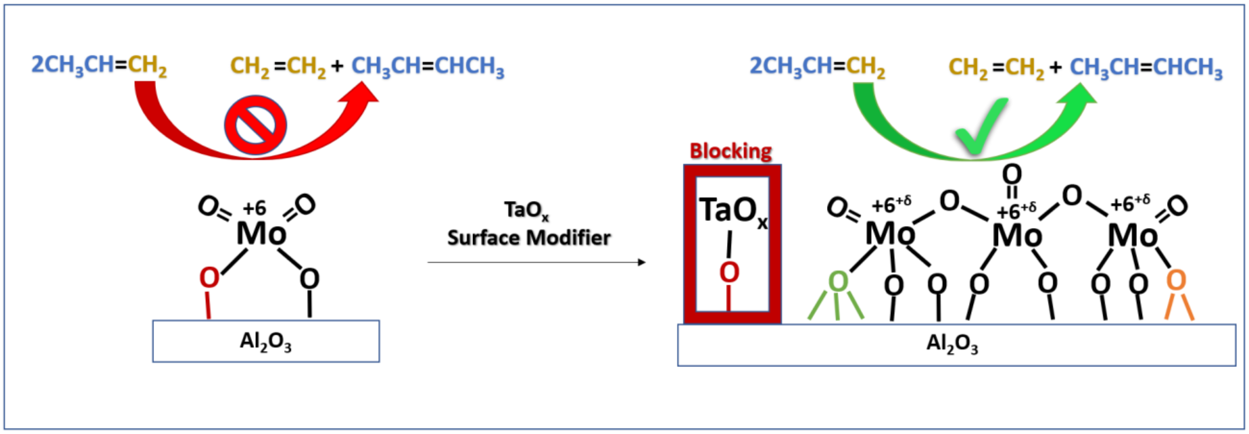
Abstract

A series of supported 3% MoO_x catalysts were synthesized by incipient-wetness impregnation of 5%-15% TaO_x surface modified γ-Al_2O_3 support. The catalysts were characterized by *in situ* spectroscopies (DRIFTS, Raman, UV-vis, XAS) and multiple chemical probes (C_2H_4/C_4H_8 titration, C_3H_6-TPSR, steady state propylene metathesis, NH_3-IR adsorption). The supported tantalum oxide phase was present as surface TaO_x sites on the γ-Al_2O_3 support that capped that Al_2O_3 surface hydroxyls. The change in available surface hydroxyls caused the subsequent anchoring of MoO_x species to occur at different surface hydroxyls. This shifted the anchoring of MoO_x species from basic (Al-OH) to neutral (Al_2-OH) to more acidic (Al_3-OH) surface hydroxyls as well as perturbation of the remaining alumina surface hydroxyls by the surface TaO_x sites. The TaO_x surface modified γ-Al_2O_3 support increased the number of activated surface MoO_x sites (Ns) by ~6x and the TOF by ~10x resulting in an increased activity of ~60x. It was found that the specific anchoring surface hydroxyls rather than the extent of oligomerization of the surface MoO_x sites control the number of activated MoO_x sites and TOF for propylene metathesis. No relationship between the nature of the surface Lewis/Brønsted acid sites and Ns and TOF were found to be present.

Keywords: metathesis, propylene, molybdate, Raman, DRIFTS, UV-vis, XAS



I. Introduction

Propylene is a critical chemical intermediate that is produced from refinery, steam cracking and on-purpose methods. The olefin metathesis reaction, as an on-purpose method for propylene production, is a reversible reaction that helps meet the global shortage of propylene. The cleavage and reformation of C=C double bonds in ethylene and 2-butene permits the produce of two propylene molecules.[1-4] Industrial heterogeneous supported MoO_x/Al_2O_3 catalysts have been applied in the Shell Higher Olefin Process (SHOP) to produce linear higher olefins since 1968.[5] Although heterogeneous supported MoO_x catalysts are easily prepared, there are multiple surface MoO_x structures due to the non-uniform nature of the surfaces of oxide supports, which requires the use of advanced molecular level characterization techniques to determine the catalytic active sites. For example, three distinct surface MoO_x structures are present on the Al_2O_3 support (isolated dioxo MoO_4 on basic Al-OH, oligomeric $MoO_{5/6}$ on neutral Al_2-OH and acidic Al_3-OH, and crystalline MoO_3 nanoparticles).[6-7] The catalytic activity of supported MoO_x catalysts is significantly influenced by the selection of the oxide support.[8-12] The SiO_2-Al_2O_3 mixed oxide support is a highly effective support for promoting olefin metathesis in comparison to the one component Al_2O_3 or SiO_2 support. Anchoring active sites at acidic surface hydroxyls of the mixed oxide support results in a greater number of activated sites.[13] This observation motivates the current investigation to examine the influence of other mixed oxide supports, such as supported $MoO_x/TaO_x/Al_2O_3$ catalysts, for olefin metathesis. The acidity of surface Brønsted sites is often proposed to be related to improved olefin metathesis activity on mixed oxide support.[9,14] For example, Hahn *et al*. examined surface MoO_x sites on various oxide supports (SiO_2, Al_2O_3, $SiO_2-Al_2O_3$) with pyridine-IR adsorption and found that the ethylene/2-butene cross-metathesis activity increased with (*i*) increasing amounts of Brønsted acid sites (*ii*) increasing oligomerization degree of the surface MoO_x sites and (*iii*) decreasing amounts of Lewis acid sites. It was claimed that protonation of propene to surface Mo (+4) - isopropoxide was driven by Brønsted acidic Mo-OH during activation. [9] Li *et al*. investigated MoO_x sites on Hβ and γ-Al_2O_3 mixed oxide support with ^1H NMR and proposed that the moderate Brønsted acidity for moderate MoO_x loadings may contribute to the ethylene/2-butene cross-metathesis activity by involving into the initial MoO_x sites activation.[14] Supporting data are generally lacking and the nature of the MoO_x sites and oxide support sites have not been well investigated. The absence of *in situ* investigation on well-defined model supported MoO_x catalysts has inhibited the fundamental understanding of this important catalytic reaction. To design a highly active model promoted MoO_x/Al_2O_3 catalyst, the basic alumina hydroxyls need to be selectively capped with an acidic promoter that will allow MoO_x to selectively anchor at the more acidic surface hydroxyls of the alumina support.[15]

In the present study, a TaO_x promoter was used to surface modify the Al_2O_3 support for propylene self-metathesis to ethylene and 2-butene by supported MoO_x/Al_2O_3 catalysts. The surface TaO_x promoter was selected since TaO_x is not active for olefin metathesis and gives rise to weak Raman bands that won't overshadow the Raman bands of the surface MoO_x sites.[15] The following aspects will be examined:(*i*) the anchoring sites of MoO_x on unpromoted and Ta-promoted Al_2O_3 support, (*ii*) the nature of surface MoO_x sites under dehydrated and propylene metathesis reaction conditions, and (*iii*) the influence of surface Lewis and Brønsted acid sites upon the activity of the propylene metathesis reaction. The objective of the present study is to establish the structure-activity relationship for olefin metathesis by supported Ta-promoted MoO_x/Al_2O_3 catalysts. The origin of the improved propylene metathesis activity on Ta-promoted MoO_x/Al_2O_3

catalysts is the consequence of modifying the MoO_x anchoring locations on the surface hydroxyls of Al_2O_3.

II. Experimental Details

a. Catalyst Synthesis.

The Al_2O_3 support (Sasol, Puralox, 200 m^2/g) was initially calcined at 500 ^oC for 16h in flowing air to remove any combustible impurities. The Al_2O_3 support was surface modified by incipient-wetness impregnation (IWI) of an ethanol solution of tantalum ethoxide (Ta-$(OC_2H_5)_5$, Sigma Aldrich, 99.98%) inside a glovebox (Vacuum Atmosphere, Omni-Lab VAC 101965). After addition of TaO_x to alumina, the TaO_x/Al_2O_3 was dried overnight in a glovebox and calcined at 500 ^oC for 4h. The supported 3% MoO_x catalysts were synthesized by IWI of aqueous ammonium heptamolybdate ($(NH_4)_6Mo_7O_{24}\cdot 4H_2O$, Alfa Aesar, 99%) onto the surface TaO_x-modified Al_2O_3 support (5%,10% and 15% TaO_x). The supported 3%$MoO_x/TaO_x/Al_2O_3$ catalysts were dried overnight at ambient conditions, further dried at 120^{o}C for 2h in flowing air, and finally calcined by ramping the temperature at 1^{o}C/min to 500^{o}C and held at 500^{o}C for 4h. The surface coverage of Ta for surface modified TaO_x/Al_2O_3 support (5, 10 and 15% TaO_x) is 0.7, 1.4 and 2.0 Ta/nm^2 corresponding to 16, 31 and 44% monolayer surface coverage, respectively). The surface coverage of Mo for all the supported MoO_x catalysts is 0.8 Mo/nm^2.

b. *In Situ* Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS).

The *in situ* DRIFTS spectra of the surface modified TaO_x/Al_2O_3 support and supported MoO_x catalysts were obtained by a Thermo Scientific Nicolet 8700 FT-IR spectrometer attached with a Harrick Praying Mantis (DRA-2). A Mercury-Cadmium-Telluride (MCT) detector was equipped to obtain the spectra with a resolution of 4 cm^{-1} with accumulations of 96 scans/min. The gas flow rates were monitored by mass flow controller (Brooks, 5850E). Approximately 20mg of loose catalysts powders was loaded into an *in situ* reaction cell (Harrick, HVC-DR2 with a CaF2 window) sealed with an O-ring (Harrick, Viton). The *in situ* cell window was cooled with flowing water during the experiments. The procedure for collecting the *in situ* DRIFTS spectra was as follows: the catalyst was dehydrated at 500°C with flowing 10% O_2/Ar (Air Gas, UHP, 30 mL/min) for 1 h. Then the temperature was cooled to 120°C then flushed with Ar (Air Gas, UHP, 30 mL/min) for 30 min. The DRIFTS spectra of dehydrated catalysts were collected at 120°C with 10% O_2/Ar. The dehydration procedure for NH_3-IR spectra was the same as indicated above. The NH_3/He (Airgas, 2000 ppm, 30 mL/min) was flowing at 120°C for 30min, then flushed with He (Air Gas, UHP, 30 mL/min) for 30min. The adsorbed NH_3 was finally desorbed by ramping temperature at 10°C/min to 500°C. The *in situ* DRFITS spectra were collected during the NH_3 adsorption and the temperature ramping. All the DRIFTS spectra were normalized by the dehydrated spectra of the oxide supports.

c. *In Situ* Raman Spectroscopy.

The *in situ* Raman spectra were obtained by a Horiba Labram HR Evolution spectrometer equipped with 4 laser sources (633, 532, 442 and 325nm). The 442 nm laser was used for collecting *in situ* Raman spectra to minimize the sample fluorescence. The laser was focused through a confocal microscope with a X10 objective (Olympus MPLN10x). The Raman spectra were calibrated by a silicon standard possessing a reference peak at 520.7 cm^{-1}. Catalysts were loaded into an *in situ* reaction cell (Harrick Scientific HVC-MRA-5) cup padded with quartz wool, which was temperature controlled by a Harrick ATC Temperature Controller unit. The spectra were collected with a 100 μm hole and 3 scans (20s/scan) by a CCD camera detector (Horiba Synapse BIDD scientific), resulting in a spectral resolution of 1 cm^{-1}. Pure TiO_2 (P-25, 1%) was physically mixed with catalysts to be used as internal standard for normalization due to the absence of Raman peaks from the pure Al_2O_3 support. The gas flow rates were monitored with same mass flow controllers as indicated above. The procedure for collecting *in situ* Raman spectra was as follows: the catalyst was dehydrated at 500°C in flowing 10% O_2/Ar (Air Gas, UHP, 30 mL/min) for 1 h. The temperature was then cooled to 30°C and flushed with Ar (Air Gas, UHP, 30 mL/min) for 30 min. Subsequently, the catalysts were exposed to 5% C_3H_6/Ar (Praxair, Purity 99%, 30 mL/min) at 30°C for 1 h and finally flushed with Ar (Air Gas, UHP, 30 mL/min) for 30 min and heating to 200°C. The 5% C_3H_6/Ar was flowing again for 1h and flushed with Ar at 200°C. The *in situ* Raman spectra were collected after dehydration and during propylene metathesis at 30°C and 200°C.

d. *In Situ* UV−vis Diffuse Reflectance Spectroscopy (DRS).

The *in situ* UV-vis spectra of the supported MoO_x catalysts were obtained with an UV-vis-NIR spectrophotometer (Agilent Cary 5000). Approximately 20 mg of catalyst powder was loaded into an *in situ* reaction cell described above. The collection of each UV-vis spectrum takes ~0.6s in the 200-800 nm range. A MgO white standard was used for the reference of background absorbance. The gas flow rates were monitored with same mass flow controllers as indicated above. The edge energy (Eg) values calculated from the UV-vis spectra determined by the intercept of the straight line for the low-energy rise of a plot of $[F(R)hv]^2$ versus the incident photon energy (hv).[16] The procedure for collecting *in situ* UV-vis spectra was the same as indicated in the above *in situ* Raman experiments.

e. *In Situ* XAS (X-ray Absorption Spectroscopy).

The *in situ* Mo K-edge X-ray Absorption Spectroscopy data were obtained at beamline 7-BM in the National Synchrotron Light Source-II (NSLS-II) of Brookhaven National Laboratory (BNL). The XAS spectra were collected by ionization chamber detectors that measured transmission beam intensities through the sample and the reference (Mo) foil used for energy calibration and alignment. Fluorescence data from the samples were measured using a PIPS detector. The catalyst pellets (~0.2g) were loaded into an *in situ* reaction cell (Nashner-Adler). A MoO_3 compound was used as reference for comparison. The procedure for collecting the *in situ* XAS spectra was similar to that for the Raman experiments described above, but 2.5% C_3H_6/He was only flowing at 200°C. The Athena and Artemis software programs were utilized for data processing and analysis.[17]The details of EXAFS fitting method are presented in previous work.[13] S_0^2, the passive electron reduction factor, is fixed as 0.82 as obtained from the fitting of EXAFS data in Mo foil.

f. Propylene-Temperature Programmed Surface Reaction (TPSR)

The C_3H_6-TPSR spectra were obtained by an Altamira Instruments system (AMI-200). The catalysts (~0.2 g) were loaded into a U-tube quartz reactor. The dehydration procedure was similar as indicated above in Raman experiments. After flushing with Ar (Air Gas, UHP, 30 mL/min) for 30 minutes at 30°C, the gas flow was switched to 5% C_3H_6/Ar (Praxair, Purity 99%, 30 mL/min) and held at 30°C for several minutes to stabilize the MS signal. The temperature was then ramped at 10°C/min up to 600 °C. An online Dycor ProLine Process Mass Spectrometer (MS) was employed to analyze the outgoing gases. The monitoring mass/charge channels were m/z=18 (H_2O), m/z=27 (C_2H_4), m/z=42 (C_3H_6), m/z=44 (CO_2) and m/z=56 (C_4H_8). The MS signals were calibrated and corrected for cracking contributions from different components.

g. Ethylene/2-Butene Titration

The C_2H_4/C_4H_8-Titration spectra were obtained by the same Altamira Instruments system (AMI-200). The initial dehydration procedure was the same as above Raman experiments. After cooling down to 30^{o}C and flushing with Ar for 30 min, 2-butene was chemisorbed on the catalyst by flowing 1% C_4H_8/Ar (Praxair, Purity 99%, 30 mL/min) at 30°C for 30 min. Afterwards, the gas flow was immediately switched to 1% C_2H_4/Ar (Praxair, Purity 99%, 30 mL/min) for 30 min to titrate the adsorbed surface intermediates from 2-butene chemisorption. The same mass/charge channels were recorded as for the above C_3H_6-TPSR experiments. The number of activated surface MoO_x sites was calculated by the amount of C_3H_6 produced during C_2H_4-C_4H_8 titration with the assumption that only one surface Mo=$CHCH_3$ intermediate was present on the surface. The MS signals were calibrated and corrected for cracking contributions from different components.

h. Steady-State Propylene Metathesis

The steady-state propylene self-metathesis catalytic activity were obtained in a fix-bed reactor under differential conditions (propylene conversion < 15%). Both the inlet and outlet of the gas tubes were heated to 200^{o}C to avoid the condensation of the propylene reactant and products (C_2H_4, C_3H_6, C_4H_8, CO_2 and H_2O) on the exit lines. Approximately 0.2 g of catalyst was loaded in the vertical tube reactor. The temperature was controlled by a clam shell furnace. The dehydration procedure was similar as indicated above in Raman experiments, then the reactor was cooled to 200^{o}C with 10% O_2/Ar and flushed with Ar (Air Gas, UHP, 30 mL/min). 1% C_3H_6/Ar (Praxair, Purity 99%, 50 mL/min) was flowing as the reactant mixture. After 1h reaction, the steady state propylene metathesis conversion was obtained. An online gas chromatograph (Agilent GC 6890) equipped with a GS-Alumina (Agilent 1153552) column connected to a flame ionization detector (Agilent Model G1531) was employed to analyze the outgoing gases from the reactor. the catalytic activities (mmol/g/h) were calculated by normalizing the conversion of propylene by the flow rate and catalyst weight. The turnover frequency (TOF) values were calculated by normalizing the steady-state activity by the number of activated MoO_x sites derived from C_2H_4/C_4H_8 titration. The GC was calibrated for all the reaction products.

III. Results

a. *In Situ* DRIFTS of Surface Hydroxyl Anchoring Sites

The *in situ* DRIFTS spectra were collected to identify the surface hydroxyls of the Al_2O_3 support that anchor the surface TaO_x and MoO_x sites and are presented in Figure S1 and the corresponding difference spectra are presented in Figures S2 and 1. The bare Al_2O_3 support has multiple surface hydroxyls: isolated Al-OH (HO-μ_1-Al_{IV} at 3787 cm^{-1}, HO-μ_1-Al_{VI} at 3765 cm^{-1}, HO-μ_1-Al_V at 3741 and 3730 cm^{-1}), bridged Al_2-OH (HO-μ_2-Al_V at 3694 cm^{-1}) and tri-coordinated Al_3-OH (HO-μ_3-Al_{VI} at 3674 cm^{-1}).[18-19] It is well established that the (110) facet of γ-Al_2O_3 is preferentially exposed (70-83%), while the (100) only represents a minor facet (17%).[18,20-21] The population of the γ-Al_2O_3 (111) facet is much less significant and can be neglected. [22] The HO-μ_1-Al_{IV} at 3787 cm^{-1}, HO-μ_1-Al_V at 3741/3730 cm^{-1} and HO-μ_2-Al_V at 3694 cm^{-1} are located on the Al (110) facet, while HO-μ_1-Al_{VI} at 3765 cm^{-1} and HO-μ_3-Al_{VI} at 3674 cm^{-1} are located on the Al (100) facet.[18-19] The more basic surface hydroxyls correspond to the higher wavenumber peaks, while the lower wavenumber peaks are associated with neutral and more acidic surface hydroxyls. [23] Thus, the acidity of Al_2O_3 surface hydroxyl follows the trend: most basic Al-OH (HO-μ_1-Al_{IV}), less basic Al-OH (HO-μ_1-Al_{VI} and HO-μ_1-Al_V), neutral Al_2-OH (HO-μ_2-Al_V) and more acidic Al_3-OH (HO-μ_3-Al_{VI}). The surface hydroxyl density of Al_2O_3 is ~6-9 OH/nm^2 with a ratio of Al_3-OH:Al_2-OH:Al-OH surface hydroxyls of ~1.3:2:1 as determined by ^1H NMR.[24-25]

The surface TaO_x promoter anchors at all five types of the alumina surface hydroxyls as indicated in Figure S2. It has been shown in prior studies that the dispersion of one metal oxide onto another metal oxide can generate new surface M_1-$(OH)^+$-M_2 Brønsted acid sites[26-27] and, thus, the newly formed peak ~3520 cm^{-1} is assigned to the Al-$(OH)^+$-Ta Brønsted acid sites.[28] The positive peak ~3785-3775 cm^{-1} is assigned to shifting of the basic Al-OH hydroxyl induced by the nearby surface TaO_x sites since the Ta-OH vibration is reported at lower wavenumbers (~3680-3743 cm^{-1}).[29] Even though the preferential anchoring sites of TaO_x on Al_2O_3 is not clear from the spectra, the DRIFTS results reveal that the surface TaO_x promoter modifies the surface chemistry of the Al_2O_3 support, thereby, modifying the available anchoring sites for anchoring of the MoO_x species.

For the unmodified surface MoO_x/Al_2O_3 catalyst, the surface MoO_x sites preferentially anchor at HO-μ_1-Al_{IV} (3787 cm^{-1}) and HO-μ_1-Al_{VI} (3765 cm^{-1}) surface hydroxyls. A minor amount of HO-μ_3-Al_{VI} (3674 cm^{-1}) also appear to be involved in anchoring MoO_x species. The addition of MoO_x to the surface modified TaO_x/Al_2O_3 support shows that the MoO_x species mainly anchor at the HO-μ_1-Al_{VI} (3765 cm^{-1}), HO-μ_1-Al_V (3741/3730 cm^{-1}), HO-μ_2-Al_V (3694 cm^{-1}), HO-μ_3-Al_{VI} (3674 cm^{-1}) and the newly-formed Al-$(OH)^+$-Ta (3520 cm^{-1}) Brønsted acid sites. A minor amount of HO-μ_1-Al_{IV} (3787 cm^{-1}) is also consumed by the anchoring of MoO_x. With the increasing of TaO_x loading (5-15%), MoO_x sites anchor at HO-μ_1-Al_{VI} (3765 cm^{-1}), HO-μ_1-Al_V (3741/3730 cm^{-1}) and HO-μ_2-Al_V (3694 cm^{-1}). The anchoring of MoO_x at the Ta-perturbed Al-OH (3785-3775 cm^{-1}) is not significant since the peak difference is minimal after anchoring of MoO_x. In summary, compared to the unmodified supported MoO_x/Al_2O_3 catalyst, the surface MoO_x sites on the supported $MoO_x/TaO_x/Al_2O_3$ catalysts preferentially anchor at the HO-μ_1-Al_{VI} (3765 cm^{-1}), HO-μ_1-Al_V (3741/3730 cm^{-1}), HO-μ_2-Al_V (3694 cm^{-1}) and HO-μ_3-Al_{VI} (3674 cm^{-1}) surface hydroxyls.

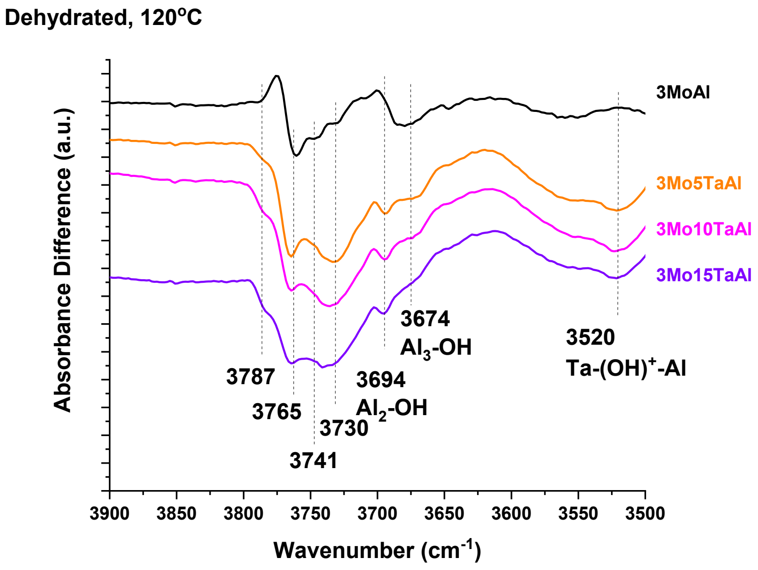


Figure 1. *In situ* DRIFTS difference spectra of the surface hydroxyl region of dehydrated supported $MoO_x/TaO_x/Al_2O_3$ catalysts (120°C). The spectrum of the dehydrated Al_2O_3 support was subtracted from the spectrum of the 3MoAl catalyst. The spectra of dehydrated surface modified TaO_x/Al_2O_3 supports were subtracted from the spectra of the corresponding 3MoTaAl catalyst.

b. *In Situ* Raman Spectroscopy

1. Dehydrated Catalysts.

The *in situ* Raman spectra of the surface modified TaO_x/Al_2O_3 support and supported MoO_x catalysts under dehydrated conditions are presented in Figures S3-S4 and 2, respectively. The γ-Al_2O_3 support doesn't give rise to any Raman bands.[16] For the surface modified TaO_x/Al_2O_3 support, two main Raman bands are present at 860 and 945 cm^{-1} corresponding to the v_s(Ta-O-Al) and v_s(Ta=O) stretches of the surface TaO_x sites, respectively. The presence of oligomeric surface TaO_x sites is indicated by Raman bands at 617 cm^{-1} and 715 cm^{-1} corresponding to v_s(Ta-O-Ta) and v_{as}(Ta-O-Ta), respectively. The Raman bands at 270 and 340 cm^{-1} are characteristic of δ(Ta-O-Ta) and δ(O-Ta-O) bending modes.[30-31] For the supported $MoO_x/TaO_x/Al_2O_3$ catalysts, the Raman bands from surface TaO_x sites are too weak to be detected and the Raman spectra are dominated by the molybdenum oxide component. The absence of strong and sharp Raman bands at 820 and 960 cm^{-1} demonstrate that crystalline MoO_3 nanoparticles are not present in these catalysts. The strong Raman band at 996-1001 cm^{-1} corresponds to the v_s(Mo=O) stretch of the surface MoO_x sites. The unpromoted 3MoAl catalysts exhibits the v_s(Mo=O) at ~996 cm^{-1} associated with isolated surface MoO_x sites anchored at the basic Al-OH surface hydroxyls.[6,16] The blue shift of v_s(Mo=O) from 996-1001 cm^{-1} with TaO_x surface modification reflects increasing oligomerization of surface MoO_x sites with increasing surface TaO_x coverage. The blue shift is also observed in the *in situ* DRIFTS

Mo=O overtone region (Figure S5). All the supported MoO_x catalysts also exhibit a band at 850 cm^{-1} from the bridging v_s(Mo-O-Al) vibration.

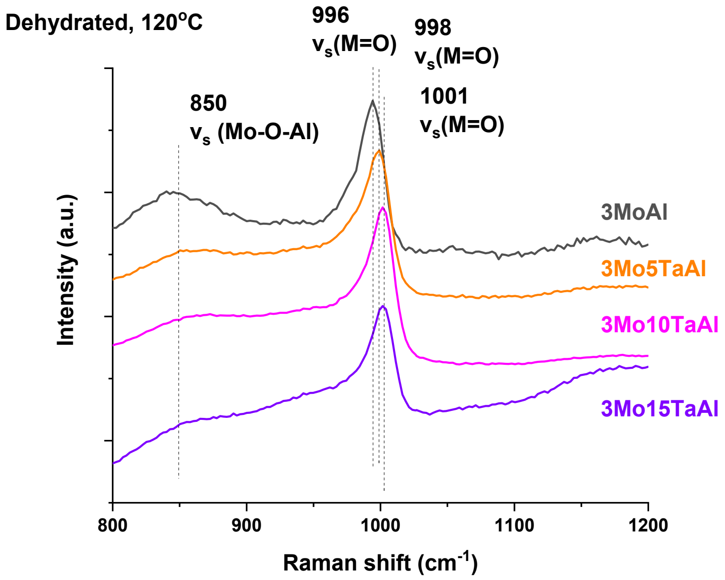


Figure 2. *In situ* Raman spectra of dehydrated supported MoO_x catalysts (120°C, 800-1200 cm^{-1}).

2. Propylene Metathesis Reaction Conditions

The *in situ* Raman spectra of the support MoO_x catalysts at 60min of propylene metathesis at 30 and 200°C are presented in Figure 3. The spectra indicate that for the supported 3MoAl catalyst, the intensity of the v_s(Mo=O) band is minimally perturbed at both 30 and 200°C. In contrast, the v_s(M=O) band of the supported 3Mo15TaAl catalyst is only minimally perturbed at 30°C, but there is a moderate decrease in intensity at 200°C. This observation reflects the ability of propylene to activate the surface MoO_x sites present on the TaO_x surface modified alumina support.

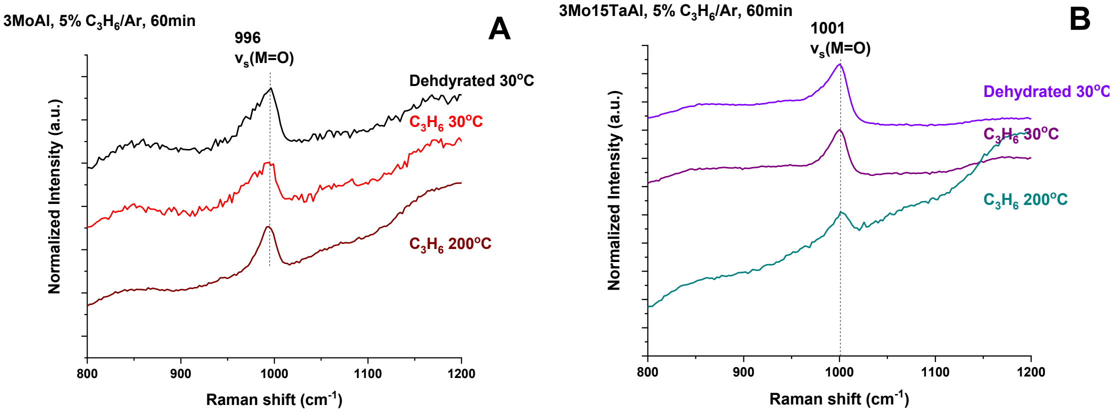


Figure 3. *In situ* Raman spectra of supported MoO_x catalysts under dehydrated conditions and at 60 minutes of propylene metathesis: (A) 3MoAl, (B) 3Mo15TaAl.

c. *UV-vis* DRS Spectroscopy

1. Dehydrated Conditions

The *in situ* UV-vis spectra and edge energy (Eg) values of dehydrated supported MoO_x/Al_2O_3 catalysts at 120°C are presented in Figure 4 and Table 1. The surface TaO_x sites on Al_2O_3 exhibit an UV-vis edge energy values of ~5.0-4.6 eV that reflect the extensive oligomerization of the surface TaO_x sites with increasing surface TaO_x coverage. To remove the contribution of the surface TaO_x sites at ~230-245 nm from the UV-vis spectra (Figure S6), the UV-vis spectra of the corresponding Mo-free TaO_x/Al_2O_3 supports were subtracted from the corresponding spectra. The resulting UV-vis edge energy reflects the degree of oligomerization of the surface MoO_x sites, which are minimally affected by the presence of the surface TaO_x sites. The $MgMoO_4$ reference compound consists of isolated MoO_4 sites and exhibits a high UV-vis edge energy of ~4.5 eV with a single Ligand-to-Metal Charge Transfer (LMCT) peak at 250 nm.[6,16,32] The $(NH_4)_2Mo_2O_7$ reference compound contains MoO_x chains with a UV-vis edge energy (Eg) value of ~3.5 eV and two LMCT peaks at 250 and 320 nm reflecting the oligomeric structure.[6,16,32] The supported 3MoAl catalyst has an intermediate edge energy value of ~3.9 eV with two comparable intensity LMCT peaks at 240 and 285 nm suggesting that isolated surface MoO_x sites co-exist with oligomeric surface MoO_x sites (Figure S7). The supported 3MoTaAl catalysts have a slightly lower edge energy ~3.8 eV with an increase in the ratio of the 285 nm/240 nm LMCT peaks with increasing surface TaO_x coverage reflects the presence of greater amounts of oligomeric surface MoO_x sites (Figure S7). The UV-vis LMCT peaks at ~240 nm and 270-290 nm of the dehydrated supported MoO_x catalysts indicate that the surface MoO_x sites are fully oxidized as Mo(+6) under dehydrated conditions.[16] This is further confirmed by the absence of UV-vis d-d peaks at ~350-800nm from reduced surface MoO_x sites. Thus, the surface MoO_x sites are present in the Mo^{6+} oxidation state and consists of both isolated and oligomeric sites, with the extent of oligomerization increasing with surface TaO_x coverage.

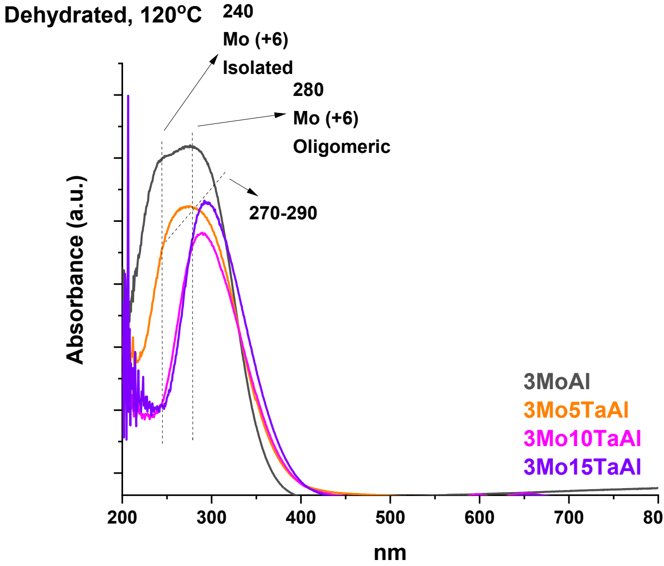


Figure 4. *In situ* UV-vis DRS spectra of dehydrated supported MoO_x/Al_2O_3 catalysts (120°C). The UV-vis DRS spectra of supported 3MoTaAl are generated by subtracting the contribution of the corresponding supported TaO_x/Al_2O_3 catalyst.

Catalysts	3MoAl	3Mo5TaAl	3Mo10TaAl	3Mo15TaAl
UV-Vis Edge Energy (Dehydrated)	3.9 eV	3.8 eV	3.8 eV	3.8 eV

Table 1. *In situ* UV-vis edge energy values of dehydrated supported MoO_x catalysts (120°C).

2. Propylene Metathesis Reaction Conditions. The *in situ* UV-vis difference spectra of the supported MoO_x catalysts under propylene metathesis reaction conditions at 30 and 200°C are presented in Figure 5. The LMCT peaks at 245-280 nm from the fully oxidized Mo(+6) are minimally perturbed at 30 °C and the absence of peaks in the d-d region from reduced Mo sites. This suggests that the surface MoO_x sites on both the supported 3MoAl and 3Mo15TaAl catalysts possess surface Mo(+6) sites at 30°C. Only when the reaction temperature is raised to 200°C does the supported 3Mo15TaAl catalyst exhibit a very weak and broad peak (only visible in difference spectra) at ~435 nm in the d-d region with the LMCT peaks of fully oxidized Mo(+6) minimally perturbed. The possible presence of some reduced surface Mo sites, however, could not be determined since adsorbed olefins also give rise to UV-vis peaks in the same region.[34-35] In summary, the isolated and oligomeric surface MoO_x sites appear to be minimally perturbed by the propylene metathesis reaction conditions.

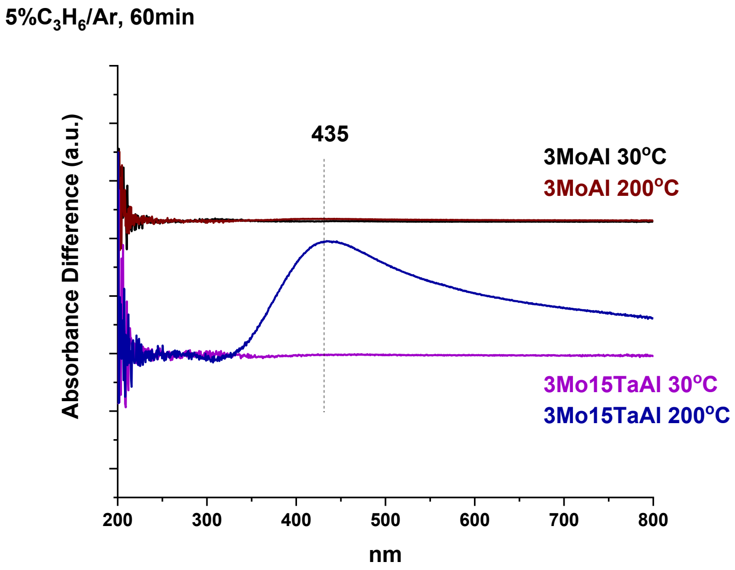


Figure 5. *In situ* UV-vis difference spectra of the supported MoO_x catalysts during propylene metathesis reaction conditions (30 and 200°C). The spectra of the dehydrated supported MoO_x catalysts were subtracted from the spectra of the corresponding supported MoO_x catalysts under propylene metathesis reaction conditions.

d. *In Situ* X-ray Absorption Spectroscopy (XAS)

The *in situ* X-ray Absorption Near Edge Structure (XANES) and Extended X-ray Absorption Fine Structure (EXAFS) spectra at the Mo K-edge of the supported MoO_x/Al_2O_3 and supported $MoO_x/TaO_x/Al_2O_3$ catalysts under dehydrated conditions and propylene metathesis reaction conditions are presented in Figures 6 and S8. The EXAFS fitting results are presented in Tables S1-S2 and Figures S9-S10. The MoO_4 coordination without inversion symmetry has a strong pre-edge peak due to the 1s(Mo) → 4d(Mo) + 2p(O) transition, but this transition is suppressed for the regular MoO_6 coordination with inversion symmetry.[36] A weak pre-edge peak due to this transition for MoO_6 coordination is present, however, for the distorted MoO_6 coordination (MoO_3 reference compound). Thus, the relatively strong pre-edge peak of all the supported MoO_x catalysts at 20003 eV is consistent with the presence of MoO_4 surface MoOx sites. represent both MoO_4 and distorted MoO_6 surface MoO_x sites. The XANES edge jump (maximum of the first derivative) of all the supported MoO_x catalysts at ~20015 eV is in the same position with that of the $Mo^{6+}O_3$ reference compound, indicating the oxidation state of surface MoO_x sites to be Mo(+6).[36] The k^2-weighted Mo K-edge EXAFS spectra demonstrate a strong peak at 1.2 Å (not corrected for photoelectron phase shift) corresponding to the terminal Mo=O bond that is shorter than the Mo-O bond at 1.6 Å in the MoO_2 reference compound with regular MoO_6 coordination[37] in the first shell (1-2 Å) of the Mo center. There is no Mo-Mo interaction in the second shell (3-4 Å) of the surface Mo center. The same Mo=O peak position suggests that the Mo=O bond lengths are same for all the supported MoO_x catalysts. The surface MoO_x sites are minimally perturbed (Figure S8) during the propylene metathesis reaction at 200°C for all the supported MoO_x catalysts. Given that oxygen and carbon atoms have close atomic masses, the difference between Mo-O and Mo-C interactions can't be captured by EXAFS. Quantitative model fitting of EXAFS yields a Mo=O bond at ~1.74Å (Table S1 and S2). The model fitted coordination number (CN) of Ta-promoted MoO_x/Al_2O_3 catalyst is higher than the CN of Ta-free MoO_x/Al_2O_3 catalysts, reflecting the increasing amount of oligomerized surface $MoO_{5/6}$ sites on the Ta-promoted catalysts.

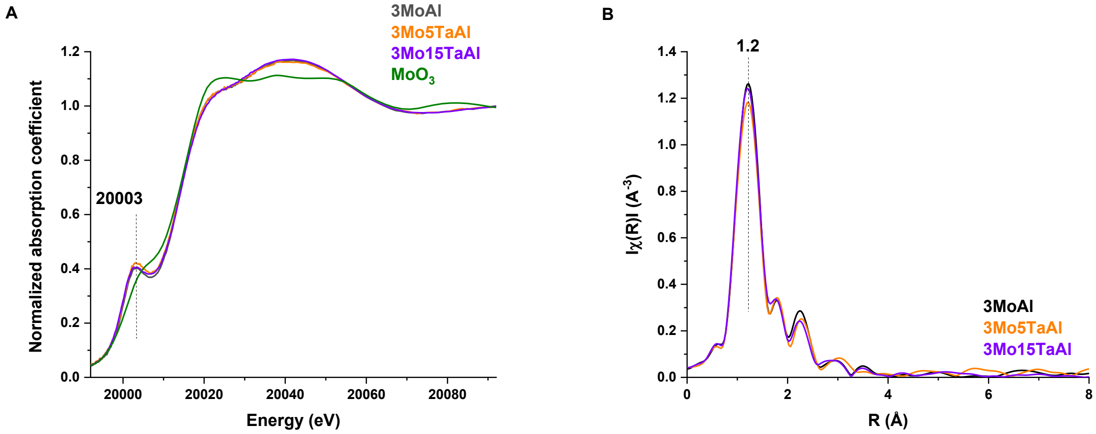


Figure 6. (A) Mo K-edge XANES spectra of dehydrated catalysts. (B) Fourier transform (FT) magnitude of the k^2-weighted Mo K-edge EXAFS data of catalysts (200°C). The k-range for FT was from 2 to 10 Å^{-1}.

d. Chemically Probing Surface Acid Sites with NH_3-IR

The *in situ* DRIFTS spectra of Al_2O_3, TaO_x/Al_2O_3, supported $3MoO_x/Al_2O_3$ and supported $3MoO_x/TaO_x/Al_2O_3$ catalysts after NH_3 chemisorption are presented in Figure 7. All the spectra exhibit the presence of surface Lewis acid sites ($\delta_{as}(NH_3^*)$ and $\delta_s(NH_3^*)$ at ~1619 and 1252 cm^{-1}, respectively) and Brønsted acid sites ($\delta_{as}(NH_4^{+*})$ and $\delta_s(NH_4^{+*})$ at ~1447-1480 cm^{-1} and 1684-1697 cm^{-1}).[31,38] The initial bare Al_2O_3 support exhibits the presence of both surface Lewis and Brønsted acid sites. The Brønsted acidity of the Al_2O_3 support is relatively weak since Brønsted acidity is not detected when chemically probed by the pyridine weaker base.[23,31,38] The IR $\delta_{as}(NH_4^{+*})$ and $\delta_s(NH_3^*)$ vibrations will be used for comparison of acidity strength since they are much stronger bands. The essentially same peak position of $\delta_s(NH_3^*)$ indicates that the acid strength of the surface Lewis acid sites is similar for all the catalysts. The vibrations from the surface Lewis acid sites are predominantly associated with the Al_2O_3 and TaO_x/Al_2O_3 supports since the surface MoO_x coverage is relative low (0.8 Mo/nm^2) compared to the surface TaO_x coverage (0.7, 1.4, 2.0 Ta/nm^2). The addition of both surface MoO_x sites and the TaO_x surface modifier introduce weaker Brønsted acid sites as indicated by the red shift of $\delta_{as}(NH_4^{+*})$ peak. With increasing surface TaO_x coverage, the Brønsted acidity of the supported 3MoTaAl catalysts is dominated by the weaker surface TaO_x Brønsted acid sites. The Brønsted acidity strength introduced by MoO_x is in-between that of Al_2O_3 and surface TaO_x sites as indicated by the moderate red shift of $\delta_{as}(NH_4^{+*})$. The strength of surface Brønsted acidity follows the trend Al_2O_3 > 3MoAl > 15TaAl ~ 3Mo5TaAl > 3Mo15TaAl. Since DRIFTS is not quantitative, only the relative ratios of the Brønsted/Lewis acid sites can be compared: Al_2O_3 (1.54) > 3MoAl (1.46) > 3Mo5TaAl (1.32) > 15TaAl (1.29) > 3Mo15TaAl (1.21). The peak areas of the Brønsted acid sites follows the trend: 15TaAl (16.7) > 3Mo5TaAl (16.3)> 3Mo15TaAl (15.7) ~ 3MoAl (15.6) >> Al_2O_3(12.7). In summary, all the catalysts have surface Lewis acid sites with similar strength, while the addition of the surface MoO_x and TaO_x sites introduce weaker surface Brønsted acid sites.

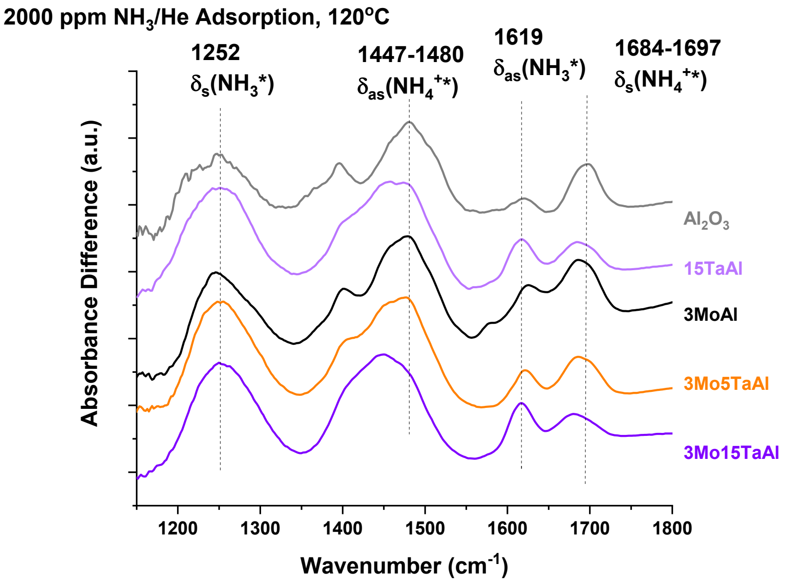


Figure 7. *In situ* DRIFTS spectra of dehydrated supported MoO_x catalysts after NH_3 adsorption and evacuation at 120°C.

e. Propylene-TPSR

The C_3H_6-TPSR spectra of the supported MoO_x catalysts are presented in Figure 8. The supported 3MoAl catalyst produces C_4H_8 from 30-600 °C with a peak temperature (Tp) of ~480-500°C. The supported 3MoTaAl catalysts, however, form C_4H_8 in several temperature ranges: ~50-150°C (Tp=65°C), ~225-375°C (Tp=280-310°C) and ~375-600°C (Tp=480-510°C). The C_3H_6-TPSR spectra suggest that there are probably 3 distinct active surface MoO_x sites in these catalysts with their specific activity increasing with decreasing Tp value. Both the amount of C_4H_8 produced and specific activity tend to increase with increasing surface TaO_x coverage reflecting the promotional effect of the surface TaO_x sites upon propylene metathesis by the supported $MoO_x/TaO_x/Al_2O_3$ catalysts.

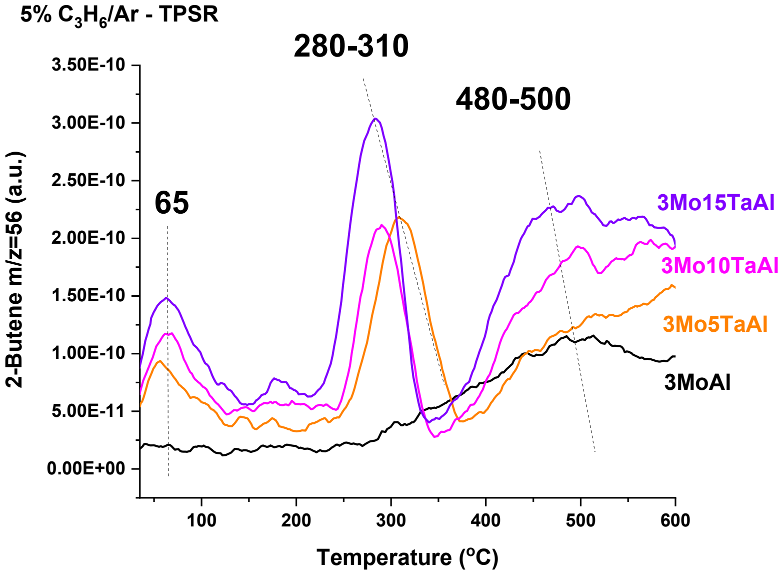


Figure 8. Propylene-TPSR spectra for the supported $3\%MoO_x/n\%TaO_x/Al_2O_3$ catalysts from 30-600°C (n = 0, 5, 10, 15).

f. Ethylene/2-Butene Titration (Number of Active Sites)

The number of catalytic active sites involved in olefin metathesis can be determined from the number of propylene molecules formed during ethylene/2-butene titration.[39-40] The time resolved titration spectra are presented in Figure 9. The Mo-free Al_2O_3 and TaO_x/Al_2O_3 supports do not yield any propylene from the C_2H_4/C_4H_8 titration, which indicates that the catalytic active site for olefin metathesis is the surface MoO_x sites. The fraction of activated surface MoO_x sites from the $C_2^=/C_4^=$ titration are given in Table 2. The supported 3MoAl possesses a small fraction of activated surface MoO_x sites (~3.2%) with the addition of surface TaO_x sites increasing the fraction of activated surface MoO_x sites by ~5-6x (~16-19%). Thus, the number of activated surface MoO_x sites is significantly increased by surface modification of the Al_2O_3 support with surface TaO_x sites.

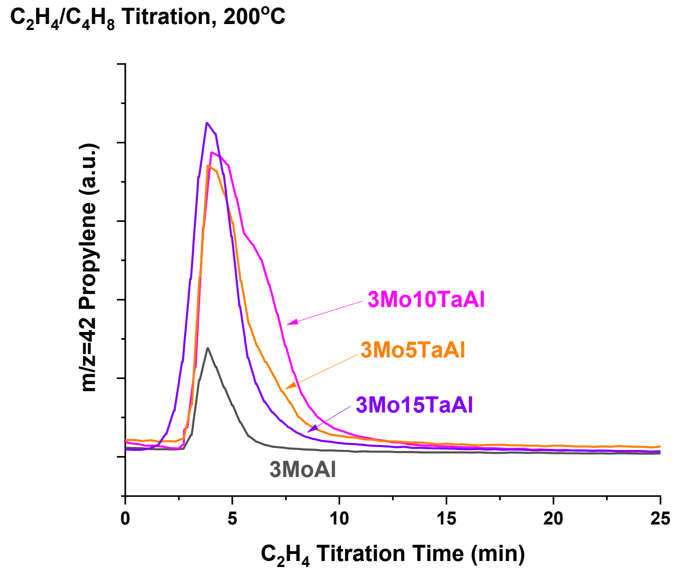


Figure 9. Time-resolved MS spectra of C_3H_6 produced during the titration of surface Mo=CHCH$_3$ with C_2H_4 for the supported MoO_x catalysts (200°C).

g. Steady-State Propylene Metathesis

The steady state catalytic activity of the supported MoO_x catalysts for propylene self-metathesis at 200°C are presented in Figure 10. The activity trend is 3Mo15TaAl > 3Mo10TaAl > 3Mo5TaAl >> 3MoAl. The turnover frequency (TOF) values were calculated by dividing the catalytic activity by the number of activated surface MoO_x sites determined from C_2H_4/C_4H_8 titration and are presented in Table 2. The TOF value increases approximately one order of magnitude with addition of surface TaO_x sites to the Al_2O_3 support. Thus, the TOF value for surface MoO_x sites is significantly promoted by surface modification of the Al_2O_3 support with surface TaO_x sites.

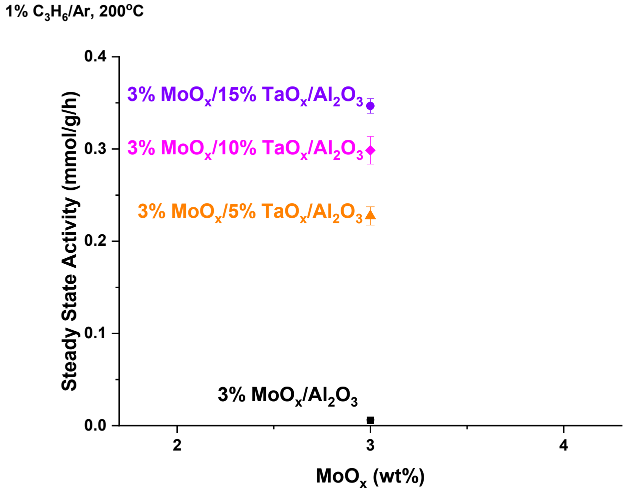


Figure 10. Steady state catalytic activity of supported $MoO_x/TaO_x/Al_2O_3$ catalysts for propylene self-metathesis at 200°C (1% $C_3^=$/Ar).

	3MoAl	**3Mo5TaAl**	**3Mo10TaAl**	**3Mo15TaAl**
Fraction of activated surface MoO_x sites	**3.2%**	**16.3%**	**18.8%**	**18.1%**
Steady-State Activity (mmol/g/h)	**0.0056**	**0.2274**	**0.2986**	**0.3466**
TOF (s^{-1})	**$2.4x10^{-4}$**	**$1.9x10^{-3}$**	**$2.1x10^{-3}$**	**$2.6x10^{-3}$**

Table 2. Fraction of activated surface MoO_x sites calculated from C_2H_4/C_4H_8 titration, steady-state activity and propylene metathesis turnover frequency (TOF).

IV. Discussion

a. Surface Anchoring Hydroxyls for MoO_x Sites

The surface hydroxyls of the Al_2O_3 and TaO_x/Al_2O_3 supports serve as the anchoring sites for the deposition of the TaO_x and MoO_x species (Figure 1). The MoO_x species for the supported 3MoAl catalyst preferentially anchor at the most basic Al-OH (HO-μ_1-Al_{IV}) and less basic Al-OH (HO-μ_1-Al_{VI}) surface hydroxyls with a minor amount also anchoring at the less basic Al-OH (HO-μ_1-Al_V) and acidic Al_3-OH surface hydroxyls. The anchoring of the surface TaO_x species on Al_2O_3, however, indiscriminately involves all five types of the surface hydroxyls and form new Brønsted acid Al-$(OH)^+$-Ta sites. Consequently, the anchoring of the surface TaO_x species affects the remaining surface hydroxyls available for the subsequent anchoring of the MoO_x species. The surface TaO_x sites partly cap the most basic Al-OH (HO-μ_1-Al_{IV}) surface hydroxyls, thus, shifting the anchoring of MoO_x to the less basic Al-OH (HO-μ_1-Al_{VI} and HO-μ_1-Al_V), neutral Al_2-OH and acidic Al_3-OH surface hydroxyls usually observed with anchoring of MoO_x at intermediate surface coverage.[6]

For the supported $ReO_x/TaO_x/Al_2O_3$ catalyst system, TaO_x surface modification of Al_2O_3 was previously found to shift the anchoring of ReO_x species from the most basic Al-OH (HO-μ_1-Al_{IV}) to the neutral Al_2-OH and acidic Al_3-OH surface hydroxyls.[15] Although the trend with surface TaO_x modification is similar for both the supported $ReO_x/TaO_x/Al_2O_3$ and $MoO_x/TaO_x/Al_2O_3$ catalyst systems (less anchoring at the most basic surface hydroxyls and anchoring at less basic, neutral and acidic surface hydroxyls), the specific anchoring sites of ReO_x and MoO_x are not exactly the same probably because of the different acidity of the MoO_x and ReO_x species.

b. Molecular Structure of Dehydrated Surface MoO_x Sites

The dehydrated supported 3MoAl catalyst contains both isolated surface MoO_4 sites (LMCT peak at ~240 nm (Figure S7), higher UV-vis Eg value (Figure S7) and lower EXAFS coordination number (Table S1) and oligomeric $MoO_{5/6}$ sites (two LMCT peak at ~285 nm (Figure S7), intermediate UV-vis Eg value (Figure S7) and higher EXAFS coordination number (Table S1)). The dehydrated supported 3MoTaAl catalysts also contain isolated MoO_4 and oligomeric $MoO_{5/6}$ sites with the fraction of oligomeric $MoO_{5/6}$ sites increasing with surface TaO_x coverage (increase in UV-vis peak at ~285 nm relative to ~240 nm (Figure S7), blue shift of v_s(Mo=O) band position (Figure 2) and higher EXAFS coordination number (Table S1)). For all the supported MoO_x catalysts, the oxidation state of MoO_x sites is predominantly Mo(+6) (absence of d-d peaks and XANES edge jump). The change of the molecular structure of the surface MoO_x sites on the supported 3MoTaAl catalysts is a consequence of the modification of the available anchoring surface hydroxyls on the Al_2O_3 support brought about by TaO_x surface modification.

The molecular structure of the surface MoO_x sites supported on Al_2O_3 has been extensively studied with *in situ* Raman[6,7,16,41], XAS[7,41-42], *in situ* UV-vis[6,16] and DFT [22,43-45]. Three distinct surface MoO_x sites are present on Al_2O_3 that depend on the surface MoO_x coverage. At low surface coverage (<1 Mo/nm^2), the surface is dominated by isolated dioxo MoO_4 sites. At high surface coverage (1-4.6 Mo/nm^2), both isolated dioxo MoO_4 sites and oligomeric mono-oxo $MoO_{5/6}$ surface sites coexist. Above monolayer coverage (>4.6 Mo/nm^2), crystalline MoO_3 nanoparticles form on top of the surface MoO_x monolayer.[6-7,16,41-42] The molecular structure of the surface MoO_x sites for the supported 3MoAl catalyst reported herein agrees with structures of the surface MoO_x sites on MoO_x/Al_2O_3 at low MoO_x surface coverage previously reported in the literature. The molecular structures of the surface MoO_x sites for the supported 3MoTaAl catalysts, however, correspond to the structures present at intermediate surface MoO_x coverage of the supported 9-13% MoO_x/Al_2O_3 catalysts (Figures 2 and Tables 1). The number of terminal oxo Mo=O bonds depends on the specific support: di-oxo and mono-oxo MoO_x sites co-exist on Al_2O_3[6], ZrO_2[16,46] and TiO_2,[47] and di-oxo MoO_x sites on SiO_2[16,32,48]. Since the MoO_x species mainly anchor at the Al_2O_3 surface hydroxyls of TaO_x surface modified Al_2O_3, both di-oxo and mono-oxo surface MoO_x sites most likely co-exist for the supported 3MoTaAl catalysts. Only when one of the anchoring sites for the MoO_x species is selectively capped by surface TaO_x site can the number of terminal Mo=O bonds in the remaining surface MoO_x site can be clearly determined with isotopic ^{18}O-^{16}O exchange.[15] Two distinct surface ReO_4 spites were identified on Ta surface modified supported ReO_4/Al_2O_3 catalysts. The surface TaO_x sites completely blocks the formation of the surface ReO_4-I sites at basic hydroxyls and shifts anchoring of the surface ReO_4 species to more neutral and acidic surface hydroxyls.[15] The observed molecular structural change of the surface MoO_x sites for the supported 3MoTaAl catalyst suggests that surface TaO_x on Al_2O_3 similarly blocks anchoring of MoO_x species at basic surface hydroxyls (Figures 1, S1 and S2). The blocking effect of the surface TaO_x sites upon the supported MoO_x/Al_2O_3 catalyst, however, is weaker than for the corresponding supported ReO_x/Al_2O_3 catalysts since not all the isolated surface MoO_4 sites, corresponding to the first ReO_4 site, are still present for the supported $MoO_x/TaO_x/Al_2O_3$ catalyst.

c. Molecular Structure of Surface MoO_x Sites during Propylene Metathesis

To perform propylene metathesis, the surface MoO_x sites require activation by propylene, resulting in the removal and replacement of terminal Mo=O bonds by surface molybdenum carbenes ($Mo=CH_3$ and $Mo=CHCH_3$).[49] The molecular structures of the surface MoO_x sites of the supported 3MoAl catalyst are not perturbed during propylene metathesis at 30 and 200°C (minimal changes in Raman (Figure 3), UV-vis (MoO_x/Al_2O_3) and XAS (Table S1)). In contrast, the surface MoO_x sites for the supported 3MoTaAl catalysts are modestly activated under propylene metathesis reaction at 200°C (Figure 3, decrease in Raman intensity from propylene coordination). The oxidation state of the surface MoO_x sites for both 3MoAl and 3MoTaAl catalysts under propylene metathesis reaction remains dominated byMo (+6) (minimal perturbation of the UV-vis LMCT peak (Figures 4 and 5) and XANES edge jump (Figures 6 and S8)) since the dehydrated surface MoO_x sites and activated molybdenum carbene both exhibit Mo(+6) (Figure 5).[5-6,8,50]

The nature of the surface MoO_x sites on Al_2O_3 during propylene metathesis has recently been examined by *in situ* Raman spectroscopies as a function of MoO_x loading.[6] For supported MoO_x/Al_2O_3 catalysts at low surface MoO_x coverage, the isolated MoO_4 sites dominate under propylene metathesis reaction conditions and do not become activated at low temperatures (<200°C).[6] The findings in the present study for the supported 3MoAl catalyst during propylene metathesis (Figure 3) are in agreement with the previously reported findings.

The *in situ* Raman spectra of supported ReO_4/Al_2O_3 catalysts revealed that the surface ReO_4-I sites anchored at basic Al-OH surface hydroxyls are minimally activated during propylene metathesis, while the surface ReO_4-II sites anchored at neutral Al_2-OH and more acidic Al_3-OH are extensively activated at low temperature (<200 °C). The Ta-surface modified supported ReO_4/Al_2O_3 catalysts only contain the surface ReO_4-II sites, formation of surface ReO_4-I is not present since the basic Al-OH sites have been capped by the surface TaO_x sites and are extensively activated at low temperatures (30°C).[15] Similar to the Ta-surface modified supported ReO_4/Al_2O_3 catalysts, activation of the surface MoO_x sites for the Ta-surface modified supported $MoO_x/TaO_x/Al_2O_3$ catalyst by propylene is enhanced because some of the basic Al-OH surface hydroxyls are capped by the surface TaO_x sites that increases anchoring of the MoO_x species at less basic, neutral and more acidic surface hydroxyl sites (Figures 1, S1 and S2).

d. Structure-Activity Relationship for Propylene Metathesis

Typically, the fraction of activated surface metal alkylidene species is only a fraction of the total supported metal oxides .[13,39,51-59] The steady-state reaction and C_2H_4/C_4H_8 titration reveal that both the number of activated surface MoO_x sites and the TOF values increase with surface TaO_x coverage (Table 2: 3Mo15TaAl > 3Mo10TaAl > 3Mo5TaAl >> 3MoAl). A similar trend is also found for activation (C_3H_6-TPSR) of the supported MoO_x catalysts at low, intermediate and high temperatures (Figure 8: 3Mo15TaAl > 3Mo10TaAl > 3Mo5TaAl >> 3MoAl). These trends correspond to two changes (i) anchoring surface hydroxyls for the surface MoO_x sites and (ii) extent of oligomerization of the surface MoO_x sites. Given that both variables are varying at the same time, it appears at first difficulty to determine the contributions of these variable to activation and TOF. However, the analogous supported $ReO_4/TaO_x/Al_2O_3$ catalysts only contain isolated surface ReO_4 sites and the surface TaO_x changes the anchoring surface hydroxyls of the surface ReO_4 sites. Given that both olefin metathesis catalyst systems behave similarly with surface metal oxide coverage and surface TaO_x modification, it appears that the dominant factor is the anchoring sites and not the oligomerization extent of the surface MoO_x sites.

DFT calculations of activated surface Mo-methylidene sites found that the location of the surface MoO_x sites on the Al_2O_3 support influence the activity of the surface Mo-methylidene towards ethylene addition.[22,43,44,45,60] The calculations predicted that on the (100) and (110) facets of Al_2O_3, when Mo-methylidene was anchored at neutral Al_2-OH or more acidic Al_3-OH surface hydroxyls, that the surface MoO_x sites were less stable with a decreased electron density of the molybdenum center, making the geometry of the surface Mo-methylidene more suitable for olefin addition.[22,45] Both monomeric and dimeric MoO_x sites can become activated sites, but the latter requires a lower activation energy. Dimeric surface MoO_x sites are more stable on the Al (100) facet, while isolated MoO_x sites are more stable on the Al (110) facet. These studies indicate that the isolated surface Mo-methylidene is less active since such sites prefer to form the less active square-pyramidal molybdacyclobutane surface intermediate. [43-44] Thus, the DFT calculations also indicate the importance of surface anchoring sites for activation of surface MoO_x sites for olefin metathesis.

For Ta-free supported MoO_x/Al_2O_3 catalysts, the amount of C_4H_8 formation during C_3H_6-TPSR at high temperature remains constant with surface MoO_x coverage.[6] On the Ta-surface modified MoO_x/Al_2O_3 catalysts, however, the amount ofC_4H_8 production at high temperature increases with surface TaO_x coverage (Figure 8). This difference is ascribed to the modification of the basic Al-OH surface hydroxyls by the surface TaO_x sites involved in anchoring isolated surface MoO_4 sites (Figures 1, S1 and S2). Analogously, the increase in production of C_4H_8 at intermediate and low temperature are related to the perturbation of the surface hydroxyls by the surface TaO_x sites involved in anchoring the MoO_x species at less basic Al-OH (HO-μ_1-Al_V) and neutral Al_2-OH of Al(110) and less basic Al-OH (HO-μ_1-Al_{VI}) and acidic Al_3-OH of Al(100), respectively. Thus, the activation and specific catalytic activity of surface MoO_x sites on the Al_2O_3 support can be tuned by modification of the available surface hydroxyl anchoring sites.

e. Influence of Surface Lewis/Brønsted Acidity on Propylene Metathesis

In the present study, the dehydrated supported MoO_x catalysts were found to possess very similar strength of Lewis acid sites (dominated by Lewis acid sites of the Al_2O_3 and TaO_x/Al_2O_3 supports) and slightly weaker Brønsted acid sites (Figure 7). A relationship between Lewis acidity and propylene metathesis activity could not be established since the Lewis acidity is dominated by the oxide supports at the low surface MoO_x coverage

(0.8 Mo/nm^2 that corresponds to ~18% of monolayer) employed in the present study. There is no relationship between Brønsted acid strength and propylene metathesis activity since the addition of surface TaO_x sites decreases the strength of the Brønsted acid sites while the propylene metathesis activity increases. The amount of Brønsted acid sites also doesn't relate with propylene metathesis activity since both the supported 3MoAl and 3Mo15TaAl catalysts have comparable amounts of Brønsted acid sites and the supported 3Mo15TaAl catalyst is much more active for propylene metathesis.

The surface acidity properties of surface TaO_x and MoO_x sites on Al_2O_3 have been documented in several studies.[23,61-63] Adsorption of pyridine on the Mo-free supported TaO_x/Al_2O_3 indicated that (*i*) at low surface TaO_x coverage, only weak Lewis acid sites are present and the amount of Lewis acid sites increase with TaO_x loading, and (*ii*) at high surface TaO_x coverage, the amount of Brønsted acid sites increase and the strength of the Lewis acid sites decrease with increasing TaO_x loading.[61] For supported MoO_x/Al_2O_3 catalysts, NH_3-TPD reveals that the total amount of acid sites initially increases and then decreases with increasing surface MoO_x coverage.[64] Pyridine-IR adsorption on supported MoO_x/Al_2O_3 catalysts indicate that the amount of Brønsted acid sites linearly increase with addition of surface MoO_x sites. The trend of amount of Lewis acid sites with surface MoO_x coverage, however, is still under debate. Boorman *et al*. and Turek *et al*. found the amount of Lewis acid sites increase with MoO_x addition, while Sagawa *et al*. found the opposite trend.[23,62-63] The different trends may be related to the use of different Al_2O_3 support materials.

Recent DFT calculations proposed that the surface silanol of SiO_2 or Brønsted acid site of USY zeolite interact with surface MoO_x sites constituting Brønsted acid sites that could play a key role in activating the surface active sites.[65-66] To minimize the influence of the oxide support contribution, pyridine-IR adsorption studies need to be performed since ammonia is too strong a basic probing molecule. Attempts have also been made to determine possible correlations between propylene metathesis activity and surface Lewis/Brønsted acidity of supported MoO_x catalysts. Hahn *et al*. and Li *et al*. proposed a correlation between Brønsted acidity and ethylene/2-butene cross-metathesis activity as addressed in introduction.[9,14] Uchagawkar *et al*. examined supported MoO_x/Silicate(TUD-1) catalysts with pyridine-IR adsorption and found that the amount of surface Lewis acid sites linearly correlated to the ethylene/2-butene cross-metathesis activity.[10] Otroshchenko *et al*. investigated supported MoO_x catalysts on individual (ZrO_2, TiO_2, Al_2O_3, SiO_2) and mixed oxide supports (ZrO_2–SiO_2, ZrO_2–PO_4, TiO_2–SiO_2; Al_2O_3–SiO_2) with pyridine-IR adsorption and NH_3-TPD. No general relationships between olefin metathesis activity and strength/amount of Lewis/Brønsted sites could be established.[12] A general conclusion about the influence of surface acid sites on olefin metathesis cannot be made from the above literature findings since these studies are clearly not consistent with each other. Possible reasons for these different observations are the use of oxide supports from different sources and presence of surface impurities. The present detailed study, however, finds that there are no relationships between surface Lewis or Brønsted acid sites and olefin metathesis.

V. Conclusions

A series of novel TaO_x–surface modified supported MoO_x/Al_2O_3 catalysts for propylene metathesis were successfully synthesized and well-characterized. The TaO_x surface modifier perturbs the surface hydroxyl chemistry of the Al_2O_3 support, which alters the available surface hydroxyls for subsequent anchoring of the MoO_x species. Consequently, the surface MoO_x species anchor at basic Al-OH surface hydroxyls perturbed by TaO_x, more neutral Al_2-OH and acidic Al_3-OH surface hydroxyls that facilitate activation and propylene metathesis activity of the resulting surface MoO_x sites. The resulting catalytic properties are dependent on the anchoring surface hydroxyls and not on the extent of oligomerization of the surface MoO_x sites and surface Lewis/Brønsted acidity. This study demonstrates for the first time that olefin metathesis activity, number of active sites (Ns) and TOF, for supported MoO_x catalysts can be tuned by modifying the nature of the anchoring surface hydroxyls on the Al_2O_3 support.

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