



# Impregnated and Co-precipitated Pd–Ga<sub>2</sub>O<sub>3</sub>, Pd–In<sub>2</sub>O<sub>3</sub> and Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> Catalysts: Influence of the Microstructure on the CO<sub>2</sub> Selectivity in Methanol Steam Reforming

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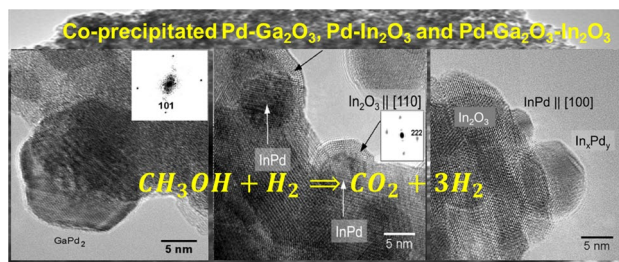
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## Abstract

To focus on the influence of the intermetallic compound—oxide interface of Pd-based intermetallic phases in methanol steam reforming (MSR), a co-precipitation pathway has been followed to prepare and subsequently structurally and catalytically characterize a set of nanoparticulate Ga<sub>2</sub>O<sub>3</sub>- and In<sub>2</sub>O<sub>3</sub>-supported GaPd<sub>2</sub> and InPd catalysts, respectively. To study the possible promoting effect of In<sub>2</sub>O<sub>3</sub>, an In<sub>2</sub>O<sub>3</sub>-doped Ga<sub>2</sub>O<sub>3</sub>-supported GaPd<sub>2</sub> catalyst has also been examined. While, upon reduction, the same intermetallic compounds are formed, the structure of especially the Ga<sub>2</sub>O<sub>3</sub> support is strikingly different: rhombohedral and spinel-like Ga<sub>2</sub>O<sub>3</sub> phases, as well as hexagonal GaInO<sub>3</sub> and rhombohedral In<sub>2</sub>O<sub>3</sub> phases are observed locally on the materials prior to methanol steam reforming by high-resolution transmission electron microscopy. Overall, the structure, phase composition and morphology of the co-precipitated catalysts are much more complex as compared to the respective impregnated counterparts. However, this induces a beneficial effect in activity and CO<sub>2</sub> selectivity in MSR. Both Ga<sub>2</sub>O<sub>3</sub> and In<sub>2</sub>O<sub>3</sub> catalysts show a much higher activity, and in the case of GaPd<sub>2</sub>–Ga<sub>2</sub>O<sub>3</sub>, a much higher CO<sub>2</sub> selectivity. The promoting effect of In<sub>2</sub>O<sub>3</sub> is also directly detectable, as the CO<sub>2</sub> selectivity of the co-precipitated supported Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> catalyst is much higher and comparable to the purely In<sub>2</sub>O<sub>3</sub>-supported material, despite the more complex structure and morphology. In all studied cases, no deactivation effects have been observed even after prolonged time-on-stream for 12 h, confirming the stability of the systems.

## Graphical Abstract

The presence of a variety of distinct supported intermetallic InPd and GaPd<sub>2</sub> particle phases is not detrimental to activity/selectivity in methanol steam reforming as long as the appropriate intermetallic phases are present and they exhibit optimized intermetallic-support phase boundary dimensions.



**Keywords** X-ray diffraction · High-resolution electron microscopy · Catalysis · Intermetallic compound · Hydrogen reduction · Catalyst activation

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## 1 Introduction

Pd-based intermetallic compounds have long been in the focus of research due to their outstanding catalytic properties in methanol steam reforming [1–5]. The associated high CO<sub>2</sub>-selectivity has tentatively been ascribed to the general presence of the intermetallic compound after reduction in hydrogen, whose electronic structure mimics that of the technologically used Cu/ZnO catalysts [6]. It is now widely accepted that the mere presence of the intermetallic compound alone is not sufficient to explain the high CO<sub>2</sub> selectivity, but rather, the close contact to the oxide phase is a prerequisite for efficient water activation, the crucial step in obtaining high CO<sub>2</sub> selectivities [7–9]. Among the studied systems, GaPd<sub>2</sub>/Ga<sub>2</sub>O<sub>3</sub> [10–16], ZnPd/ZnO [5, 17–21] and InPd/In<sub>2</sub>O<sub>3</sub> [22–24] have been scrutinized most and many of their structural, physico-chemical and catalytic properties have been already determined satisfactorily. As the simultaneous presence of both intermetallic compound and (partially reduced) oxide supports (monoclinic Ga<sub>2</sub>O<sub>3</sub>, hexagonal ZnO and cubic In<sub>2</sub>O<sub>3</sub>, respectively) is of utmost importance to induce a bifunctional synergism and, thus, to obtain high CO<sub>2</sub> selectivities, to search for synthesis methods in order to obtain a potentially larger intermetallic-oxide interface concentration is imperative. So far, apart from thin film or other model catalyst approaches [4, 7, 8, 14, 19–22], preparation of those catalysts is basically performed using standard incipient wetness impregnation pathways.

In this work, to increase the supposedly catalytically active interface, we follow a Pd and Ga<sub>2</sub>O<sub>3</sub> and In<sub>2</sub>O<sub>3</sub> co-precipitation approach using nitrate precursor solutions, respectively. In due course, the structure and catalytic properties are directly compared to their impregnated counterparts. The present work also focuses on the possible difference between using either Ga<sub>2</sub>O<sub>3</sub> or In<sub>2</sub>O<sub>3</sub> as active catalyst support, because Ga<sub>2</sub>O<sub>3</sub>-containing catalysts are known to exhibit a significantly lower CO<sub>2</sub> selectivity as compared to their In<sub>2</sub>O<sub>3</sub>-containing counterparts. This task is tackled by deliberately promoting a Pd–Ga<sub>2</sub>O<sub>3</sub> catalyst with In<sub>2</sub>O<sub>3</sub> in the co-precipitation process. Additionally, we present long-term activity measurements for the entire set of catalysts to elucidate deactivation, an undesired catalytic property that has not been addressed in detail for this class of materials so far. Special attention will be given to a detailed comparison of the structure and morphology of both (inter)metallic and oxide particles before and after the methanol steam reforming treatment, thus extensive high-resolution electron microscopy experiments are an integral part of the work.

## 2 Experimental

### 2.1 Catalyst Preparation

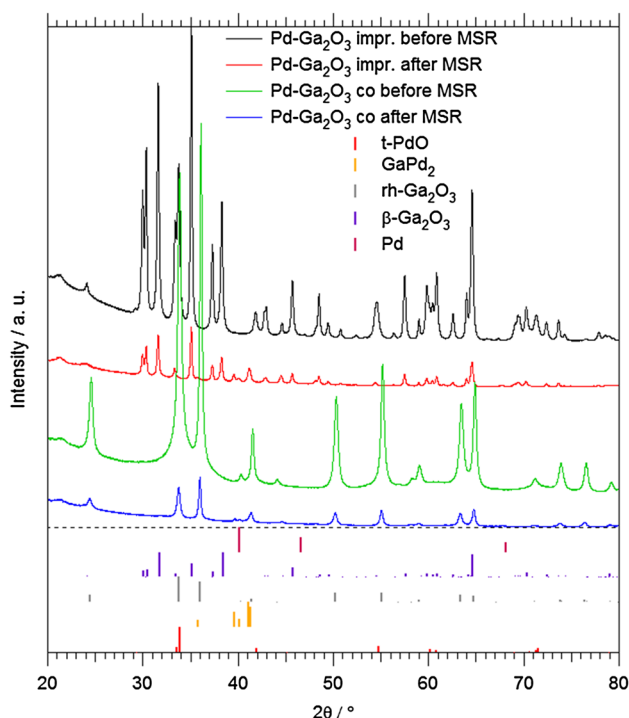
In order to suppress a potential influence of the preparation routine on the catalytic properties, the synthesis protocols were kept as similar as possible for all catalysts. This particularly refers to the way Pd is introduced, as well as to the solvents and precipitation agents used.

For the co-precipitated Pd/Ga<sub>2</sub>O<sub>3</sub> catalyst, 100 mg Pd (Goodfellow Pd foil 99.99%) were dissolved in a mixture of 5 mL HNO<sub>3</sub> (65%) and 1 mL HCl (37%) while gently heating. Subsequently, the volume was increased with distilled H<sub>2</sub>O to 50 mL. Separately, 1.5 g Ga (Goodfellow Ga metal 99.9999%) were dissolved in HCl (37%) at 373 K. Both solutions were unified and diluted to 100 mL total volume using distilled H<sub>2</sub>O. Afterwards, NaOH (5%) was added dropwise at 353 K until a pH value of 7–8 was reached. The resulting precipitate was allowed to age overnight and subsequently filtrated and dried at 373 K. Remaining Cl was removed by thorough washing. To obtain the pre-catalyst, the powder was calcined in air at 773 K for 4 h (which also removes the remnants of HNO<sub>3</sub> decomposition).

Similarly, the respective co-precipitated Pd/In<sub>2</sub>O<sub>3</sub> and Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> catalysts were synthesized. For the former, In metal foil (Goodfellow 99.999%) was dissolved in HNO<sub>3</sub> and In(OH)<sub>3</sub> precipitated by addition of NaOH (5%). 2.4 g In(OH)<sub>3</sub> were then dissolved in 5 mL HCl (37%) and diluted using distilled H<sub>2</sub>O up to 20 mL total volume. The Pd-containing solution (preparation exactly as above) was then added and the unified solution treated as the Pd–Ga<sub>2</sub>O<sub>3</sub> catalyst above.

The catalyst containing both Ga<sub>2</sub>O<sub>3</sub> and In<sub>2</sub>O<sub>3</sub> was prepared by unifying the Pd- and Ga<sub>2</sub>O<sub>3</sub>-containing solutions (preparation as above) with the respective In(OH)<sub>3</sub> solution (0.24 g in 5 mL HCl 37%). Further aging, filtration and calcination were performed as above. Impregnated Pd/Ga<sub>2</sub>O<sub>3</sub> and Pd/In<sub>2</sub>O<sub>3</sub> have been prepared following a classical wet impregnation technique detailed elsewhere [10, 12].

All catalysts were subsequently characterized by X-ray diffraction (XRD) and (high resolution) electron microscopy (HRTEM) prior to and after methanol steam reforming. As the XRD (Figs. 1, 2, detailed discussion in Sect. 3.1.) and subsequent TEM analyses reveal, all three catalysts, after calcination, consist of Ga<sub>2</sub>O<sub>3</sub> and In<sub>2</sub>O<sub>3</sub> grains decorated with small PdO particles. To ensure similar starting conditions and to induce formation of the intermetallic compound/oxide interface, oxidative treatments (O<sub>2</sub>, 1 bar flowing, 673 K) and then activation in hydrogen stream (H<sub>2</sub>, 1 bar flowing, Pd–Ga<sub>2</sub>O<sub>3</sub>: 673 K; Pd–In<sub>2</sub>O<sub>3</sub>:

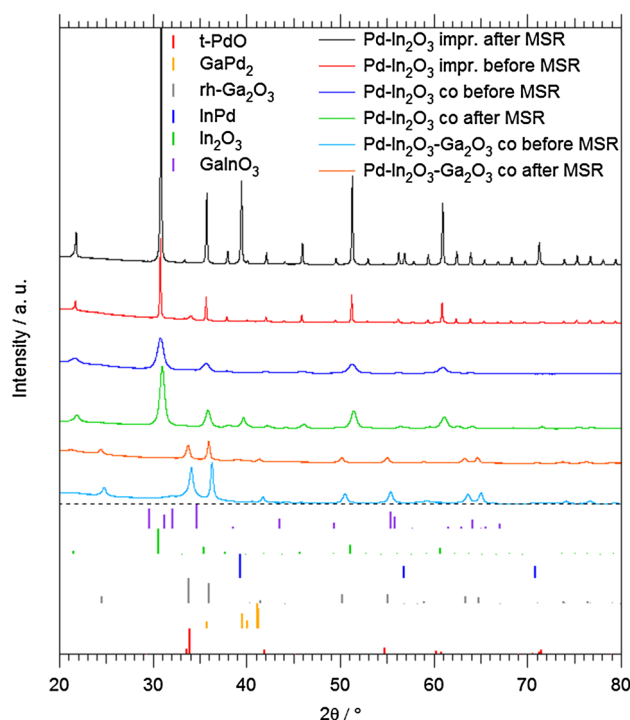


**Fig. 1** PXRD data of impregnated and co-precipitated Pd-Ga<sub>2</sub>O<sub>3</sub> before oxidation and after the catalytic testing. Reference diffractograms for tetragonal PdO (#43-1024), orthorhombic GaPd<sub>2</sub> (#50-1443), rhombohedral Ga<sub>2</sub>O<sub>3</sub> (#43-1013), monoclinic Ga<sub>2</sub>O<sub>3</sub> (#43-1012) and cubic Pd metal (#46-1043) for phase analysis are shown as vertical bars. Data of the H<sub>2</sub> pre-reduced state (after calcination and before MSR) are almost identical to those after MSR and are therefore not shown

523 K; Pd-Ga<sub>2</sub>O<sub>3</sub>-In<sub>2</sub>O<sub>3</sub>: 473 K) were carried out prior to the actual catalytic measurement. Flow rates between 0.01 and 5.00 mL min<sup>-1</sup> have been used.

## 2.2 Catalytic Experiments

For all long-term catalytic measurements, a plug-flow reactor setup (PID Eng&Tech) was used. The flow reactor setup consists of a reactor core, which is represented by a 20 cm long steel cylinder, the inner walls of which are coated by silica to prevent influences by any spurious catalytic activity of steel. The catalyst is positioned within this cylinder using quartz glass wool. The steel tube is further located inside a furnace, allowing temperatures up to 773 K. At the upper gas inlet, a thermocouple is integrated, which extends down into the catalyst bed inside the reactor tube. The reactor itself is connected to the gas supply and discharge ports via Swagelok® quick connectors for easy removal and exchange of catalysts. The gas feed is provided by a constant flow in top-to-bottom direction over the catalyst bed. The gas inlet and outlet are connected to each other by a six-way valve, which serves as a bypass of the reactor section if needed.



**Fig. 2** PXRD data of impregnated and co-precipitated Pd-In<sub>2</sub>O<sub>3</sub> and co-precipitated Pd-Ga<sub>2</sub>O<sub>3</sub>-In<sub>2</sub>O<sub>3</sub> before oxidation and after the catalytic MSR run. Reference diffractograms for tetragonal PdO (#43-1024), orthorhombic GaPd<sub>2</sub> (#50-1443), rhombohedral Ga<sub>2</sub>O<sub>3</sub> (#43-1013), cubic In<sub>2</sub>O<sub>3</sub> (#06-0416), hexagonal GaInO<sub>3</sub> (#21-0333) and cubic In<sub>0.52</sub>Pd<sub>0.48</sub> (#46-1011) for phase analysis are shown as vertical bars. Data of the H<sub>2</sub> pre-reduced state (after calcination and before MSR) are almost identical to those after MSR and are therefore not shown

The various gases are introduced via mass-flow controllers, which makes a wide range of different gas mixtures available. Furthermore, a heated injection valve is located next to the inlet port, which is equipped with a Gilson HPLC pump, enabling liquids to be mixed with the gas stream after vaporization (flow rate 0.01–5.00 mL min<sup>-1</sup>). Most parts (except for gas analysis and external liquid pump) are placed inside a temperature-controlled area of 393 K to exclude condensation phenomena. For similar reasons, the injector as well as the gas-feed pre-heating unit are kept at elevated temperatures. After passing the reactor section, the gas stream exits the temperature-controlled area and, subsequently, all liquid contents (in this case methanol and water) are removed by a Peltier separating unit in addition to a Nafion® membrane only penetrable for gases. The dry gases are detected by a Varian micro-GC system consisting of three separate chromatography columns for hydrogen, carbon monoxide and carbon dioxide, respectively.

For all experiments, a methanol–water mixture of 1:1 composition was used under flowing conditions. The steam flow was set to 1 mL min<sup>-1</sup> and mixed with the carrier-gas

stream (8 mL min<sup>-1</sup> N<sub>2</sub>/He mixture, the latter as internal standard) before entering the reactor section. The total pressure in the apparatus is limited to 1 bar. The reactor setup shows no conversion in MSR under the conditions applied.

As for the selectivity, no CH<sub>4</sub> is observed. The CO-selectivity can be obtained by subtracting the selectivity to CO<sub>2</sub> from 100%. Hydrogen selectivity is 100%, since no other hydrogen-containing product is detected.

### 2.3 Structural Characterization

Powder X-ray diffraction was conducted on a STOE-STADIP-MP powder diffractometer in Bragg–Brentano geometry (Cu K<sub>α1</sub>-radiation, Ge(111) monochromator) from 2θ = 5° to 100°.

A Philips CM200FEG microscope operated at 200 kV and equipped with a field emission gun, Gatan imaging filter, and an energy-dispersive X-ray (EDX) analyser was used for TEM studies. The coefficient of spherical aberration was Cs = 1.35 mm, and the information limit was better than 0.18 nm. Selected areas were processed to obtain the power spectra (PS, square of the Fourier transform of the image), which were used for measuring interplanar distances (± 0.5%) and angles (± 0.5 deg) for phase identification. Projected areas have been measured and equivalent diameters calculated for a certain number of catalyst particles in each sample; in all cases (except for the impregnated Pd/Ga<sub>2</sub>O<sub>3</sub>) the values of standard error of the mean diameter were ≤ 0.3 nm. Frequency distributions of particle sizes fitted well to lognormal functions.

## 3 Results and Discussion

### 3.1 Structural Characterization

#### 3.1.1 X-ray Diffraction

X-ray diffraction patterns collected for all catalysts before and after the catalytic treatments are highlighted in Figs. 1 and 2. For the impregnated/co-precipitated Pd–Ga<sub>2</sub>O<sub>3</sub> catalysts (Fig. 1), similarities but also distinct differences arise. In the state before catalysis (i.e. before hydrogen pre-reduction and after oxidation in air), the impregnated Pd–Ga<sub>2</sub>O<sub>3</sub> catalyst is composed of PdO and β-Ga<sub>2</sub>O<sub>3</sub>, which is expected since impregnation was performed on phase-pure commercial β-Ga<sub>2</sub>O<sub>3</sub> powder (black diffractogram in Fig. 1 with majority of reflexes corresponding to lilac bars, PdO best visible at the characteristic split reflex at 2θ = 34°). After H<sub>2</sub> pre-reduction and the subsequent long-term presence in the methanol steam reforming mixture, GaPd<sub>2</sub> and mainly unaltered β-Ga<sub>2</sub>O<sub>3</sub> are detected (red diffractogram). GaPd<sub>2</sub> is also found on the co-precipitated catalyst after the

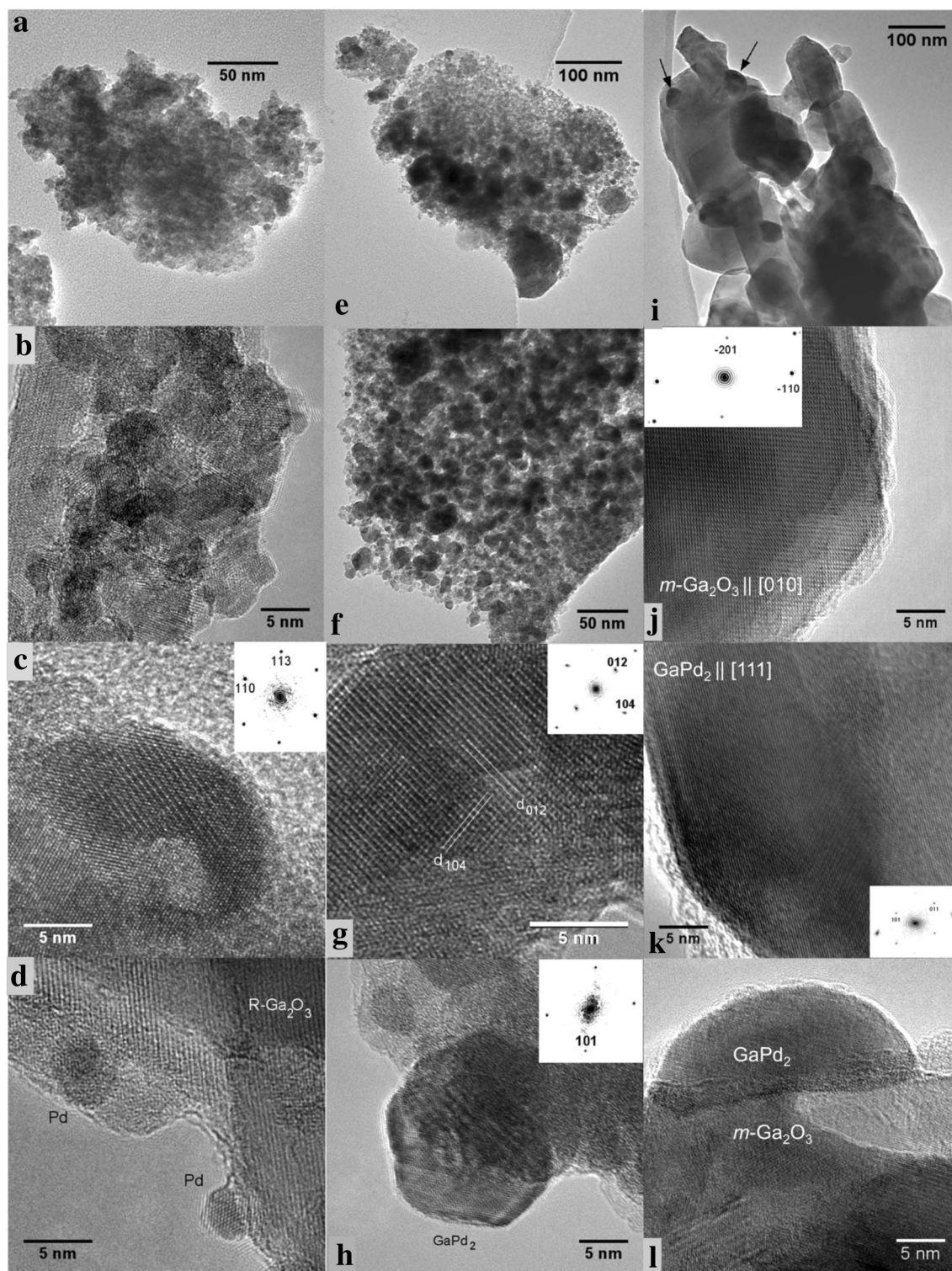
pre-reduction/catalytic treatment, but the catalyst support structure before and after catalytic treatment is rhombohedral (α-)Ga<sub>2</sub>O<sub>3</sub>, which obviously results from the co-precipitation procedure favouring this polymorph. Remarkably, metastable rhombohedral Ga<sub>2</sub>O<sub>3</sub> persists during each step of a catalytic cycle, that is, after pre-oxidation, pre-reduction and catalytic treatment (light grey bars/green and blue diffractograms in Fig. 1).

Structurally, the impregnated/co-precipitated Pd–In<sub>2</sub>O<sub>3</sub> materials appear less complex (Fig. 2). In both cases, before oxidation, tetragonal PdO/cubic In<sub>2</sub>O<sub>3</sub> is present. After the MSR treatment, the structure of the catalysts is characterized as InPd/cubic In<sub>2</sub>O<sub>3</sub>.

Apparently, the Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> catalyst is the crystallographically most complex system (Fig. 2). Before oxidation, weak signals of PdO are present alongside those of cubic In<sub>2</sub>O<sub>3</sub> and rhombohedral Ga<sub>2</sub>O<sub>3</sub>. After catalysis, the latter two are still present, in addition to very weak and broad signals of InPd. GaPd<sub>2</sub> is not visible in the XRD patterns, but may partially overlap with the broad InPd reflection at 2θ = 39°. It is, however, locally detectable in HRTEM images (cf. Fig. 3f). The same is true for the hexagonal ternary oxide GaInO<sub>3</sub>, detected also by HRTEM, which appears to have formed during the co-precipitation process.

#### 3.1.2 High-Resolution Electron Microscopy

EDX spectra (not shown) taken in 14 different areas reveal the mean ratio of Ga:Pd to be 80:20 ± 4 (std.err.) in the fresh PdO–Ga<sub>2</sub>O<sub>3</sub> catalyst after calcination. Analyses of lattice spacings and angles in HRTEM images allow the unambiguous phase identification in most cases (examples are given in Fig. 3g, h, j, k). In general, the structure of the co-precipitated catalyst did not change dramatically during the catalytic reaction, except for the particle size (see Table 1) and their composition. Only some small Pd particles individually supported on rhombohedral gallium oxide (α-Ga<sub>2</sub>O<sub>3</sub>)—Fig. 3d—or those intermixed with differently sized oxide particles (Fig. 3b) have been observed in the fresh catalyst. Occasionally, amorphous material and gallium oxide particles with the cubic spinel-like structure have been detected. Monoclinic Ga<sub>2</sub>O<sub>3</sub> as the thermodynamically most stable Ga<sub>2</sub>O<sub>3</sub> polymorph appears to be absent at all stages. During reduction and subsequent reaction, elemental palladium is transformed to GaPd<sub>2</sub> with much larger particle size (Fig. 3e, f, h). Frequently, the GaPd<sub>2</sub> crystals display {101} and {001} facets (Fig. 3h). The surfaces of the GaPd<sub>2</sub> particles are clean and not covered with any overlayers, but in several cases, single crystalline particles displayed inhomogeneous contrast of “core–shell” type (not shown) with darker cores and lighter shells—probably due to depletion of the sub-surface regions with Pd. This is supported by EDX analyses of individual intermetallic particles which show



**Fig. 3** TEM and HRTEM images of the co-precipitated and impregnated Pd-Ga<sub>2</sub>O<sub>3</sub> catalysts: **a–d** freshly prepared by co-precipitation and calcination in air at 773 K; **e–h** co-precipitated, after the MSR run; **i–l** impregnated, after the MSR run. Insets in **c, g, h, j, k** exam-

ples of power (FFT) spectra used for phase identification and determination of crystal orientation. Arrows in **i** show some of the GaPd<sub>2</sub> particles

**Table 1** Overview of the structural and catalytic findings by HRTEM, XRD and methanol steam reforming

Support	Phases (XRD)	Phases (HRTEM)	Ga(In):Pd (EDX)	D <sub>vol.wtd</sub> (Pd phase), nm (TEM)	Surface area (Pd phase) m <sup>2</sup> g <sup>-1</sup> (TEM)	CO <sub>2</sub> Selectivity (%)	Conversion (%)
Ga <sub>2</sub> O <sub>3</sub>	<b>rh-Ga<sub>2</sub>O<sub>3</sub>/t-PdO</b>	<b>rh + c-Ga<sub>2</sub>O<sub>3</sub>/Pd</b>		<b>3.2</b>	<b>25.6</b>		
	rh-Ga <sub>2</sub> O <sub>3</sub> /GaPd <sub>2</sub>	rh + c-Ga <sub>2</sub> O <sub>3</sub> /GaPd <sub>2</sub>	47:53	18.6	4.4	90	82
	<i>m-Ga<sub>2</sub>O<sub>3</sub>/GaPd<sub>2</sub></i>	<i>m-Ga<sub>2</sub>O<sub>3</sub>/GaPd<sub>2</sub></i>	39:61	88.4	0.9	59	58
In <sub>2</sub> O <sub>3</sub>	<b>c-In<sub>2</sub>O<sub>3</sub>/t-PdO</b>	<b>c-In<sub>2</sub>O<sub>3</sub>/Pd</b>		<b>5.6</b>	<b>14.7</b>		
	c-In <sub>2</sub> O <sub>3</sub> /InPd	c-In <sub>2</sub> O <sub>3</sub> /InPd	51:49	23.5	3.5	97.5	91
	<i>c-In<sub>2</sub>O<sub>3</sub>/t-PdO</i>	<i>c-In<sub>2</sub>O<sub>3</sub>/InPd, InPd<sub>2</sub></i>	46:54	12.7	6.5	99	50
Ga <sub>2</sub> O <sub>3</sub> /In <sub>2</sub> O <sub>3</sub>	<b>rh-Ga<sub>2</sub>O<sub>3</sub>/t-PdO</b>	<b>rh-Ga<sub>2</sub>O<sub>3</sub>/rh-In<sub>2</sub>O<sub>3</sub>/h-GaInO<sub>3</sub>/Pd/GaPd<sub>2</sub></b>	n/a	<b>4.1</b>	<b>20.1</b>		
	rh-Ga <sub>2</sub> O <sub>3</sub> /t-PdO/InPd	rh-Ga <sub>2</sub> O <sub>3</sub> /c-In <sub>2</sub> O <sub>3</sub> /GaPd <sub>2</sub> /InPd		8.5	9.6	97.5	60

Bold values represents fresh co-precipitated catalyst  
 Normal values represents co-precipitated catalyst after MSR reaction  
 Italic values represents impregnated catalyst after MSR reaction

some deficiency of Pd with respect to the stoichiometric ratio Ga:Pd = 1:2 in most cases. Locally, Ga<sub>7</sub>Pd<sub>3</sub> is also present as a minority phase in the catalyst after reaction. It is noteworthy that, in contrast to XRD, no Pd oxide was found with HRTEM in neither fresh, nor in the reacted material, probably because of its instability under the electron-beam in high vacuum.

In contrast to the co-precipitated materials, where only rhombohedral Ga<sub>2</sub>O<sub>3</sub> was found, in the impregnated catalysts, large single-crystalline particles (sometimes of sub-micrometer size) of the monoclinic Ga<sub>2</sub>O<sub>3</sub> polymorph (with elemental Pd particles decorating them prior to reduction/catalysis) were covered with GaPd<sub>2</sub> after reduction/catalysis—Fig. 3i–k. The particles exhibit a tendency to wet the surface of the support, displaying some kind of metal-support interaction—Fig. 3l. On average, the GaPd<sub>2</sub> particles are closer to the stoichiometric composition, according to EDX, but nevertheless did not correspond exactly to the nominal formula.

EDX spectra (not shown) taken in eight different areas yield a mean ratio of In:Pd = 83:17 ± 5 (std.err.) in the fresh co-precipitated and calcined Pd-In<sub>2</sub>O<sub>3</sub> catalyst. Both phases (elemental Pd and bcc In<sub>2</sub>O<sub>3</sub>) are well crystallized (Fig. 4a–c); no amorphous material was found. Pd particles are distributed on the In<sub>2</sub>O<sub>3</sub> surfaces without clustering. They display clean surfaces, sharp edges and, quite frequently, twin boundaries (Fig. 4b, c)—a feature that is known to increase the activity of Cu in the industrial Cu/ZnO/Al<sub>2</sub>O<sub>3</sub> catalyst [25]. In addition to pure Pd, a few particles of InPd<sub>2</sub> have been locally detected in the spent impregnated catalyst, highlighting the increased intermixing ability of Pd and In.

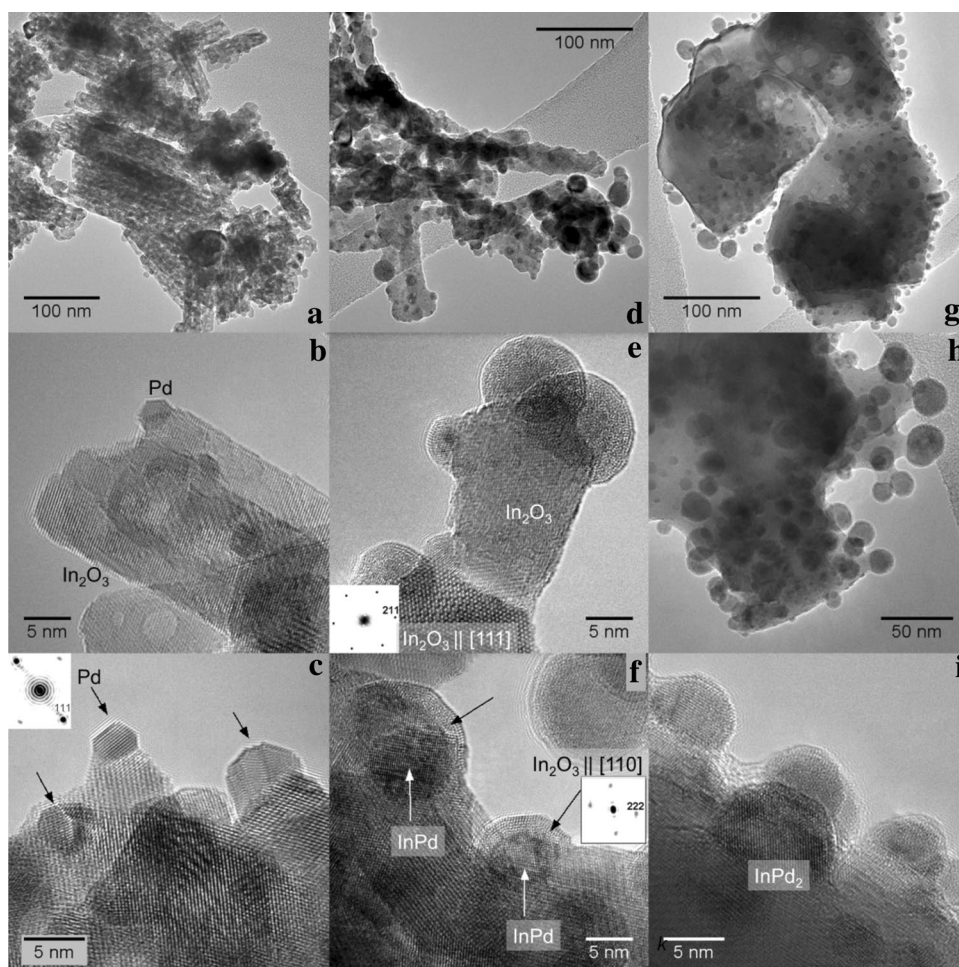
In most cases, the identification of Pd-containing phases from HRTEM data is ambiguous for the Pd–In<sub>2</sub>O<sub>3</sub>

catalyst studied after the MSR run, because of the strongly distorted structure of the particles—especially in the impregnated system—that could probably be caused by non-stoichiometry (variable In/Pd ratio). Nevertheless, the structure of InPd fits the majority of the HRTEM images in the co-precipitated system, and InPd<sub>2</sub> for the impregnated catalyst. This is in agreement with XRD (except for InPd<sub>2</sub>). On average, EDX analyses of individual particles reveal the compositions to be close to the stoichiometric composition of InPd in the co-precipitated catalyst after the reaction, but the In:Pd ratio was shifted towards Pd in the impregnated material. Both types of particles partially exhibit shells of distorted In<sub>2</sub>O<sub>3</sub> (Fig. 4e, f, i), which are thicker in the co-precipitated (up to 2 nm), and thinner and less-ordered in the impregnated catalyst.

For the Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> system, the composition could be determined by EDX to be Ga:In:Pd = 65:17:18 ± 2 (std.err.) in the fresh Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> material. Along with the individual gallium and indium oxides, the hexagonal phase of GaInO<sub>3</sub> has been detected with HRTEM in freshly prepared mixed-oxide supported catalyst (Fig. 5a, b). The palladium particles in the fresh catalyst were similar to those in the single-oxide materials: they exhibited a cuboctahedral shape.

After reaction, the majority of Pd-containing particles have been identified as GaPd<sub>2</sub> and InPd (or In<sub>x</sub>Pd<sub>y</sub> with probably variable In:Pd ratio)—Fig. 5 b, f–h. The former were typically embedded in an amorphous matrix (similar to Pd in the freshly prepared catalyst)—Fig. 5c, d, g—and displayed shells (also amorphous), but the latter had clean surfaces (Fig. 5h). In the fresh catalyst, several particles of the rhombohedral polymorph of In<sub>2</sub>O<sub>3</sub> have been found. Table 1 quickly summarizes the main findings of the XRD

**Fig. 4** TEM and HRTEM images of co-precipitated and impregnated Pd–In<sub>2</sub>O<sub>3</sub> catalysts: **a–c** freshly prepared by co-precipitation and calcination in air at 773 K; **d–f** co-precipitated, after the MSR run; **g–i** impregnated, after the MSR run. Insets in **c**, **e**, **f** examples of power (FFT) spectra used for phase identification and determination of crystal orientation of indicated phases. Black arrows in **c** point to Pd particles, in **f** to In<sub>2</sub>O<sub>3</sub> shells on InPd particles. Elemental Pd in the fresh catalyst is due to e-beam reduction of PdO in the electron microscope



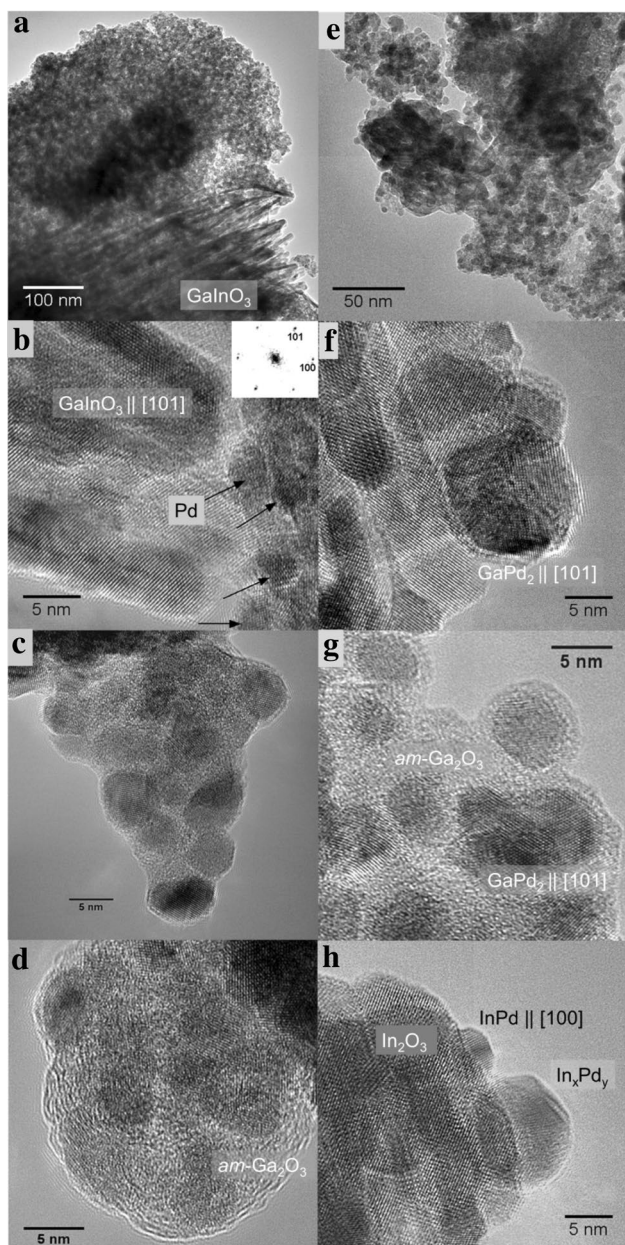
and TEM work in direct comparison with the catalytic findings, discussed in Sect. 3.2.

### 3.2 Catalytic Characterization in Methanol Steam Reforming

The respective catalytic patterns are shown in Fig. 6. For all of the studied catalytic materials, the methanol conversion and CO<sub>2</sub> selectivity are shown as a function of the time-on-stream. To focus on eventual deactivation, long-term experiments up to 12 h time-on-stream have been performed. In order to highlight possible activity and selectivity improvements by the co-precipitation preparation, the catalytic properties are directly compared to those of already well established impregnated materials.

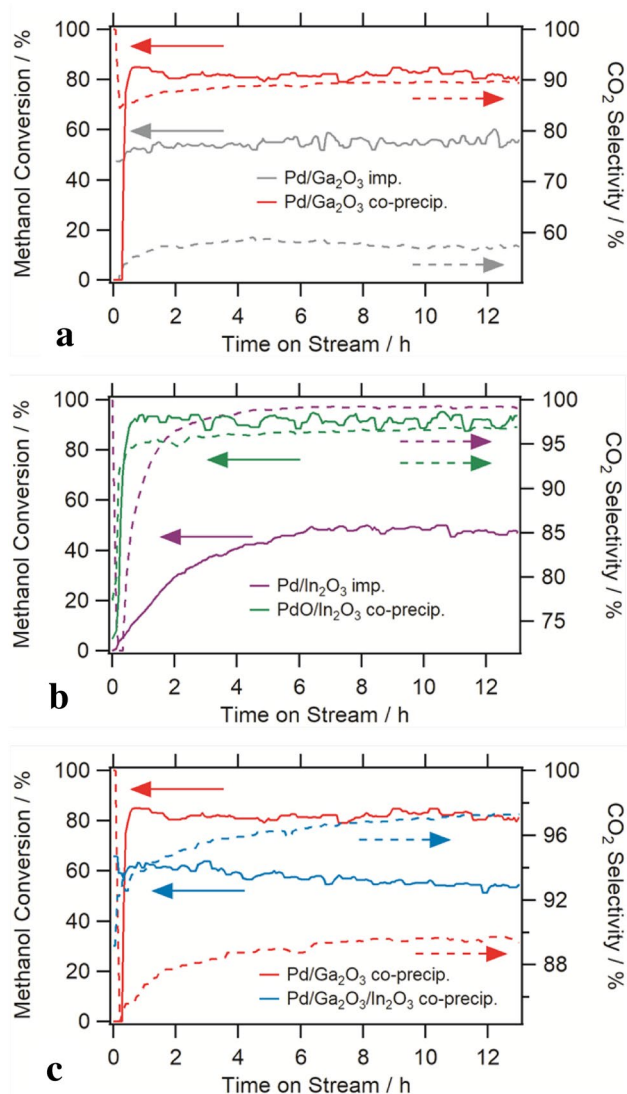
The catalytic data in Fig. 6a for the Pd–Ga<sub>2</sub>O<sub>3</sub> materials show that in contrast to the impregnated Pd–Ga<sub>2</sub>O<sub>3</sub> catalyst, which exhibits a comparably low activity (58% methanol conversion) and a low CO<sub>2</sub> selectivity (~59%), the co-precipitated Pd–Ga<sub>2</sub>O<sub>3</sub> catalyst displays a much higher CO<sub>2</sub> selectivity at around 90% (increasing from 88 to 91% in the course of the reaction), with an at the same time also much improved conversion (82%). Deactivation on the time scale

of the experiment is clearly absent for both systems. The observed catalytic patterns are interesting from a structural point of view, since both the HRTEM and the XRD data reveal that in both cases, a GaPd<sub>2</sub> phase has formed after reduction/during the catalytic treatment. Slight compositional variations have been monitored, but without structural breakdown of the GaPd<sub>2</sub> phases. The results therefore directly prove what has already been derived from corresponding studies on support-free bulk GaPd<sub>2</sub> intermetallic compounds:[8] the mere presence of the GaPd<sub>2</sub> intermetallic compound is not enough to enable a high CO<sub>2</sub> selectivity in methanol steam reforming. Rather, a synergistic action between intermetallic and oxidic support material must take place to enhance the water splitting capability of the intermetallic-oxide interface. Exactly this beneficial interface seems to be formed by co-precipitation, which then directly gives rise to improved CO<sub>2</sub> selectivity. In the Pd–Ga<sub>2</sub>O<sub>3</sub> case, co-precipitation also causes the exclusive formation of a GaPd<sub>2</sub>-rhombohedral Ga<sub>2</sub>O<sub>3</sub> (α-Ga<sub>2</sub>O<sub>3</sub>) interface, which apparently is also active and selective in methanol steam reforming. The presented catalytic properties of this co-precipitated GaPd<sub>2</sub>/α-Ga<sub>2</sub>O<sub>3</sub> material moreover strongly resemble similar studies of GaPd<sub>2</sub>/α-Ga<sub>2</sub>O<sub>3</sub> catalysts, where



**Fig. 5** TEM and HRTEM images of the co-precipitated Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> catalyst **a–d** freshly prepared by co-precipitation and calcination in air at 773 K; **e–h** co-precipitated, after the MSR run. Inset in **b** example of powder spectra used for phase identification and determination of crystal orientation. Black arrows in **b** point to Pd particles. Elemental Pd in the fresh catalyst is due to e-beam reduction of PdO in the electron microscope

$\alpha$ -Ga<sub>2</sub>O<sub>3</sub> was impregnated by small Pd particles and subsequently subjected to hydrogen reduction to induce the formation of GaPd<sub>2</sub> intermetallic particles [8]. The increase of activity and selectivity could also be explained by remnants of elemental Pd after pre-reduction, which are successively transformed into GaPd<sub>2</sub> during methanol steam reforming (which might be easier if the metal-oxide interface is more extended).



**Fig. 6** Comparative methanol steam reforming reaction profiles measured on a set of Pd–Ga<sub>2</sub>O<sub>3</sub>, Pd–In<sub>2</sub>O<sub>3</sub> and Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> catalysts. **a** shows the comparison of methanol conversion and CO<sub>2</sub> selectivity vs. time-on-stream between a conventionally impregnated Pd–Ga<sub>2</sub>O<sub>3</sub> catalysts and a co-precipitated one. In **b** the same is highlighted for the Pd–In<sub>2</sub>O<sub>3</sub> systems. **c** Finally shows the comparison between an In<sub>2</sub>O<sub>3</sub>-doped Pd–Ga<sub>2</sub>O<sub>3</sub> catalyst and an accordingly In<sub>2</sub>O<sub>3</sub>-free material. Prior to the methanol steam reforming reaction (molar ratio methanol:water = 1:1) at 573 K, pre-oxidation at 673 K in oxygen for 1 h, as well as pre-reduction in hydrogen (1 h) has been performed. Pre-reduction for Pd–In<sub>2</sub>O<sub>3</sub> and Pd–Ga<sub>2</sub>O<sub>3</sub> 523 K, for Pd–Ga<sub>2</sub>O<sub>3</sub>–In<sub>2</sub>O<sub>3</sub> 473 K. Solid lines represent conversion, dashed lines refer to CO<sub>2</sub>-selectivity

A slightly different pattern is observed for the Pd–In<sub>2</sub>O<sub>3</sub> catalysts (Fig. 6b). Here, the structural situation of both co-precipitated and impregnated catalysts is less complex, since, in both cases, after reduction and during catalysis, only cubic In<sub>2</sub>O<sub>3</sub> and (compositionally slightly variable) InPd as the main phases are present. This is then directly reflected in the trends of the activity and CO<sub>2</sub> selectivity. In both cases,



CO<sub>2</sub> selectivities of > 95% have been obtained. The methanol conversion of the co-precipitated InPd/In<sub>2</sub>O<sub>3</sub> catalyst, is however, much higher (90 vs. 40% on the impregnated one).

Finally, Fig. 6c reveals how the CO<sub>2</sub> selectivity of a co-precipitated GaPd<sub>2</sub>/Ga<sub>2</sub>O<sub>3</sub> can be directly improved by promotion with In<sub>2</sub>O<sub>3</sub>. In comparison to the former, the CO<sub>2</sub> selectivity of the latter can be improved from 90 to almost 98%. The methanol conversion of the In<sub>2</sub>O<sub>3</sub>-doped material at 60% is somewhat lower than that of the undoped sample (80%) and decreases slightly in the course of the reaction, indicating some deactivation.

## 4 Conclusions

We have shown how the catalytic properties of already well-established intermetallic methanol steam reforming catalysts on Pd basis, namely GaPd<sub>2</sub>/Ga<sub>2</sub>O<sub>3</sub> and InPd/In<sub>2</sub>O<sub>3</sub>, can be steered and exemplarily improved by a co-precipitation approach to synergistically alter the intermetallic compound-supporting oxide interface. This is especially evident for the GaPd<sub>2</sub>-Ga<sub>2</sub>O<sub>3</sub> catalyst, where the use of co-precipitation gives rise to a selectivity improvement also for the undoped GaPd<sub>2</sub> sample, which can be further beneficially influenced by In<sub>2</sub>O<sub>3</sub> doping. This improvement can be achieved despite the increased structural complexity and chaotic morphology of the GaPd<sub>2</sub>/InPd/Ga<sub>2</sub>O<sub>3</sub>/In<sub>2</sub>O<sub>3</sub> material. Apparently, the presence of a variety of distinct support- and intermetallic particle phases is not detrimental to activity/selectivity as long as the appropriate intermetallic phases are present and exhibit optimized intermetallic-support phase boundary dimensions.

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