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Accepted Article

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Optimizing Ni-Fe-Ga alloys into Ni\textsubscript{2}FeGa for the hydrogenation of CO\textsubscript{2} into methanol

Thomas E. L. Smithsuysen\textsuperscript{[a]}, Monia R. Nielsen\textsuperscript{[b]}, Tim Pruessmann\textsuperscript{[c,d]}, Anna Zimina\textsuperscript{[c]}, Thomas L. Sheppard\textsuperscript{[c,d]}, Jan-Dierk Grunwaldt\textsuperscript{[c,d]}, Ib Chorkendorff\textsuperscript{[a]}, Christian D. Damsgaard\textsuperscript{[a,b]}

Abstract: A screening study of the catalytic performance of ternary alloy nanoparticles containing nickel, iron and gallium supported on silica for methanol synthesis from CO\textsubscript{2} and H\textsubscript{2} was performed. Catalysts were prepared by incipient wetness impregnation and subsequently reduced in H\textsubscript{2} before catalytic testing. Ni\textsubscript{2}FeGa showed the best performance of the tested catalysts in terms of methanol yield. An optimization of the preparation was done to improve activity and selectivity, reaching performance close to that of prepared commercially available Cu/ZnO/Al\textsubscript{2}O\textsubscript{3}/MgO at low reaction temperatures and pressure. Extensive in situ characterisation using environmental TEM, in situ XRD and in situ EXAFS of the formation of the Ni\textsubscript{2}FeGa catalyst explains an optimal reduction temperature of 550°C: warm enough that the three atomic species will form an alloy while cold enough to prevent the catalyst from sintering during the formation.

Introduction

Human energy consumption is both a current and urgent issue, due to its direct relation towards increased financial needs and the impact on nature as a whole, for example the current prevalence of fossil-based carbon feedstock beings an anthropogenic source of global warming. The present problem of having an energy infrastructure mainly running on carbon-fuels could be mitigated by utilizing the emitted CO\textsubscript{2} for synthesizing fuels, thus having a closed sustainable loop of combustion and recycling. The methanol economy presents such a scenario, where CO\textsubscript{2} from point-sources in the short term and air-capture in future endeavours is reacted with H\textsubscript{2} to create methanol\textsuperscript{[1-4]}. Having H\textsubscript{2} produced from renewable electricity by electrolysis makes this fuel feedstock sustainable. The bulk chemical of methanol is a resource used both as a combustion fuel or additive to gasoline and more importantly as a feedstock for synthesizing other products such as formaldehyde, dimethyl ether, acetic acid and olefins\textsuperscript{[5]}. The commercial production of methanol uses syngas reacted over Cu/ZnO/Al\textsubscript{2}O\textsubscript{3}\textsuperscript{[6-9]}, where the syngas consisting of a mixture of H\textsubscript{2}, CO\textsubscript{2} and CO is mostly supplied from steam reforming of natural gas or gasification of coal. This methanol catalyst system has been highly optimized through the last century with typical working conditions around 200-300 °C and 50-100 bar pressure, but with the drawback that sintering of Cu nanoparticles reduces their activity over time\textsuperscript{[10,11]}. Furthermore CO in the feed-gas is necessary to thermodynamically hinder the production of water from CO\textsubscript{2} through the reverse water gas shift reaction (rWGS) which inhibits the methanol synthesis\textsuperscript{[12-15]}. The desire to use mainly CO\textsubscript{2} as a carbon-source therefor requires new catalysts that are able to suppress the rWGS by higher selectivity. Given the potential of methanol as a sustainable energy carrier on a global scale\textsuperscript{[16-19]} and the need for utilizing delocalized production in more rural and underdeveloped regions, there is a desire to develop novel catalysts that work sufficiently at lower pressure and temperature than the current large methanol plants and with sufficient selectivity and resistance to sintering.

A development from the well-established Cu/ZnO is the use of post-transition metals such as gallium and indium. Even though these materials are much more costly than Cu and Zn, they behave differently to their industrial counterparts making them interesting for research into novel catalysts. One rather unconventional reaction mechanism discovered is the active site formed by producing water, leaving oxygen vacancies in In\textsubscript{2}O\textsubscript{3}, which gets remedied by CO\textsubscript{2} bonding and formation of methanol since the reaction-pathway for forming CO is not energetically favoured\textsuperscript{[15,14]}. Experimental work showed that In\textsubscript{2}O\textsubscript{3} is very selective and stability-wise outperforms Cu/ZnO/Al\textsubscript{2}O\textsubscript{3} when reacting CO\textsubscript{2} and H\textsubscript{2} in 1:4 at 300 °C and 5 MPa\textsuperscript{[15,16]}. Improvement of this catalyst has been achieved through doping of metals e.g. Pd\textsuperscript{[17-19]}. Also reported is the use of Ga\textsubscript{2}O\textsubscript{3}/Pd by Fujitani et al. which at the time competed well with the Cu/ZnO based catalyst\textsuperscript{[20]}. For the renowned Cu/ZnO/Al\textsubscript{2}O\textsubscript{3}, Ga\textsubscript{2}O\textsubscript{3} has been used as a structural promoter for dispersing the copper\textsuperscript{[21]},
but also actively promoting the reaction. Medina et al. investigated Cu-Ga supported on silica, where it was found that gallium improved the methanol selectivity and the intrinsic activity of Cu[24]. They found using in situ DRIFTS that formate species were adsorbed on Ga₂O₃ and suggested that Ga₂O₃ promoted the formation of methanol by adsorbing carbon-species and using H₂ migrating from metallic copper.

Apart from using solid oxides, forming intermetallics of transition metals with gallium or indium as very active catalysts has been achieved with good results in the last decade. Well-known methanation and Fischer-Tropsch catalysts have been adjusted this way towards making methanol. Most notably is the PdₓGaₚ₋ₓ that has been reported as a very active methanol catalyst with an intrinsic activity at least double that of Cu/ZnO/Al₂O₃[26] Pd-based intermetallics such as PdₓGaₚ and PdZn[30] have also shown able to perform the syngas-to-dimethyl ether reaction with notable activity and doing so more selectively and stable than Cu/Zn. Pd-In and Ni-In alloys has also been synthesized[31,32], where the similar Pd-In proved most active but the InₓPd was much more selective, explained by the fact that the indium is partly oxidized in the InₓPd-alloy[32]. Furthermore Co-Ga[33] and Ni-Ga[34-36] catalysts have been discovered based on determination and optimizing of the rate-limiting reaction step based on work done by Grabow et al. on the Cu(111) face[37]. Especially the NiₓGaₚ has been found to be the most active, but the catalyst struggles through deactivation by coking[38].

Given the previous success of making active catalysts for methanol synthesis using alloys composed of gallium together with other transition metals, the research presented in this article will evolve around the compositional phase-space of Ni-Fe-Ga. Recent papers showing ternary alloys for hydrogenation of alkynes[38,39] inspired the screening of NiₓFeₓGaₚ for methanol synthesis presented in this article, especially the Heusler alloys[40,41] which are a frequent intermetallic crystalline phase for ternary transition metal alloys.

In this work a screening consisting of five different NiₓFeₓGaₚ/SiO₂ has resulted in an active NiₓFeₓGaₚ/SiO₂ catalyst. Afterwards this catalyst has been optimized in its synthesis procedure and studied using in situ characterisation methods. The final catalyst is one that selectively produce methanol at 160-200°C and is stable for 100+ hours at 190°C. At high temperatures beyond 200°C it suffers from lower selectivity and activity compared to commercially supplied Cu/ZnO/Al₂O₃/MgO.

Results and Discussion

Ni-Fe-Ga/SiO₂ survey study

Catalytic performance of the Ni-Fe-Ga/SiO₂ catalysts. To find an optimized composition of Ni-Fe-Ga/SiO₂, five different catalysts with variable Ni:Fe:Ga concentrations were prepared for the methanol synthesis reaction, all reduced at 800 °C for eight hours in H₂ directly before running the reaction. The starting point was taken from the Heusler intermetallic of NiₓFeₓGa (expected nominal composition), which has been produced as supported nanoparticles before[42], and making different catalysts with increasing amount of gallium in them, and so Niₓ₂FeₓGa₁₃ and NiFeGa₂ were also tested. Additionally the binary alloys of NiFe and FeGa were tested: NiFe since it was desired to try a catalyst in the setup that did not contain gallium even though Ni-Fe alloys have already been reported[43] and FeGa because Fe-Ga alloys have to our knowledge not been published for any catalytic reaction. Testing the catalytic activity of pure iron and nickel were not performed, as they are well known hydrocarbon-catalysts[44-46]. In Figure 1 the yield of methanol and selectivity are shown recorded at different temperatures.

Regarding the activity of the tested catalyst, the stoichiometric Heusler NiₓFeₓGa reached the highest methanol rate, though compared to Cu/ZnO/Al₂O₃/MgO under similar conditions in Figure 3, it have only one third of the activity. Increasing the content of gallium reduced the rate of methanol formation but increased the selectivity to methanol. With the lowest methanol rates and selectivities are NiFe and FeGa: NiFe because it produced much more CO and methane as shown in Figure S2 in the supplementary. Dimethyl ether was not measured beyond the detection limit. Uncertainties are estimated by propagation of error.

Figure 1. Top, the methanol yield per mole of Ni, Fe and Ga. Bottom, the methanol selectivity of the tested Ni-Fe-Ga/SiO₂. The noted composition is the expected nominal composition. FeGa is neglected from the selectivity because it did not produce a measurable amount of any detected gasses. Reaction conditions: 1.2 bar, 100 ml/min of CO₂H₂ in 1:3, GHSV of 8000 h⁻¹ and a GHSV of 8000 Nm³ h⁻¹. Detected by-products are CO, CH₃ and C₂H₄ and concentrations of these are shown in Figure S2 in the supplementary. Dimethyl ether was not measured beyond the detection limit. Uncertainties are estimated by propagation of error.

Besides the different activities, all the catalyst behaved in the same manner, showing decreased methanol formation rate at elevated temperatures, which is due to the increased CO production inhibiting the methanol equilibrium through the production of water by RWGS. All catalysts showed optimum methanol yield at temperatures around 210 °C though this optimum is readily controlled by the gas velocity.
Crystalline phase and chemical composition of Ni-Fe-Ga catalysts. To support the activity experiments, characterization of the catalysts was done ex situ to the activity experiments using XRD, TEM and SEM-EDX. Table 1 shows the macroscopic composition of Ni, Fe and Ga normalised to a Heusler stoichiometry (sum of four). Here it is apparent that within a standard deviation, the expected nominal and measured composition prior and after catalytic experiments are the same, except for the FeGa where prior and post composition differs little from a single standard deviation. Therefore the different catalysts will be referred to with their nominal composition.

Table 1. Collection of results for the different catalysts in the survey-study, including EDX spectroscopy and particle diameter estimated with ex situ TEM and ex situ XRD. The nominal composition is based on the weighted precursor nitrate-salts. Values in parenthesis denote the standard deviation on the last digit based on the sample collection.

<table>
<thead>
<tr>
<th>Target</th>
<th>Nominal</th>
<th>EDX Pre-test</th>
<th>EDX Post-test</th>
<th>TEM D(r) [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni2FeGa</td>
<td>Ni2FeGa</td>
<td>Ni2FeGa</td>
<td>Ni2FeGa</td>
<td>7.4(3.7)</td>
</tr>
<tr>
<td>Ga</td>
<td>Ga</td>
<td>Ga</td>
<td>Ga</td>
<td></td>
</tr>
<tr>
<td>Ni1.3FeGa0.3</td>
<td>Ni1.3FeGa0.3</td>
<td>Ni1.3FeGa0.3</td>
<td>Ni1.3FeGa0.3</td>
<td>5.6(1.5)</td>
</tr>
<tr>
<td>Ga</td>
<td>Ga</td>
<td>Ga</td>
<td>Ga</td>
<td></td>
</tr>
<tr>
<td>NiFeGa2</td>
<td>NiFeGa2</td>
<td>NiFeGa2</td>
<td>NiFeGa2</td>
<td>6.0(2.6)</td>
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<tr>
<td>NiFe</td>
<td>NiFe</td>
<td>NiFe</td>
<td>NiFe</td>
<td>8.0(3.4)</td>
</tr>
<tr>
<td>FeGa</td>
<td>FeGa</td>
<td>FeGa</td>
<td>FeGa</td>
<td>9.2(3.2)</td>
</tr>
</tbody>
</table>

Figure 2. Left, XRD of the tested Ni-Fe-Ga/SiO2 catalysts acquired after catalytic reaction. Lines denote reference-patterns of a face centred cubic lattice and a body centred cubic lattice, with a cubic unit-cell length of 3.6 Å and 2.9 Å. Stars denote a crystal-structure of diamond with lattice-length 3.55 Å. X-ray source was a Cu-Kα with wavelength 1.5418 Å. Top right, High resolution TEM of Ni2FeGa/SiO2 with Fourier transform denoting fcc crystal-planes. Bottom right, bright field TEM of Ni2FeGa/SiO2.

tetragonal Heusler, Ni2FeGa has been shown to be able to undergo the martensitic transformation similarly that of iron going continuously from a bcc to an fcc structure, both for alloyed ribbons and for large single crystals. Therefore it is likely that Ni-Fe-Ga alloyed nanoparticles individually pick between fcc and bcc phases dependent on small fluctuations in the local atomic environment or the chemical composition of the three components. The compositions were found to fluctuate from nanoparticle to nanoparticle, as ex situ STEM-EDX and STEM-EELS of Ni2FeGa shows, Table S2 in the supplementary. This observation also substantiates the claim that ternary-alloyed nanoparticles have been made.

BF-TEM images like the one shown in Figure 2, bottom right, were acquired for all the tested catalysts, exemplified in Figure S4 in the supplementary information. Size distributions based on BF-TEM in Table 1 show a trend, where more gallium-rich alloys produce smaller nanoparticles. FeGa and NiFe have on average 2.6 nm larger nanoparticles than the gallium-containing ternary alloys. For the ternary alloys the resulting nanoparticles are smaller, where the largest nanoparticles are Ni2FeGa are also the ones with the highest methanol yield. Thus the difference in activity towards making methanol is not explained by difference in surface areas.

In part conclusion, addition of gallium has changed the selectivity of Ni-Fe catalysts from methane towards methanol. Furthermore the survey has shown that there is an optimum of gallium content for improving the activity, but this can be done only at the expense of selectivity.

Optimization of Ni2FeGa/SiO2

Catalytic performance of the Ni-Fe-Ga/SiO2 catalysts. Following the screening-study, the most active catalyst i.e. Ni2FeGa/SiO2 was optimized further in terms of reduction temperature. 800 °C in high concentrations of H2 for eight hours was initially chosen based on literature. Therefore visible within the sample nanoparticle. Even in the case where an intermetallic long-range order is achieved of either Heusler or
samples of NiFeGa/SiO₂ were prepared by 4 hours of reduction at 300 °C, 400 °C, 500 °C, 550 °C, 600 °C and 700 °C respectively, after which they were all tested for their catalytic activity. Figure 3 shows the outcome in terms of methanol yield and selectivity both in terms of reduction temperature and compared to our prepared sample of the commercially available Cu/ZnO/Al₂O₃/MgO.

The most similar catalyst would be NiFeGa/SiO₂, which is similar in activity compared to Cu/ZnO/Al₂O₃/MgO. The obtained activity of NiFeGa showed that nanoparticles were very hard to detect until heating the sample to 300 °C. The area illuminated during heating is shown in Figure S11 of supplementary, showing that nanoparticles are not visible at 200 °C. Figure 4 presents HR-TEM images taken at 300 °C and 500 °C alongside size-distributions made for these temperatures. The atomic planes found with HR-TEM show both metallic nanoparticles with close-packed planes of ~2.1 Å agreeing with the ex situ XRD, and particles with larger interplanar distances of 2.4 Å and 2-9 Å which could be oxides. Here it has been found that the nanoparticles grew in size from an average of 3.4 nm to 3.8 nm when heating from 300 °C to 500 °C. During the microscopy, STEM-EDX was performed on individual nanoparticles by parking the beam and acquiring an EDX-spectrum. The quantifications of all the spectra are gathered in Table S3 in the supplementary.

A clear optimum in catalytic performance is found when the NiFeGa/SiO₂ has been reduced at 550 °C for 4 hours, both in terms of methanol yield and selectivity, where both values are increased two-fold compared to the sample reduced at 800 °C for 8 hours. As Figure 3 Top clearly shows there is an increase and decrease in both methanol yield and selectivity around the reduction temperature of 550 °C, showing that two different formation processes must take place at low and high reduction temperatures. NiFeGa reduced at 550 °C performs similarly at low temperature as the Cu/ZnO/Al₂O₃/MgO but is outperformed at higher temperatures as Figure 3 bottom shows. In literature the most similar catalyst would be NiGa/SiO₂ reported by Studt et al., which is similar in activity compared to Cu/ZnO[34] and thus also more active than NiFeGa. The obtained activity of NiFeGa in this work is achieved with lower gallium content and with a 150 °C decrease in reduction temperature compared to NiGa/SiO₂ as it was reported[34].

Especially at reaction temperatures above 200 °C, the NiFeGa performance falls short of the Cu/ZnO/Al₂O₃/MgO, which is due to the lower activity of NiFeGa and poisoning through coking at higher temperatures. On repetition of the catalytic test, the NiFeGa had lost almost half its activity after being heated to 250 °C in reaction conditions. It could easily be regenerated through reduction in H₂ producing methane and methanol in the process. This is shown in Figure S7-8 in the supplementary. Long-term stability test of NiFeGa/SiO₂, as is shown in Figure S8 right, showed an initial decrease in activity over a course of hours before keeping a stable methanol yield and selectivity for 100 hours. Upon reactivation in H₂, the initial activity and selectivity are obtained.

Based on size-distributions from an ex situ TEM analysis of the NiFeGa/SiO₂ catalysts reduced at >550 °C, surface activity has been estimated and found not to be significantly different for these samples, which means that loss in activity due to a higher reduction temperature is mainly due to decrease in surface-area through sintering. This is shown in Figure S10 of the supplementary in terms of size distributions and surface activity versus reduction temperature plots.

In situ investigation into the reduction and thereby the formation of NiFeGa/SiO₂. To understand the properties achieved through reducing at different temperatures and why 550 °C is an optimum, several in situ methods were utilized during the reduction of metal-nitrates into the NiFeGa/SiO₂, which are E-TEM, XRD and XANES/EXAFS.

Environmental Transmission Electron Microscopy. Visualization of a fresh non-reduced sample of NiFeGa showed that nanoparticles were very hard to detect until heating the sample to 300 °C. The area illuminated during heating is shown in Figure S11 of supplementary, showing that nanoparticles are not visible at 200 °C. Figure 4 presents HR-TEM images taken at 300 °C and 500 °C alongside size-distributions made for these temperatures. The atomic planes found with HR-TEM show both metallic nanoparticles with close-packed planes of $\sim 2.1 \text{ Å}$ agreeing with the ex situ XRD, and particles with larger interplanar distances of 2.4 Å and 2-9 Å which could be oxides. Here it has been found that the nanoparticles grew in size from an average of 3.4 nm to 3.8 nm when heating from 300 °C to 500 °C. During the microscopy, STEM-EDX was performed on individual nanoparticles by parking the beam and acquiring an EDX-spectrum. The quantifications of all the spectra are gathered in Table S3 in the supplementary.

Figure 4. Left, in situ HR-TEM images, at 300°C a large oxide particle with interatomic spacing of 2.4 Å and 2.9 Å, and two small metallic nanoparticles showing $\sim 2.1 \text{ Å}$ interatomic spacing. At 500°C the quantity of the latter having fringes of 2.1 Å has increased. Right, size-distribution based on in situ TEM images, showing a small increase in the sizes of the nanoparticles at higher temperature.
Due to time constraints only 9 individual spectra were acquired which is not nearly statistically significant. Nonetheless comparing STEM-EDX with SEM-EDX of the whole sample stated in Table S4 in the supplementary, show that on average the concentration of iron and gallium is lower than the macroscopic measurement. Thus, if the nanoparticles are representative, the different Ni-species are reduced more than the corresponding Fe- and Ga-species. This corresponds very well to the fact that oxides such as FeO and Ga2O3 have a higher formation enthalpy and are harder to reduce compared to NiO.2,5 This also means that an enlargement of the nanoparticles from 300 °C to 500 °C is not sintering, as this would show on the yield per mass of methanol, but instead the reduction of new species that alloy in the nanoparticles.

In Situ X-ray Diffraction. Reducing the metal-nitrates into Ni3FeGa/SiO2 in H2 while performing XRD showed large changes of the crystalline structure together with production of various gases measured by QMS, both results shown in Figure 5 and 6. From the XRD Fig. 5, broad peaks appear at 100-300 °C producing 2θ-peaks at ~35° and ~60°, which can very well be Fe2O3 (ICSD cc.: 15840), Fe3O4 (ICSD cc.: 26410) or Ga2O3 (ICSD cc.: 34243). Metal nitrates decomposing into solid oxides agrees well with the QMS Fig. 6, where at 100 °C multiple species are produced being H2O, NO, and CO2, and at 200 °C N2 is produced. H2O rises again at 250 °C, which correlates with a 2θ-peak at 43° appearing in the XRD pattern. This corresponds very well to an fcc phase of Ni (ICSD cc.: 43397) or NiFe (ICSD cc.: 5116, 103555, 103559), especially because the peak intensifies as the temperature rises together with corresponding fcc-peaks appearing at 350°C. In principle the 2θ-peak at 43° could also be FeO (ICSD cc.: 31081) or NiO (ICSD cc.: 9866) as these would be intermediates before forming metallic nanoparticles but if this is the case, they are very ephemeral. At 550 °C H2O rises again, very well corresponding to Ga2O3 finally being reduced and alloying into the metallic nanoparticles, which is showing as two new 2θ-peaks appearing at 75° and 51° at very low intensity at 650°C and 750°C. 2θ-peaks at 44°, 51° and 75° resembles a bcc phase corresponding to the Heusler crystal structure of Ni3FeGa (ICSD cc.: 157384), though it might not be intermetallic but random in its atomic positions. In conclusion this means that from lower to higher temperatures, the nanoparticles appear to transition from pure Ni into Ni-Fe and finally in the ternary alloyed Ni-Fe-Ga, when the temperature is high enough that Fe and Ga can be reduced. This agrees with the in situ ETEM where it has been concluded that small nanoparticles at low temperatures are containing mostly nickel.

In Situ X-ray Absorption Spectroscopy. The real-space Fourier-transform of the extended fine structure of all the measured edges are shown in Fig. 7. The results show for all edges that when heating in H2, amplitudes from back-scattering on the nearest neighbour elongate from ~1.8 Å to 2.2 Å. Furthermore at well above 200 °C, this structure is still apparent. Since the nitrate-salts will be decomposed at such temperatures as the mass spectroscopy from the in situ XRD shows in Figure 5, this must be scattering from an oxygen neighbour showing that the metals are only partially reduced at lower temperatures. Comparing the different edges it is also obvious that nickel is reduced much more easily than iron and drastically more than gallium, which agrees with the analysis from the in situ XRD and ETEM. Linear combination fitting of the XANES using the oxides and the metal at the corresponding edge gave additional insight into the reduction behavior (Figure S16 in the supplementary information). All the edges show intermediate species of oxides when heating from low to high temperatures in agreement with EXAFS and XRD as well.

![Figure 5. in situ XRD of the formation of Ni3FeGa/SiO2 a fresh non-reduced sample, while heating the sample in 90% H2/He. Lines denote reference-patterns of a face centred cubic lattice and a body centred cubic lattice, with a cubic unit-cell length of 3.6 Å and 2.9 Å. X-ray source was a Cu-Kα-anode with wavelength 1.5418 Å.](image)

![Figure 6. Fourier-filtered Quadrupole Mass-spectroscopy of the outlet gas during in situ XRD. Parentheses denote the detected mass. All detected masses and unfiltered data are shown in Figures S12-14 in the supplementary.](image)

![Figure 7. In situ real-space represented K-weighted EXAFS of the formation of Ni3FeGa/SiO2 from a fresh non-reduced sample. Samples were heated at the denoted temperature in 5% H2/He, and subsequently cooled to 50°C for a proper acquisition of the absorption spectrum. Corresponding XANES are shown in Figure S16 in the supplementary. The dotted lines show fits to data acquired after heating at the highest temperature with parameters given in Table 2. Two separate samples were experimented on, firstly measuring the Ni and Fe K-edges, and subsequently measuring the Ga K-edge.](image)
was Fe nanoparticles hydrogenating CO synthesised, ternary alloy has been achieved after heating to 500°C. Debye-Waller factor of Ni, Fe and Ga are almost identical, which is exemplified in Figure S20 in the Supplementary info. Furthermore the direct back-ordering giving a well-alloyed nanoparticles, and thus there is not any long-range ordering giving a well-defined coherence in the absorption spectrum. Furthermore the direct back-scattering paths from Ni, Fe and Ga are almost identical, which is exemplified in Figure S20 in the Supplementary info. Looking at the Ga K-edge, this element is not fully reduced and alloyed shown by the scattering amplitudes were so correlated that only the sum could be determined by the data. The coordination number has been defined to this value, as the determined value of the amplitude S(2) from the reference foil is too low to keep fitting of the coordination number within physical limits. Ga2O3 has two non-equivalent positioned gallium-atoms within its unit-cell, meaning that three almost identical scattering paths happen within the first 1.91 Å. These paths have been collectively written in the table as a single O-neighbour of distance 1.81-1.91 Å and the coordination of 5.67 is the sum.

Fitting of the EXAFS spectra acquired after heating to the highest temperature are shown as dotted lines in Fig. 7 and the values for the fitting parameters are presented in Table 2. Looking at the values acquired from the Ni and Fe K-edges, they are almost identical in terms of coordination number, distance and Debye-Waller factor (thermal vibration), thus it is clear that they have a very similar atomic environment. This would certainly be the case if they alloy, though the data do not allow for distinguishing between Ni, Fe and Ga species in the fit. This is probably due to the fact that the sample consists of ternary alloyed nanoparticles, and thus there is not any long-range ordering giving a well-defined coherence in the absorption spectrum. Furthermore the direct back-scattering paths from Ni, Fe and Ga are almost identical, which is exemplified in Figure S20 in the Supplementary info. Looking at the Ni K-edge, this element is not fully reduced and alloyed shown by the scattering of an oxygen-atom. Furthermore, the coordination of the Ni/Fe/Ga neighbours is lower meaning that gallium resides more frequently at the surface. The scattering distances from Ga K-edge are equal to the corresponding paths for the Ni and Fe K-edges showing that the reduced gallium has alloyed and a ternary alloy has been achieved after heating to 500°C.

The best catalyst in this study was found to be Ni2FeGa/SiO2. After optimization of the catalyst preparation, the most active and selective catalyst was found by reducing in H2 at 550°C for four hours. This final catalyst was compared to a commercial copper-based methanol synthesis catalyst, achieving similar activity at temperatures below 200 °C, but higher temperatures caused the Ni2FeGa to suffer from lower selectivity and coking.

Comprehensive in situ characterisation of the Ni2FeGa using XRD, TEM and XAS showed how it can alloy from Ni-, Fe- and Ga-nitrate salts. The optimized reduction temperature of 550 °C is exactly the heat-limit at which the Ni2FeGa is forming in fully ternary metallic nanoparticles, but also cold enough that small nanoparticles are produced increasing the surface area.

Ni2FeGa/SiO2 cannot currently out-perform other state-of-the-art catalysts in the field, however, this work shows how the approach of using multiple species with different reduction potential can offer an advantage: producing small alloyed catalytically active nanoparticles.

**Experimental Section**

**Synthesis**

The synthesis of SiO2 supported Ni2FeGa nanoparticles was performed using incipient wetness impregnation and subsequent reduction in H2 at elevated temperatures. Nickel(II)nitrate hexahydrate (10816, Alfa Aesar), iron(III)nitrate nonahydrate (529303, Sigma-Aldrich) and gallium(III)nitrate hydrate (11150, Alfa Aesar) were diluted in millipore water and impregnated in ground high surface area silica powder (44740, Alfa Aesar) resulting in 16.7 wt% metal loading on SiO2. Nominal loadings and EDX analysis of composition can be found in Table 1 and Table S1, S2 in the supplementary info. The powder had a grain-size of 105-210 μm. Impregnated silica was subsequently dried for 2 hours at 80 °C in air after which they were loaded in quartz glass-tube

### Table 2: Fitting parameters of Ni2FeGa after being heated to ≥500°C: coordination number N, scattering length R, Debye-Waller factor o, γ-Ni2FeGa crystal structure was used for fitting the Ni and Fe K-edges, while both γ-Ni2FeGa and Ga2O3 was used for the Ga K-edge.

<table>
<thead>
<tr>
<th>Edge</th>
<th>Neighbour(s)</th>
<th>N</th>
<th>R(2) (Å)</th>
<th>o(2) (Å)</th>
<th>Residual factor</th>
<th>Fitting range (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni K</td>
<td>Ni/Fe/Ga</td>
<td>11.0 ±1.0</td>
<td>2.52 ±0.01</td>
<td>0.008 ±0.001</td>
<td>0.013</td>
<td>1.0 to 4.1</td>
</tr>
<tr>
<td></td>
<td>Ni</td>
<td>4.4 ±1.3</td>
<td>3.56 ±0.01</td>
<td>0.012 ±0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ni/Fe/Ga</td>
<td>15 ±4</td>
<td>4.36 ±0.01</td>
<td>0.014 ±0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe K</td>
<td>Ni/Ga</td>
<td>12.0 ±1.6</td>
<td>2.51 ±0.01</td>
<td>0.010 ±0.001</td>
<td>0.026</td>
<td>1.0 to 4.1</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>4 ±2</td>
<td>3.55 ±0.01</td>
<td>0.014 ±0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ni/Fe</td>
<td>15 ±6</td>
<td>4.35 ±0.01</td>
<td>0.018 ±0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ga K</td>
<td>O</td>
<td>5.7 ±0.3</td>
<td>1.81 ±0.02</td>
<td>0.006 ±0.004</td>
<td>0.010</td>
<td>1.1 to 4.0</td>
</tr>
<tr>
<td></td>
<td>Ni/Fe</td>
<td>6.4 ±0.4</td>
<td>2.51 ±0.01</td>
<td>0.011 ±0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe/Ga</td>
<td>2.2 ±0.5</td>
<td>3.55 ±0.01</td>
<td>0.016 ±0.001</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Ni/Ga</td>
<td>8.2 ±1.3</td>
<td>4.35 ±0.01</td>
<td>0.019 ±0.002</td>
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<td></td>
</tr>
</tbody>
</table>

[a] Change in Scattering-length and Debye-Waller factor have been fitted for each crystal structure, and not for each individual scattering-path. [b] Ni, Fe and Ga species could not be distinguished, as the scattering amplitudes were so correlated that only the sum could be determined by the data. [c] The coordination number has been defined to this value, as the determined value of the amplitude S(2) from the reference foil is too low to keep fitting of the coordination number within physical limits. [d] Ga2O3 has two non-equivalent positioned gallium-atoms within its unit-cell, meaning that three almost identical scattering paths happen within the first 1.91 Å. These paths have been collectively written in the table as a single O-neighbour of distance 1.81-1.91 Å and the coordination of 5.67 is the sum.

**Conclusion**

In this work, Ni-Fe-Ga supported nanoparticles were synthesised, characterised and tested for their catalytic ability in hydrogenating CO2. It was found that introducing gallium into Ni-Fe nanoparticles tunes the selectivity from producing methane into producing methanol. The binary FeGa without any nickel was unique in its inability to catalyse hydrogenation of CO2, though no further substantial analysis went into illuminating this property.
reactors to allow a plug-flow and heated using a tube furnace. Here they were reduced in 1.2 bar 90% H2 in Ar at 800°C for eight hours before being tested in the same reactor for their catalytic performance.

Pellets of CuO(63.5%)/ZnO(24.7%)/Al2O3(10.1%)/MgO(1.3%) (45776, Alfa Aesar) were purchased and ground to a grain-size of 105-210 μm and diluted with SiO2 (the same material used as the support of Ni2FeGa). The powder was loaded in a quartz glass-tube reactor and reduced in 1.2 bar 10% H2 in Ar at 220°C for 3 hours, then subsequently tested for its catalytic activity. The preparation of the commercial catalyst ensures that CuO is reduced to Cu. The choice of preparation is based on a TPR, shown in Figure S1 in the supplementary. Dilution of the commercial catalyst in SiO2 was done to achieve equal weight of Cu and Ni2FeGa while also having equal geometric dimensions of the reactor-bed. ZnO and MgO are here considered as being support-material of the commercial catalyst.

**Catalytic testing**

Directly after reducing the catalysts in the plug-flow reactor, the reactor was cooled down to 130°C and the gas-flow changed to 25% CO2, 75% H2 and traces of Ar at 1.2 bar, with a GHSV of 8000 h⁻¹ and a GHSV per weight of 130000 Ncm-3 h⁻¹. Exact weights of loaded catalyst are written in Table S1 in the supplementary. The reactor-temperature was changed step-wise up and down twice between 145°C and 250°C in 15 °C step and with 1.5 hours steady-state per step. Gas samples were collected approximately every 15 mins at the reactor-exhaust with a gas chromatograph (Agilent 7890a) mounted with a TCD and FID using an 80 mm QO4 capillary column on the FID line; 19095P-MS6 molecular sieve column on the TCD-line; 19091J-413 capillary column on the FID line. Any gas sample taken close to a temperature-change was discarded.

**Characterisation**

Transmission electron microscopy (TEM) and spectroscopy. After catalytic tests, samples were loaded on a 300-mesh lacy carbon Au TEM-grid (AGS166A3H, Agar Scientific). Bright-field imaging for nanoparticle size-distributions was performed in ultra-high vacuum on a Tecnai T20 G² (FEI) with a LaB6-thermionic filament operated at 200 kV. Size-distributions (Figure S9) were measured by drawing the outline of each observed nanoparticle, measuring the area and calculating a corresponding circular diameter. High Resolution TEM (HR-TEM) and STEM including energy dispersive X-ray spectroscopy (EDX) and electron energy loss spectroscopy (EELS) was performed in ultra-high vacuum on a Titan E-Cell 80-300ST TEM (FEI) with a FEG operated at 300 kV on two samples of Ni2FeGa/SiO2 after reduction and catalytic testing: one reduced at 500°C and one at 800°C (Figure S3).

**Powder X-ray diffraction (XRD).** Samples having undergone catalytic testing were pressed to pellets in steel-casings designed for powder XRD. The XRD was performed on the samples in an Empyrean (Malvern Panalytical) with a CuKα-anode. The diffracted beam was filtered through a monochromator and the sample was spun with 3.75 rotations/min.

**Scanning electron microscopy (SEM) and EDX.** Powder samples both before and after synthesis and test in the plug-flow reactor were loaded on Aluminium stubs with double carbon-tape. SEM-EDX was performed using a Quanta FEG 200 ESEM (FEI) operated at 20 kV and a 0.1 bar vapour pressure. EDX data was collected using an 80 mm² X-Max silicon drift detector (Oxford instruments) with 124 eV energy-resolution. The procedure was to scan the beam well within individual catalytic grains for between 30-60 seconds to gather a converged EDX-spectrum. A minimum of eight spectra were gathered for each individual sample.

**Environmental transmission electron microscopy and spectroscopy.** Impregnated sample of stoichiometry Ni2FeGa was ground and diluted in 1.2 bar propanol after which it was immediately drop-casted on a Nanochip XT through-hole chip (DENSSolutions), in minimal amount to allow for TEM-transparency. After drying in air the chip was loaded on a DENSSolutions Wildfire heating holder and loaded into a Titan E-Cell 80-300ST TEM (FEI) with a FEG operated at 300 kV. A continuous flow of H2 at 1.2 mbar was set and the sample was briefly viewed in TEM-mode and low magnification before heating the sample. The sample was heated chronologically to 200°C, 300°C and 500°C while during BF-TEM. At lowest magnification and a spread beam the sample was briefly investigated in order to find proper spots where the sample was sufficiently transparent. A spot was chosen for imaging when heating and cooling, and all other imaging was conducted on un-exposed areas in order to minimise beam damage. HR-TEM and STEM-EDX were performed interchangeably after heating to 300°C and 500°C.

In situ X-ray diffraction and quadrupole mass spectrometry (QMS). Impregnated sample of stoichiometry Ni2FeGa was loaded on a ceramic holder and mounted into a furnace with X-ray transparent beryllium windows (XRF 900, Anton Paar) situated within an Xpert Pro diffractometer (Malvern Panalytical) with a CuKα-anode. The diffracted beam was filtered through a monochromator. A continuous flow of H2 at 1 bar was set and with a gas velocity matching the synthesis and catalytic tests performed in the plug-flow reactor. The sample was heated to 750°C in steps of 50°C and with three diffraction-angle scans at each temperature over 1.7 hours. The gas-exhaust was monitored using QMS supplied by Pfeiffer. In order to filter mass-signals from heating and desorption of surface-condensed water, a high-frequency bandwidth-filter was applied to the QMS data. All raw data, filtering and resulting reduced data is available in Figure S13-15 in the supplementary. The Inorganic Crystal Structure Database (ICSD) has been used for recognizing different crystal structures and ICSD collection codes are noted in parentheses when discussed in the text.

In situ X-ray absorption spectroscopy (XAS). Impregnated sample of stoichiometry Ni2FeGa was loaded into a 1.5 mm(Ø) capillary with a bed length of 4 mm and a gas-flow of 5% H2 in He with pressure equilibrated with the atmospheric conditions. XAS experiments were performed at the CAT-ACT beamline at the synchrotron light facility at Karlsruhe Institute of Technology (KIT). Heating was performed with a gas-blower and Eurotherm heat regulator and energy was calibrated from a reference metal foil chosen dependent on the measured edge. Spectra for an analysis of the EXAFS were all acquired at 50°C after treating the sample at higher temperatures (see below), and quick XANES spectra were acquired while heating the sample. The procedure of the experiment was to heat the sample for a specific duration of time before cooling down to 50°C and acquiring a spectrum for EXAFS, then subsequently heating the sample again to a higher temperature. Two individual experiments were performed at different times with a modestly varying setup: one for acquiring the Ni and Fe K-edges with a gas-flow of 3 ml/min, and one for acquiring the Ga K-edge with a gas-flow of 50 ml/min. For the Ni and Fe K-edges the sample was heated to 248°C for 50 mins, 375°C for 30 mins and 581°C for 10 mins, all with a heating ramp of 40°C/min at which XANES of the Ni and Fe K-edges were acquired. For the Ga K-edge the sample was heated to 222°C for 50 mins, 339°C for 30 mins and 498°C for 10 mins, all with a heating ramp of 10°C/min at which XANES of the Ga K-edge was acquired. This procedure was devised during the experiment based on the time at which XANES of the Ni K-edge did not change noticeably.

Absorption was in all experiments measured in transmission mode with a reference foil: A Fe foil for the Fe K-edge, a Ni-foil for the Ni K-edge and a W-foil for the Ga K-edge. Data was calibrated and normalised using Athena and subsequently the EXAFS acquired after heating at the highest temperature were fitted using Artemis. Linear combination fitting has been done and is available in Figure S16-19 in the supplementary.

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