Understanding the structure of nanocatalysts with high resolution scanning/transmission electron microscopy

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Abstract. Nanomaterials including nanoparticles, nanowires and nanotubes play an important role in heterogeneous catalysis. Thanks to the rapid improvement of the electron microscopic techniques and with the advent of aberration corrected electron microscopy as well as theoretical methodologies, the potential effects induced by nanocatalysts are better understood than before by unravelling their atomic structure. A brief introduction to advanced electron microscopic techniques namely aberration corrected scanning transmission electron microscopy (Cs-STEM) is presented and subsequently two examples of nanocatalysts are considered in the present review. The first example will focus on the study of bimetallic/core-shell nanoalloys. In heterogeneous catalysis, catalysts containing two or more metals might show significantly different catalytic properties compared to the parent metals and thus are widely utilized in several catalytic reactions. Atom-by-atom insights of the nanoalloy based catalysts ex: Au-Pd will be described in the present review using a combination of advanced electron microscopic and spectroscopic techniques. A related example on the understanding of bimetallic clusters by HAADF-STEM will also be presented in addition to nanoparticles. In the second case understanding the structure of transition metal chalcogenide based nanocatalysts by HRTEM and aberration corrected STEM, for the case of MoS₂ will be discussed. MoS₂-based catalysts serve as model catalysts and are employed in the hydrodesulphurisations (HDS) reactions in the removal of sulphur from gasoline and related petrochemical products. They have been studied in various forms including nanowires, nanotubes and nanoplates. Their structure, atomic insights and as a consequence elucidation of their corresponding catalytic activity are thus important.

1. Introduction

Electron microscopic techniques present a very powerful approach to the systematic elucidation of structure of nanocatalysts and thereby enable correlation of their corresponding catalytic activity. In the case scanning/transmission electron microscopy (S/TEM) one employs different imaging modes to obtain different and yet complementary information of nanostructured catalysts. The common imaging modes include bright-field (BF), dark-field (DF) and phase contrast imaging [1]. In comparison to all these imaging modes the high-angle annular dark field (HAADF) imaging or Z-contrast imaging provides a significant advantage since in this case it is possible to differentiate alloys of two different materials from the difference related to their atomic number (intensity Iα atomic number Z₁.⁴⁶). In the case of aberration corrected electron microscopes HAADF-STEM
imaging technique offers extreme resolution limits and thus single atom imaging based on the Z-contrast is now routinely achieved. In combination with spectroscopic techniques such as energy-dispersive X-ray analysis (EDS) and electron energy loss spectroscopy (EELS) one can obtain single atom information combined with their corresponding chemical information [2]. Figure 1 shows a Z-contrast STEM simulation of single atoms of different elements, arranged in a 4x4 matrix. The line scan through the centre of the atomic positions is shown at the right of the simulated image. The trend follows approximately as $I \propto Z^{1.46}$ relation as shown by Pennycook [2].

![Z-contrast STEM simulation](image)

**Figure 1.** Profiles of intensity obtained from a series of HAADF-STEM simulated images (at a defocus of -41 nm). Note the intensity variation with the different elements. In each case the columns of elements have the same number of atoms.

In the field of catalysis, nanoalloys of transition metals have generated tremendous interest since they display structures and properties which are quite distinct and different from those of the pure elemental clusters: the structures of binary clusters may be quite different from the structures of the corresponding pure clusters of the same size. When two metals combine to form a nanoparticle there are two situations that can be produced: (i) either the particles form strictly what can be thought of as an alloy, or (ii) a core-shell structure is produced. In the former case, the two atomic species are distributed homogeneously on the particle; in the latter, a core of one of the metals is surrounded by a thin shell of the other metal forming a complex shape. Usually, the metal with larger size and lower surface energy will be on the outside layer, but the opposite may happen depending on the synthesis conditions. The core-shell structure is believed to be a very important factor affecting the electronic properties of the cluster. In reality, bimetallic particles are more complex. A nanoparticle might have an incomplete core or it may have a eutectic type of structure, where the two metals form separated particles joined in an interface. Understanding such an atomic structure is also not trivial [3]. Nanoscale transition-metal (TM) nanoparticles exhibit enormous complexity, with their structure and properties intimately connected and, at times, varying dramatically. Alloyed nanoparticles have been shown to improve catalytic, magnetic, optical, and biomedical properties needed in a wide range of applications. For example oxygen reduction reaction (ORR) electrocatalysts, consisting of Pt and another late transition metal (M, where M = Ru, Rh, Pd, Au), have a very high activity compared to that of pure Pt ORR catalysts [4]. Real-world bimetallic catalysts, usually composed of nanoscale bimetallic transition metal clusters well-dispersed on non-catalytic supports, lies at the heart of numerous important industrial applications. For example, late transition metal alloy catalysts are the
major working horses in the petroleum industry for the production of lead-free gasoline with high octane numbers and are indispensable ingredients in three-way catalysts used in combustion cars for substantially cutting down the environmentally-detrimental emission of NO\textsubscript{x} and CO [4]. In general, bimetallic systems offer many more possibilities than their single-metallic counterparts in tailoring surface physical and chemical properties, and therefore, represent a very promising field in which a rational design of novel and cost-efficient bimetallic catalysts and structure elucidation need to be achieved – a demanding challenge of the discipline in meeting our society's ever increasing demands for more environmentally benign and energy efficient technologies. The lack of detailed structural information at the atomic scale in real-world bimetallic catalysts under working conditions remains one of the major hurdles for an ultimate rational design of bimetallic catalysts for industrial applications [5].

In the present review a combination of aberration corrected STEM along with HRTEM imaging is presented to understand the nature and structure of nanocatalysts. Thus in the first example of nanocatalysts, bimetallic nanoparticles obtained by chemical routes are presented. Chemical routes can enable the production of metal nanoparticles with a well-controlled size and shape distribution. Bimetallic nanoparticles of Au-Pd find important applications in catalysis. Their catalytic performance is directly related to the structure, alloy formation and variation of composition in the structure. Although the standard idea is that bimetallic nanoparticles can be either an alloy or a core shell structure, in the present example a more complex structure has been shown. Thus the structure and composition of complex three-layered Pd-Au nanoparticles by using aberration corrected high angle annular dark field scanning transmission electron microscopy (HAADF-STEM) has been investigated. The investigations reveal that the nanoparticles are composed of an evenly alloyed inner core, an Au-rich intermediate layer, and a Pd-rich outer shell. The structure is more complicated than what simple models can predict. Additional studies of this system were also carried out to identify and understand the interface structure better. This was done by carrying out spectral and chemical analysis (STEM-EDS, STEM-EELS). Apart from the three-layered core-shell structures it has also been possible to observe in some cases a four-layered core-shell structure as well. The entire core-shell structure is not rigid and there is indeed intercalation of Au-Pd into the other layers as well. In addition stacking faults present in the nanoparticles have been located. The problem of the interface structure between the layers is also investigated and the results are presented [6, 7].

In the second example transition metal chalcogenide nanocatalysts are presented. Molybdenum disulphide/tungsten disulphide (MoS\textsubscript{2}/WS\textsubscript{2}) is a compound very useful for its properties; it is used as lubricant, catalyst in hydrodesulphuration, in hydrogen fuel storage, etc. [5]. Transition metal chalcogenides like MoS\textsubscript{2} or WS\textsubscript{2} are quasi two dimensional (2D) compounds. Atoms within a layer are bound by strong covalent forces, while individual layers are held together by van der Waals (vdW) interactions. Although there are a large number of polytypes observed in the case of the transition metal chalcogenides the most notable experimentally observed polytypes in the case of MoS\textsubscript{2} and WS\textsubscript{2} based on the stacking sequence of the layers are either a hexagonal polymorph with two layers in the unit cell – 2H (P6\textsubscript{3}/mmc) symmetry, rhombohedral with three molecular layers in the unit cell layers – 3R (R3\textsubscript{m}) symmetry and the less common trigonal with one layer – 1T. MoS\textsubscript{2} nanoplates that find important applications in catalysis have been investigated by using advanced electron microscopic techniques namely aberration corrected STEM and HRTEM [8].

For the electron microscopy analysis, the samples were dispersed in ethanol and a drop of this suspension was deposited onto a holey carbon grid. The samples were characterized using the aberration (Cs) corrected JEOL JEM-ARM200F (ARM) 200 kV FEG-STEM/TEM, equipped with a CEOS Cs corrector on the illumination system. The probe correction was performed through a dodecapole corrector (CEOS GmbH) aligned through the CESCOR software, to finally obtain a twelve-fold Ronchigram with a flat area of 50 mrad. The pixel spacing was calibrated using Si [110] lattice images in the HAADF mode, and confirmed by using gold standard particles. Images were commonly recorded for 10 to 16 s. The HAADF as well as the BF images were acquired using a digiscan camera. In order to reduce the noise of the images and to obtain clearer images the raw data
was filtered using the 2D Wiener filter and the Richardson-Lucy / maximum entropy algorithm implemented by Ishizuka. The EDS analysis was performed using EDAX instrumentation attached to the JEOL-ARM microscope. Spectra, line scans as well as chemical maps for the various elements were obtained using the EDAX Genesis software. One- and two-dimensional electron energy loss spectroscopy (EELS) analysis was performed with a GIF-Tridiem spectrometer.

2. Bimetallic nanoparticles

2.1. Nanoparticles obtained by chemical methods – The case of the three-layered Pd-Au-Pd nanoparticles

HAADF and BF images for nanoparticles with composition Au1Pd5 are shown in figures 2a and b, respectively. The three-layer structure observed in these nanoparticles was found to be dependent on the diameter. It was observed that 25 % of the nanoparticles had a diameter of 5.5 ± 1.3 nm, and only displayed two clear layers. The remaining 75 % of the nanoparticles showed a size of 12.7 ± 0.8 nm, with three layers being evident.

![Figure 2](image)

Figure 2. (a) Low magnification HAADF, and (b) BF-STEM images of Au-Pd nanoparticles obtained by successive reduction of monometallic ions.

A closer look at the nanoparticles is provided by the ultra-high resolution HAADF images of the nanoparticles in figure 3. From the image (figure 3a) it can be seen that formation of the three-layers in the nanoparticle is clearly evident. The diameter of the nanoparticles is ~ 8 nm. This consists of a Pd core (A ~ 2 nm) – Au-rich first shell (B ~ 3 nm) – Pd-rich outer shell (C ~ 3 nm) as can be seen from the contrasts in the HAADF images in figure 3a. The shape of this particle corresponds to a truncated octahedron, which has (111) and (100) facets. Figure 3b shows a three layer particle with the (100) orientation in which one can see roughness on the surface, and distortion in the core of the nanoparticle. In some nanoparticles it may also be seen that the Au atoms are indeed diffused into the Pd-rich outermost shell as can be seen from the bright atom contrast in the Pd-layer. Figures 3c and d show the case of the atom by atom intercalation of Au in the Pd-layer. This shows how gold can be present in the Pd-layers and is not entirely rigid. So indeed the layers are alloys of different concentrations [9].
Figure 3. Aberration-corrected STEM images of the three layer Pd-Au nanoparticles: (a) Atomic-resolution HAADF-STEM image of a truncated cuboctahedral Au/Pd nanoparticle. The contrast of the three distinct regions (marked A-C) can be clearly seen. (b) Nanoparticles with surface roughness and distortions at the core. (c, d) Au intercalation into the Pd-layer. (Reprinted with permission from Ref. 6, Copyright (2011) Elsevier).

EDS line scan in the case of the three-layer Pd-Au-Pd nanoparticles reveal the following interesting features as can be seen in figure 4. The Pd L- and the Au L- and M-signals can be clearly traced across the region of the individual Pd- and Au-layers with the maximum intensity of the signals varying between the respective layers (figure 4b). In addition we have also carried out EDS elemental mapping for the respective elements. Figure 5 shows the chemical maps of the Au-Pd nanoparticles. It can be seen from the figure that the Pd (K, L) and Au (L, M) maps clearly reveal the presence of the individual elemental contrasts in the three-layer core-shell structure of the nanoparticles. With the information obtained from the STEM-EDS line scans and elemental maps of the individual nanoparticles the presence of the core-Pd – first shell-Au – outer shell-Pd is clearly confirmed without any ambiguity.

The distribution of the chemical elements of the three-layer nanoparticle (figure 6a) was investigated by EELS, and the result for the EELS line profile of Pd-M_{4,5} is shown in figure 6b. For purposes of comparison, the figure also shows the high-angle annular dark field (HAADF) intensity line profile of the same particle (figure 6d). From the EELS profile (figure 6c) it can be noted that, the distribution of Pd appear to be in accordance with the presence of Pd in the core and in the outermost shell as is the case for a tri-layer particle. However the EELS Au-M_{4,5} signal at 2206 eV turns out to be weak, as expected for a heavy element, but high enough to show the presence of Au in the particle. From the comparison between the Pd EELS profile and the HAADF profile, it can be inferred that there exists a region close to the centre of the particle as well as in the outermost shell which is rich in Pd. The corresponding EELS map of Pd reveals clearly the presence of Pd in the core and in the outermost shell of the tri-layered nanoparticles as is shown in figure 7.

It is worthy to mention that in case of these nanoparticles occasionally four-layered structure is seen. Shown in figure 8 is the case of the four layer nanoparticles wherein it can be seen that near the surface there is an extra layer of atoms of gold and this suggests a 4 layered structure. This is a different case from the previously mentioned three-layered nanoparticles and has not been reported till date.
Figure 4. (a) and (b) Characterisation of the Au and Pd elemental distribution across the nanoparticle by STEM-EDAX line-scanning technique across the individual three-layer nanoparticle. The Pd L- and the Au L- and M-line scan signals can be clearly seen varying in intensity along the different regions of the nanoparticles. (a) Shows the analysed area and the direction of analysis. (Reprinted with permission from Ref. 6, Copyright (2011) Elsevier).

Figure 5. Elemental maps of the nanoparticles – Pd (K, L) and Au (L, M) maps.

A particle in its <110> orientation is shown in figures 9a and b in the HAADF and BF-STEM modes respectively. Profiles of the first and second layer of the particle are shown in figures 9c and d respectively. The profiles show a very rough surface; this can only be explained if we consider two factors. One, atoms of gold migrated to the surface causing an increase in signal in those particular columns. Two, there are incomplete columns of atoms (e.g., steps) on the surface.

The BF-STEM images of the three layer nanoparticle (figures 10a and b) along with the HAADF image (figure 10c) are displayed (Au/Pd). The incident electron beam direction is along [110]. The side surfaces of the particles can be indexed as {111} and {100} planes, as labelled in figure 10a and d. The centre of the nanoparticles is round but the exterior surface is in the shape of a square. The real shape of these particles can be associated with the truncated-octahedron. This is extremely interesting since the individual metals themselves will tend to form icosahedral or decahedral shapes. On the other hand we have not observed these shapes in bimetallic Au/Pd [22]. This is a very
Figure 6. The distribution of the chemical elements of the three-layer nanoparticles (a) investigated by EELS, and the result for the EELS line profile of Pd-M_{4,5} is shown (b). Linear Pd EELS profile performed on the particles (c), and its corresponding HAADF intensity profile (d). (Reprinted with permission from Ref. 6, Copyright (2011) Elsevier).

Figure 7. EELS map of Pd reveals clearly the presence of Pd in the core and in the outermost shell of the tri-layered nanoparticles.
Figure 8. Aberration-corrected STEM images of the four layer Au/Pd nanoparticles. The contrast of the four distinct regions (marked A, B, C and D) can be clearly seen.

Figure 9. (a) and (b) HAADF and BF-STEM images of Au_{1}Pd_{4} nanoparticle. c) and d) shows the intensity profile of the first two atomic layers of the nanoparticle. (Reprinted with permission from Ref. 6, Copyright (2011) Elsevier).
Figure 10. The BF-STEM images of the three layer nanoparticle (a and b) along with the HAADF image (c) are displayed. A higher magnification of the BF-STEM image of (a) is shown in (b) and the HAADF image shown in (c) clearly gives indication of the variation in the stacking sequence leading to the stacking faults which is in combination with SPDs. (d) Atomistic model of Au/Pd modified cuboctahedron with the three layers and showing the \{100\} and \{111\} facets: a Pd-rich inner-core, Au-rich intermediate-shell, and a Pd-rich exterior shell. (Reprinted with permission from Ref. 6, Copyright (2011) Elsevier).

significant fact that shows how the structure can be changed with the chemical composition. The HAADF intensity is taken into account considering the variation in intensities that change significantly when one moves from the Pd-rich layer to the Au-rich layer. In this case the profile of the layers show the same thickness within a particular layer attributing uniformity in the thicknesses of the layers and variation in intensity arising only as a consequence of the difference in their atomic numbers between Pd and Au.
The nanoparticles have defects at the \{111\} surface in all the directions (figure 10 a). In order to see the defects clearly, a higher magnification of the BF-STEM image of figure 10a is shown in figure 10b and along with the HAADF image shown in figure 10c clearly gives indication of the variation in the stacking sequence leading to the stacking faults. Although the standard stacking sequence is ABCABC... in face-centred cubic (FCC) structures, in the regions marked in the images (figures 10b and c) this sequence is not followed. Instead, the sequence becomes ABCAB… (FCC-HCP structure), as can be seen in the figure 10b and ABCAB… in figure 10c. This corresponds to stacking faults. In addition the presence of Shockley partial dislocations (SPDs) can be observed (figure 10a). The formation of stacking faults in Au-Pd core-shell structures has been shown to be linked to SPDs [6]. A partial dislocation is accompanied by the presence of a stacking fault. It may be noted here that the large strain involved in the formation of the three-layer structures may be alleviated to some extent by the formation of such stacking faults and related defects. The stacking faults are also evident in the case of the Au$_1$Pd$_4$ tri-layer particles. Figures 11a and b are the HAADF STEM and the BF-STEM images which shows a variation in the stacking sequence from the previously mentioned case. Here the stacking sequence of ABCBA is produced by twinning and the layer C corresponds to the twinning mirror plane [6].

![Figure 11. HAADF and BF-STEM images of Au$_1$Pd$_4$ nanoparticle showing the presence of twinning. (Reprinted with permission from Ref. 6, Copyright (2011) Elsevier).](image)

2.2. Clusters
Metal atomic clusters consist of groups of atoms with well-defined compositions and one or very few stable geometric structures. They represent the most elemental building blocks in nature – after atoms – and are characterized by their size, comparable to the Fermi wavelength of an electron, which makes them a bridge between atoms and nanoparticles or bulk metals, with properties very different from both of them.

2.3. Catalysis
Small clusters have been found to own a catalytic activity not observed in their bulk analogues or even nanoparticles, which makes them very attractive as new catalytic materials. Quantum chemical calculations indicate that such high reactivity is due to under coordination of the metal atoms forming
the cluster. Several families of metal clusters have been found to possess surprisingly high and selective catalytic activity when immobilized on a support. For example, platinum clusters with 8 – 10 atoms can be used as catalysts for the oxidative dehydrogenation of propane, while gold clusters with 6 - 10 atoms have been shown to be highly active for catalysing propene epoxidation. The control and tunability of the catalytic oxidation of CO by Au20 clusters deposited on MgO surfaces has also been studied. Thus it has been found that the active site on the cluster is characterized by enhanced electron density, which activates the adsorbed O2 molecule and promotes the bonding of CO. Small metal clusters have been also found to display electrocatalytic activities different from the material in bulk or as nanoparticles. Although this is a field not too much explored so far, these electrocatalytic properties make metal clusters to be promising materials in fuel-cell applications [10, 11].

It is indeed interesting to note that the ultimate resolution of observing individual atoms/small clusters have been achieved using probe aberration corrected STEM. Shown in figure 12, are the very small bimetallic clusters of Pd-Ir (inside the circle). The size of the cluster is just about ~ 2 nm. It is interesting to note that based on the Z-contrast, the two different atoms can be distinguished very clearly (Pd, Z = 46, Ir = 77). In addition in the vicinity of these small clusters it is also possible to locate individual atoms of Ir/Pd (outside the circle) [7].

Figure 12. Clusters of Pd-Ir are shown (inside the circle). It is possible to distinguish each element based on the Z-contrast (Pd = 46, Ir = 77). Notice also the presence of individual atoms (outside and close to the circle).

3. MoS2 nanoplates
Figures 13a and b show the SEM micrograph of the MoS2-plates synthesized at 700 °C and annealed at 900 °C and 1000 °C, respectively starting from MoO3 and S powder. Both the images show the presence of hexagonal plates with nanometric size in the sample. The size of the plates is approximately 30 - 35 nm of diameter and the plates are hexagonal in shape. In the figures the hexagonal plates are stacked in agglomerates consisting of the plates, which can be distinguished individually. These agglomerates can be broken down by ultrasonication.

Figure 14a shows the BF-STEM image of a MoS2-plate, revealing in detail the stacks of Mo; with this image it was possible to measure the Mo–Mo distances in the a1-, a2- and a3-directions. Distances of 2.76 Å in the a1-direction, 2.8 Å in the a2-direction and 2.87 Å in the a3-direction are obtained; these values correspond to Mo–Mo interatomic distances. A line profile is shown in the inset of figure 14a. Thus the hexagonal atomic structure of MoS2 is observed with a resolution sufficient enough to resolve the Mo–Mo interatomic distance. Figure 14b shows the diffraction pattern wherein, the a1-, a2- and a3-directions are indicated in the figure. Thus it is possible to clearly see the crystal array of MoS2, corresponding to a hexagonal crystal system.
Figure 13. SEM micrographs of the MoS$_2$-plates synthesized and annealed at: (a) 700 °C - 900 °C; (b) 700 °C - 1000 °C. (Reproduced by permission of The Royal Society of Chemistry).

Figure 14. Bright field high resolution STEM image and selected area electron diffraction pattern from the MoS$_2$-plates. (a) BF-STEM image showing the stacks of Mo-atoms, the inset $a_1$, $a_2$ and $a_3$ in the figure shows the directions in the six fold zone axis and the measurements of the Mo–Mo interatomic distances, (b) electron diffraction pattern shows the hexagonal symmetry in the $<001>$ direction. (Reproduced by permission of The Royal Society of Chemistry).

Figure 15 shows a three-layered MoS$_2$ plate, forming a Moiré pattern composed by the three individual layers of MoS$_2$. The upper inset of figure 15 shows a HRTEM micrograph of a Moiré pattern, a Moiré lattice is observed; the lower inset shows the fast Fourier transform (FFT) of the layers, three sets of hexagonal spots can be seen, corresponding to the three layers; the angles between
the layers are measured in the figure, the angle between the first two layers is 19°, and the angle between the next two layers is 16°. These are the rotational angles of the layers, here three layers were found and their superimposition causes the Moiré pattern. Some of the plates observed contained Moiré patterns of three layers and some of them with two layers. There are also cases of single plates. Figure 16 shows a HRTEM micrograph of a MoS$_2$ plate seen in the lateral view. The inset in the left shows the diffraction pattern of the interior, it was possible to obtain the direction of the crystal, that results to be [000n], where n is even. The inset in the right shows an amplification of the main image, several bands of different size are observed, the broad lines are molybdenum, as it has a high atomic number and a high atomic weight; the thin lines are sulphur. The lines are regular and are alternating in the image revealing the stacks of S–Mo–S forming sandwiches, three of these layers form a unit cell in MoS$_2$, one of which is marked in the inset of figure 16. The measured distances between three atoms of Mo in a cell unit was found to be $c = 0.12$ nm or 1.2 Å. These results agree with the parameters obtained with the XRD, and with the reported values in literature of $c/2 = 6.53$ Å (shown in the right inset of figure 16).

![Figure 15. Image showing the superimposition of three plates of MoS$_2$ and the formation of a Moire pattern.](image)

It must be noted that from the measured catalytic activity it is found that the selectivity and activity of these MoS$_2$-nanoplate catalyst are very high, corresponding not to an unpromoted MoS$_2$ catalyst but almost that of a doped MoS$_2$ with cobalt. Theoretical analysis performed on unrotated as well as rotated 2H-MoS$_2$ and monitoring the total average energy in both cases yielded indication that the Moiré patterns observed in the rotated case are in stable states. On the other hand, energy bands on both systems indicate that for the rotated case the system indicates a trend toward the metallicity of the system, this is not observed when the system is unrotated, which could explain the enhancement in the catalytic properties. It is hoped that such improved catalysts will lead to a cleaner gasoline and to a cheaper HDS process.
4. Conclusions
Understanding the structure of nanomaterial catalysts has tremendously improved in recent years with the advent of aberration corrected electron microscopes. Two different examples have been described to showcase the recent developments in this field of nanocatalysis. In the first example, the case of bimetallic three-layered Au-Pd nanoparticles is presented. Unravelling the atomistic structure of nanoalloys is vital towards providing the complete understanding towards the way catalysts behave under different situations. This has been accomplished by a combination of atomic scale imaging and simultaneous spectral analysis. In the second example, the structure and intricate details of MoS$_2$-nanoplates have been deciphered using aberration corrected STEM and HRTEM. These catalysts find important applications in the removal of sulphur compounds from gasoline and hence it is critical to understand their structure and morphology at the atomic level (especially when promoters are incorporated into their structure). This thereby provides to enhance their activity and selectivity, towards specific catalytic processes. Thus it is clear that the current state of the art aberration corrected electron microscopic techniques provide to enhance our understanding of nanocatalysts in an unprecedented manner [12-14].

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