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Seeing and measuring with electrons: Transmission electron microscopy today and tomorrow – An introduction

Voir et mesurer avec un faisceau d'électrons : La microscopie électronique à transmission aujourd'hui et demain – Une introduction

Christian Colliex

Laboratoire de physique des solides, UMR CNRS 8502, Bldg. 510, Université Paris-Sud, 91405 Orsay, France

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ABSTRACT

This dossier in *Comptes rendus Physique* is devoted to the most recent technologies and methodologies in electron microscopy available in 2014, which have provided this instrument with unique capabilities for atomic-level investigations in the domain of materials science. The present introduction provides some basic information required for an easier reading of the following manuscripts. It therefore focuses on column design, signal acquisition strategy, aberration correction, resolving power, *in situ* experiments and novel approaches, illustrated with a description of a few of their present and future fields of use.

RÉSUMÉ

Ce dossier des *Comptes rendus Physique* est consacré à une revue des développements méthodologiques et technologiques les plus récents en microscopie électronique, et qui offrent en 2014 à cette génération d'instruments des possibilités tout à fait uniques pour explorer la matière condensée à l'échelle atomique. Ce texte d'introduction a pour but de résumer, pour le lecteur potentiel des chapitres qui suivent, une information de base. Il rappelle donc des généralités sur la conception des colonnes, sur les stratégies d'acquisition du signal, sur la correction des aberrations, sur le pouvoir de résolution, sur les expériences *in situ* et sur d'autres approches innovantes. Quelques domaines privilégiés d'utilisation présente et future sont identifiés et décrits.

Deepening our knowledge about the matter around us has constituted a permanent quest for humanity over the past centuries. It has been driven not only by a plain curiosity but it was rapidly motivated by a will to create and engineer new generations of objects with improved structural or functional properties. With the advent of the electron microscope (EM), the first design of which by Ernst Ruska in the early 1930s has been recognized by the award of the 1986 Nobel Prize in

E-mail address: christian.colliex@u-psud.fr.

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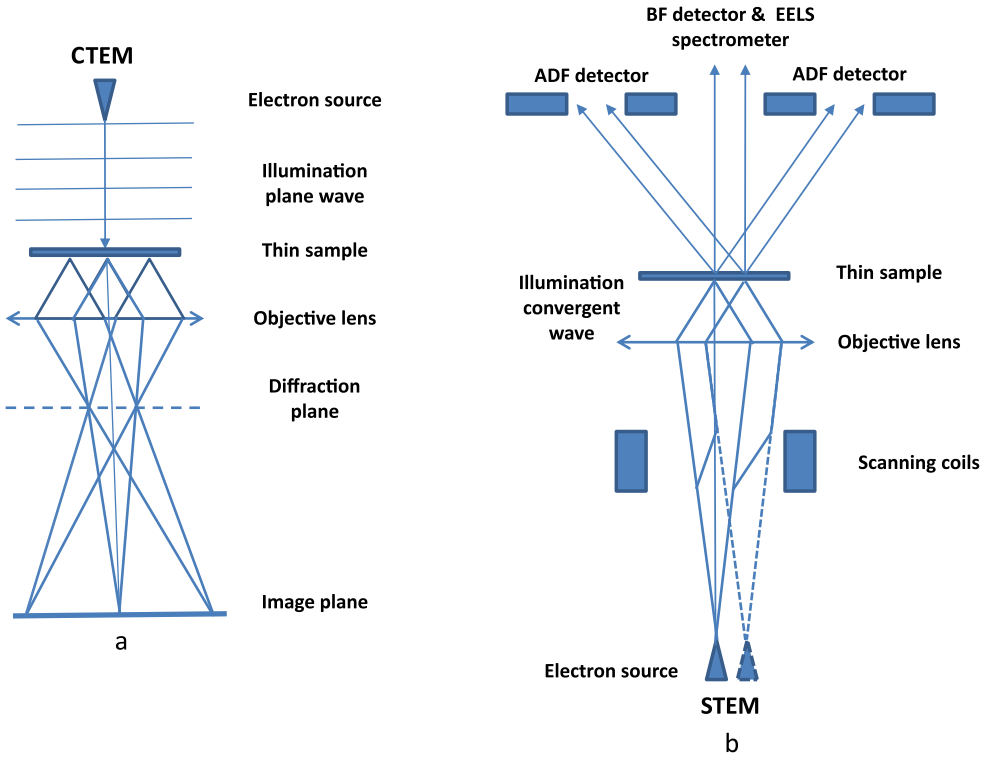

Fig. 1. (Color online.) Ray diagrams for imaging and diffraction in the CTEM (a) and in the STEM (b).

Physics, a new world made of atoms became accessible. But, observing it, measuring it, analyzing it, down to its ultimate atomic components, has proved not to be easy despite the short wavelength λ of the electron in a TEM (transmission electron microscope) with an accelerating voltage of a few tens or hundreds of kV, typically two orders of magnitude smaller than the distance between neighboring atoms in condensed matter. The contributions gathered in this dossier in *Comptes rendus Physique* offer a survey of the state of the TEM technologies and working modes today, together with a glimpse into its present and potential impact in some selected domains of use.

In order to make the following papers more comprehensible to a general audience, this introduction provides some general information on the basics of TEM imaging, diffraction and analysis.

1. General design of a TEM: a summary

In a TEM, the specimen is prepared as a thin foil through which the primary electron beam is transmitted. The main parts of the microscope column are therefore the source of accelerated electrons (the gun), the electron optics components for illumination and imaging, the detectors for capturing the electrons after their interaction with the specimen and thus accessing to the different useful signals. In the continuation of the early work by Ruska, see for a detailed description [1], the first configuration adopted for the design of electron microscope columns was directly inspired by that of optical microscopes. This approach, named CTEM for Conventional Transmission Electron Microscopy, relies on the illumination of the specimen with a parallel beam of electrons. The imaging lens, or objective lens, delivers a diffraction pattern in its back focal plane and an image which is magnified on the observation screen or two-dimensional detector (see Fig. 1a). Although it had been first constructed by Manfred von Ardenne in the late 1930s, see for a review [2], the STEM for Scanning Transmission Electron Microscope, became operational only 30 years later thanks to the work of Albert Crewe and his colleagues [3,4]. In this instrument (see Fig. 1b), the primary beam is focused into a very small probe of electrons on the surface of the specimen: the imaging lens, also called objective pre-field or focusing lens, is therefore located before the specimen. In the simplest design, there is no electron optics between the specimen and the detector(s) which is used to capture the imaging or diffraction signal. The image is sequentially built, point by point, while scanning the electron probe over the specimen surface.

Improvement of the spatial resolution δ in these instruments has been a permanent goal for researchers over the past decades. If the limiting factor is diffraction, $\delta = \lambda / \sin\alpha$, with α the angular aperture of the imaging lens. Consequently, one approach is to increase the accelerating voltage and therefore reduce λ: in the sixties, at Toulouse in particular, under the leadership of Gaston Dupouy, TEMs operated at 1 MV (and higher) acceleration voltages were built [5]. In fact, however, the origin of the resolution limit of about $100 \times \lambda$ is due to the poor quality of the objective lens acting on the electrons, which does not permit large angular apertures. Its aberrations have been identified very early after the first realization of

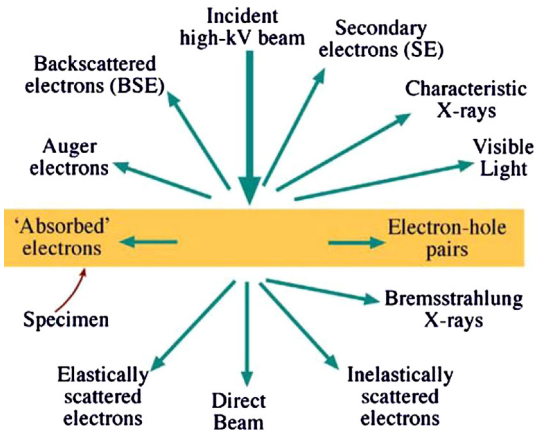

Fig. 2. (Color online.) Signals generated when a high energy beam of electrons interacts with a thin specimen: some can be considered as primary events such as scattering processes, others are secondary events, such as emission processes, resulting from the de-excitation from an excited state in the target (from D. Williams, C.B. Carter, Transmission Electron Microscopy, 2nd edition, Springer, 2009, p. 7).

an electron microscope column, the two most important ones being the spherical aberration C_s which increases as the third power of the semi-angle (α) and the chromatic aberration C_c, which is proportional to the angle α and to the width δE of the electron energy distribution of the electrons in the lens. The correction of these aberrations has therefore constituted a great challenge which has motivated efforts of all the great names in the field of electron optics, such as Otto Scherzer, Dennis Gabor and Walter Glaser, from the 1930s to the 1970s, culminating in the success of two groups in Germany and in the UK and in the USA in the late 1990s (see [6] for a comprehensive historical review).

2. Useful signals in a TEM

Spatial resolution (δ) in any optical instrument such as a microscope, measures the possibility of discriminating two points A and B of a specimen separated by this distance. But how can one first identify the existence and position of any point A? In order to answer this question for the electron microscope, it is necessary to consider in more detail the interaction mechanisms between the incident electron and the atoms (ions and electrons) constituting the solid specimen. (See Fig. 2.) This is basic physics involving scattering, absorption, emission processes with associated cross sections. They are responsible for the intensity of the different signals $I(x, y)$ to be captured by the detectors, governing the contrast $C = \Delta I/\bar{I}$ and the signal-to-noise SNR in an image. An image is actually a 2D distribution of intensities I on a grid of pixels of size $\delta \times \delta$. To distinguish the signal, that is the variation ΔI in a pixel with respect to the average intensity $\bar{I}$, it must be greater that its variance $(\bar{I})^{1/2}$. A relationship between SNR, the contrast C and the resolution δ is to be found in electronics textbooks: $\mathrm{SNR} = DC^2\delta^2$, where SNR must be greater than a threshold value, typically 5, in order to be detected. D is the dose expressed in electrons/surface unit. As a consequence, the spatial resolution is not the only significant parameter governing the performance and the useful output of any microscope; its associated signal of interest must be taken into account.

The commonly used signal in CTEM is related to the elastically scattered electrons (which includes diffraction when the specimen is crystalline). For improving the resolution, one needs to increase the angular acceptance of the imaging lens, while it is necessary to reduce it with the introduction of a small aperture to improve the contrast, especially when the scattering object is of small size such as an isolated atom. Consequently, one has to implement imaging conditions which reveal changes of the phase contrast on the transmitted beam rather than the "amplitude contrast" contained in the scattered beam.

In STEM, the situation is quite different. Scattering mechanisms of the electrons, either elastically at large angles or inelastically scattered at small angles but discriminated with the help of a magnetic spectrometer (i.e. the EELS signal), provide significant contrast even with ultra-small incident probes. Elastically scattered electrons can be captured with annular dark field (ADF) detectors, which deliver signals sensitive to the Z number of the probed atoms (see Fig. 1b). Furthermore, for each position of the probe on the specimen, different signals of complementary nature can be acquired simultaneously. In particular, signals carrying spectral information can be measured together with topographic ones, which has led to the widespread use of spectrum-imaging modes [7]. The recent evolution and future impact of the multi-signal modes in the STEM will be emphasized below and is illustrated in several contributions to this issue.

3. The correction of aberrations in TEMs opens up the exploration of the sub-angstrom world in condensed matter

Shortly after the construction of the first electron microscope in 1933 by Ernst Ruska, a spatial resolution clearly superior to that of the light microscope was achieved, but the electron optical community soon became aware of the impossibility

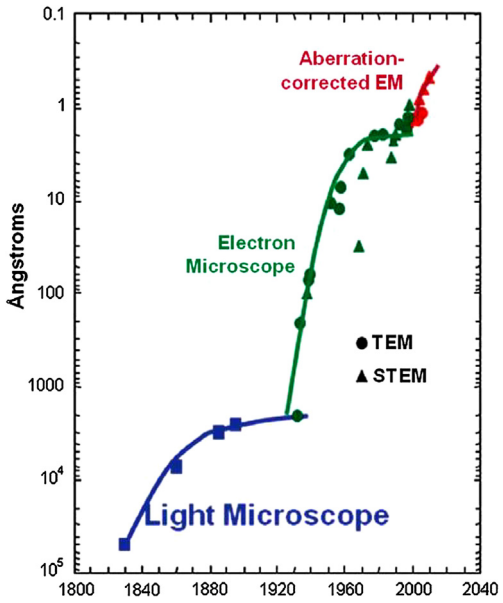

Fig. 3. (Color online.) Hardware advances in imaging microscopies. The first jump around year 1930 corresponds to the input of the EM with respect to the light microscope, the second jump before year 2000 illustrates the input of the EM aberration correction (figure adapted from H. Rose, in: P. Hawkes (Ed.), Advances in Imaging and Electron Physics, vol. 153, Elsevier, 2009).

to design an aberration-free electron objective lens with cylindrical revolution symmetry. This is known as the "Scherzer theorem" [8]. Over the next forty years, all the experts in electron optics extensively proposed and tested different solutions without real success, i.e. with the construction of a corrector that could bring the performance of the equipped microscope column to a level better than that of the uncorrected one. However, the feasibility of a hardware aberration corrector for high resolution electron microscopy, had been demonstrated during this period.

It was only in the mid-1990s that independently, two teams demonstrated successful realizations. They both used non-round multipole lenses, of hexapole type for the German group involving Rose, Haider, Urban and their collaborators [9], of quadrupole–octopole type for the group at Cambridge, Krivanek, Dellby and their collaborators [10]. Among the factors which have noticeably contributed to these successes presented in 1997–1998, one must point out the extreme mechanical precision and electric stability of the corrector elements and the development of sophisticated software for the computer control of the corrector alignment and of the measurement of the remaining aberrations. The progress in spatial resolution introduced by these correctors is illustrated in Fig. 3.

The German team followed a suggestion from Rose [11] that one solution for aberration correction relies on the coupling of two strong hexapoles and of additional round transfer lenses to reduce off-axial and higher order aberrations in an image forming lens to be fitted on a CTEM instrument. However, an appropriate alignment procedure is required and the computer-guided use of diffractograms recorded under tilted illumination, has proved to be essential. This was demonstrated in the 1998 Nature paper [9], where an improvement of the point resolution from 0.24 to 0.14 nm for a standard 200 kV Philips microscope with a field emission source, was shown. The adventure went on with the foundation in 1996 by Haider and Zach of the company CEOS, which has become the world's leading manufacturer of TEM correctors for most companies, while maintaining a strong activity in innovation and high-tech projects resulting in the delivery by the company FEI of the TEAM microscope at Berkeley and of the PICO one at Jülich.

In the same period, around the mid-1990s, another successful project has emerged in the UK at Cambridge University where the efforts of Krivanek and coworkers have created the positive conditions for the design and realization of a C_s corrector, made of a combination of quadrupoles and octopoles, to be implemented on a dedicated VG STEM column. Preliminary results recorded with this first-generation, proof-of-principle C_s corrector were presented at conferences by the end of 1997. A company, Nion Co., was created in the USA in 1997 by Krivanek and Dellby, with the goal of designing and manufacturing high-end electron-optical instruments and devices. After having demonstrated increased performance of such a corrector when installed on a 300-kV VG machine, with the resolution of pairs of atomic columns separated by 78 pm and transfer of information to below 70 pm [12], the team embarked onto a brand new adventure, i.e. the design and building of an entirely new scanning transmission electron microscope (STEM), which is described together with a selection of most recent results in [13].

Today, one can estimate that thanks to the successful efforts and realizations of all the researchers mentioned above, the era of the aberration-corrected electron microscopy is definitely open. A few hundred instruments equipped with such correctors are now in operation around the world. It is therefore useful to evaluate how far this technological step has really, and to what extent, opened new possibilities and allowed the emergence of new fields of research. Relying on

the present situation dominated by aberration-corrected microscopy for giving access to the Å and sub-Å domain, **Hawkes**, in his contribution to this issue, identifies alternative or correlated approaches to explore future directions in high-resolution electron microscopy.

4. Pushing further the extraction of information from ultra-high-resolution images in the CTEM

As we know how to correct the defects of a lens, how can we transfer this progress to the correction of images, and from there to an upgraded solving of materials science problems, preferably in connection with their macroscopic properties? For instance, what is the real input of the real space visualization of the atomic structure conveyed in images displaying contrast variations with atomic resolution? How local is the information, how can it be related to the exact position of atomic columns, close to a defect for instance? The Jülich group has proved to be quite instrumental in this aspect by working out conditions, called negative spherical-aberration imaging conditions, in which atoms appear bright on a dark background. The strong contrast, generated in this mode, has been responsible for the first direct imaging of oxygen atom columns in oxides, such as $SrTiO_3$ and $YBa_2Cu_3O_7$ [14], and one step further of their quantitative concentration in oxygen in twin boundaries in $BaTiO_3$ [15].

In the present issue, the retrieval of the 3D information from a series of tilted images, known as electron tomography, is extensively discussed by **Bals and coworkers**, while **Koch and Van den Broek** focus onto the measurement of the 3D positions of atoms to the highest accuracy in a TEM.

An alternative and very powerful approach to the determination of the phase and amplitude resulting from the interaction of the TEM electrons with an object, lies in the electron holography. Based on pioneering ideas of Dennis Gabor, it has been fully implemented in the electron microscope only with the advent of a very bright and coherent source, the field emission gun (FEG). The widely adopted off-axis holography mode consists in recording in the image plane an interference pattern between a reference wave and that transmitted through the specimen, after which the image wave is reconstructed, both in terms of phase and amplitude, with the help of numerical Fourier optics. It is therefore basically a lens-less method, rather insensitive to the lens aberrations, which has demonstrated capabilities of retrieving the whole structural information down to the information limit (0.1 nm), i.e. better than the point-to-point resolution (0.2 nm) of the uncorrected microscope (see [16] for a review). Moreover, holography techniques have fully demonstrated their impact for the mapping of fields, either magnetic or electric, which are not visible in the standard TEM modes. The demonstration by Tonomura et al. [17] of the Aharonov–Bohm effect, which states that the phase of an electron wavefunction can be shifted by a nearby magnetic field even if the electron does not pass through it, is one of its greatest achievements. In a contribution to this issue, **Pozzi et al.** survey the successes and limitations of the various phase contrast imaging techniques.

5. Optimizing the information acquisition with the tiny probe of the STEM

Two ingredients can be identified as having been determinant in the development and success of the STEM instruments, as they were already present in the early microscopes developed by Crewe and coworkers: (i) the use of a field emission source to deliver a sufficiently high beam current into a typically sub-nm size primary electron probe and (ii) a strategy designed to collect as many as possible of the electrons that have interacted with the specimen [3]. The recording of the first images of individual atoms (U and Th) deposited on a thin layer of carbon has immediately attracted considerable attraction [4]. Over the following decades, dedicated STEM instruments manufactured by the UK company Vacuum Generators, incorporating cold FEGs working at primary voltages of 100 kV (and eventually 300 kV) and delivering a probe current of a few hundred pA in a probe of 0.25 to 0.5 nm, have been fully exploited by groups at Cambridge, Orsay, ASU, Cornell and ORNL, to record both ADF images for structural investigations and EELS data for chemical and electronic characterization. In particular, they have demonstrated, between 1990 and 2000, unique performances for capturing the signature of single atoms [18] and performing spatially resolved analysis at the atomic level [19–21].

The introduction of aberration correctors in STEM microscopes, either of dedicated or of hybrid CTEM/STEM type, has generated an explosion of spectacular results issuing from an attainable resolution down to 50 pm at 200 kV and from an increased current up to 1 nA in a probe of 150 pm. As a typical example of these potentialities, one can quote the ADF discrimination of individual B, C, N and O atoms within a monolayer of h-BN incorporating impurities [22]. Another advantage of the ADF signal is that it increases monotonically (close to linearly) with specimen thickness, contrary to the oscillating behavior with thickness exhibited by HREM CTEM images. Consequently, ADF STEM imaging has become the favorite input for 3D reconstruction using tilt series and back projection algorithms, as it is illustrated in the contribution of **Bals et al.** in this issue, who demonstrate the full 3D reconstruction of an individual nanoparticle atom by atom [23].

With the EELS characteristic signals, mapping the elemental composition atomic column by atomic column in crystalline thin foils has recently become an essential output [24]. Altogether, most recent experiments have confirmed that an atom-by-atom and atomic column-by-atomic column electron spectroscopy, which delivers an information on the local electronic structure, bonding, charge transfer, coordinence, site symmetry and distortions, extending far beyond the elemental identification, is possible; see Fig. 4.

These novel potentialities have already demonstrated their rich impact in detailed studies of interfaces in oxide materials for instance, as demonstrated in very recent reviews such as [25]. They have also been used for individual atom labeling and valence determination in adjacent peapods in a carbon nanotube [26,27], see also the paper by **Suenaga** here. As it

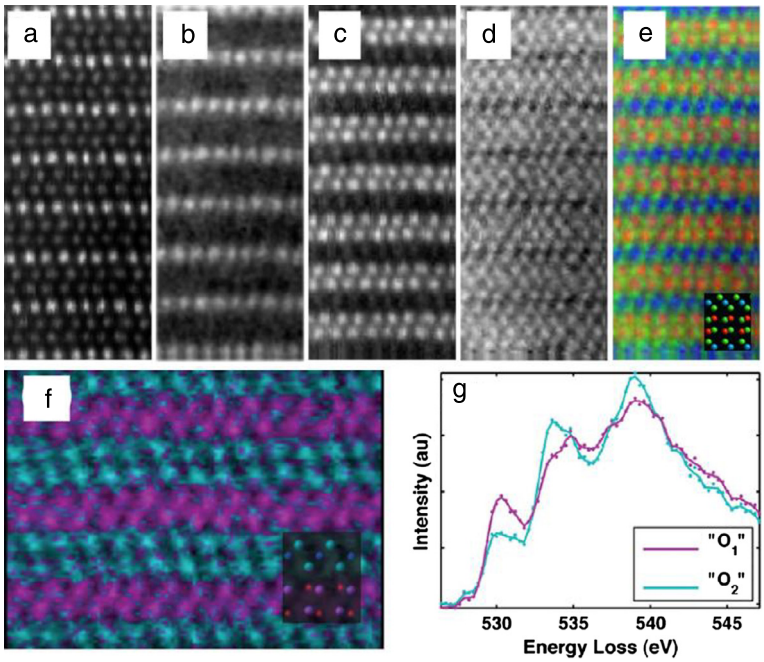

Fig. 4. (Color online.) Mapping the chemical environment of O atoms with EELS in $LuFe_2O_4$. (a) is the simultaneously-recorded annular dark field image showing the repetition of Lu layers separated by with double layers of Fe. (b) is the Lu-$M_{4,5}$ EELS map, (c) the Fe–$L_{2,3}$ and (d) the O–K edge map. In (e), the maps of (b)–(d) are overlaid with the Lu plotted in blue, Fe in red, and O in green. The inset shows the bulk $LuFe_2O_4$ crystal structure color-coded accordingly. The field of view in images (a)–(e) is 2.8 nm by 7.4 nm. In (f), local bonding information is extracted from an O–K edge map with a 3.4 nm by 2.5 nm field of view. Two distinct components were present in the O–K edge fine structure (g), and fit to the spectroscopic image as shown in (f). These two spectra reflect the two nonequivalent oxygen sites, "O1" and "O2". The inset to (f) shows the crystal structure with Fe plotted in red, Lu in blue, and "O1" and "O2" in magenta and turquoise respectively. (Courtesy of D. Muller, reproduced from [28] AIP, all rights reserved.)

relies on the use of the fine structures visible on the characteristic edges in the EELS core-loss domain, extending typically from 50 to 2000 eV in energy range, this achievement has sometimes been described as "a synchrotron in a TEM".

Another large advantage of the EELS spectroscopy is that it can also cover the whole spectral range in the low energy range from 1 to 50 eV, thus complementing the atomic-type electronic response discussed above with that of the valence and conduction electron populations, either of collective plasmonic type or associated to individual interband transitions. Over the spectral domain extending from the near IR to the near UV domain encompassing the visible range, EELS has recently demonstrated its very rich ability to investigate, at an unprecedented spatial resolution well below the photon wavelength, the plasmonic and photonic response of nanostructures [29], thus becoming a highly performing alternative to near-field photon microscopy and spectroscopy. This domain of research is presently in rapid and spectacular expansion because the mapping of these local electron oscillations and of the fields which they generate, provides clues for the creation, modification and manipulation of local light fields. Within this context, inelastic scattering constitutes an alternative technique to mapping electromagnetic fields, complementary to that conveyed in the holography methods. It is extensively discussed in the contribution by **Kociak et al.** in this issue.

It so happens that the STEM microscope was conceived as a basic physics instrument quite well suited to the incorporation of specific and complementary detectors. In particular, recent developments have consisted in adding specific detectors for the acquisition of secondary emission products under the impact of the primary electron probe: (i) X-ray spectrometers and detectors for elemental identification which have also demonstrated capabilities of atomic column resolution and of single atom detection [30]; (ii) photon spectrometer and detector for capturing the photon emission signal in and around the visible domain with the sensitivity of a single color center or a single quantum dot or disk [31], and recently modified to realize the first demonstration of quantum nano-optics of single photons in a TEM [32], see again **Kociak et al.** for further description and comments. Both techniques can be run in the spectrum-imaging mode and will therefore bring key information in many domains of condensed matter physics. The prospective view of the future multi-signal STEM microscope is therefore illustrated in Fig. 5.

6. The TEM as a laboratory for new experiments and measurements

The potential of the TEM fully equipped for imaging and spectroscopies, is nowadays significantly extended below its traditional use for the investigation of static structures under vacuum, at room T and in equilibrium, by the rapid development of dedicated specimen stages. *In situ* observations and measurements can be performed under quite diversified external physical and mechanical constraints or environments. Basically, the TEM of either CTEM or STEM type, is evolving

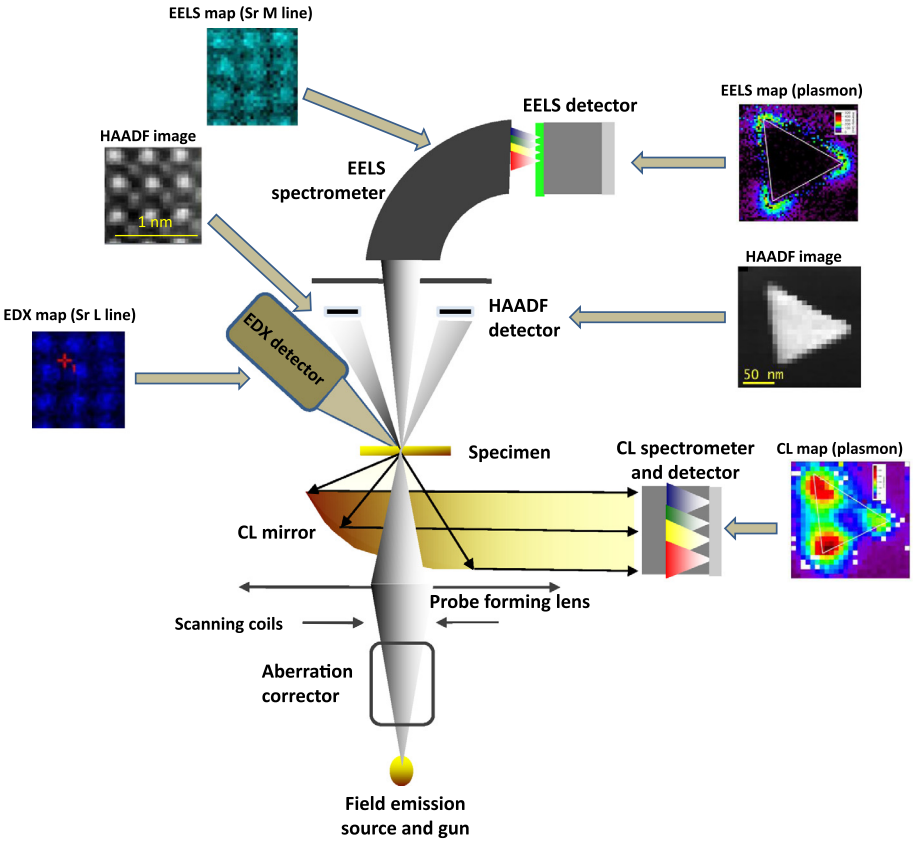

Fig. 5. (Color online.) Illustration of the multi-signal strategy in a modern STEM instrument, displaying two channels of parallel information: ADF, EELS and EDX elemental mapping of the atomic structure and composition in $SrTiO_3$ (left); ADF, EELS plasmon map and cathodoluminescence (CL = photon emission spectroscopy) on a single Ag nanoplatelet (right).

into a "nanolaboratory", where transport properties through nanostructures or surface reactivity of molecules on substrates can be monitored under close electron microscope observation and analysis. For this purpose, *in situ* specimen stages are built, where the thin foil can be heated, strained, probed with electrical contacts, submitted to various gas atmospheres or immersed in liquids during inspection at high magnification. They are introduced between the objective pole pieces so that the gap between these limits the dimensions of the nanolab. In the present issue, several contributions focus on these innovative extensions of the conventional domain of use of TEMs. **Boyes and Gai** describe most recent progress in the visualization of reacting atoms under various temperature (T) and pressure (p) environments, and in a very different domain **Legros** discusses how the implementation of stages with controlled mechanical stress opens the field of moving dislocations and constitutes an essential tool for broadening our knowledge of plasticity.

Among the instrumental factors contributing positively, the aberration correctors can be mentioned again, because they allow the use of objective lenses of larger gaps and affordable space. Another one is the access to microsystem technologies and to the latest generation of piezodrivers elaborated by the STM community. As recent illustrations, the observation of the solution growth of colloidal Pt nanoparticles [33] and of Pt_3Fe [34] nanorods has been reported by two groups at Berkeley using the TEAM project microscopes. TEM in liquids is nowadays feasible as illustrated by **Schuh and de Jonge** in this issue, see also [35].

Although many fields of research in condensed matter could potentially benefit from time-resolved studies in the nm and sub-nm range (i.e. phase transformations, melting and solidification, and eventually creation and breaking of bonds), the development of time-resolved electron imaging has remained rather slow over the past decades. Bostanjoglo at Berlin [36] developed a high-speed TEM to investigate laser-induced fast non-periodical processes on the ns time scale (DynamicTEM). More recently, this field of research has spectacularly and convincingly exploded under the impulse of Zewail and colleagues at Caltech. They introduced ultra-fast electron microscopy in the UTEM machine, with multiple shots made of a very small number of electrons (typically one per pulse) to monitor highly reversible processes with a spatial resolution of 1 nm and a time resolution down to about 100 fs. In their contribution to this issue, **Baskin and Zewail** fully review their work at Caltech leading to "4D electron microscopy imaging in time and space" [37].

Inspired by previous work in photon optics which has shown that photons can carry orbital angular momentum, recent studies initiated by the theoretical prediction of Bliokh et al. [38] have led to the practical realization of electron vortex

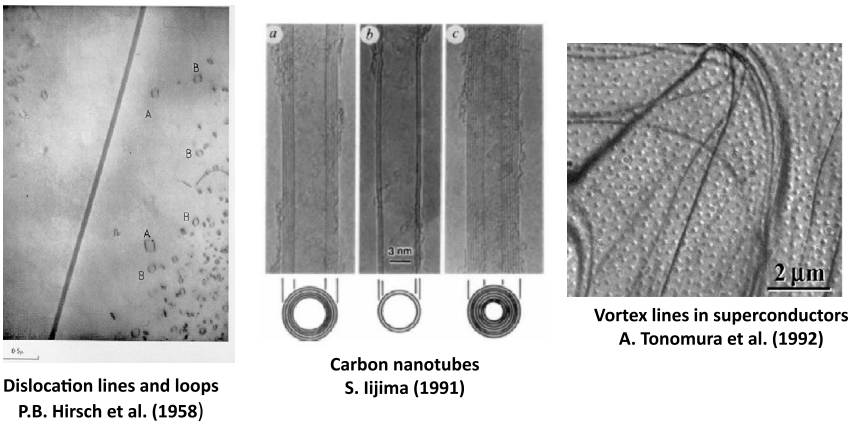

Fig. 6. A few major discoveries realized with a TEM.

beams also carrying an angular orbital momentum ℓ [39]. A first practical application of such a shaped beam has been demonstrated in the study of the chirality in inelastic transitions exhibiting magnetic sensitivity, as involved in magnetic circular dichroism spectra. In their contribution, **Verbeeck et al.** discuss how the new possibilities of shaping the electron primary beam can optimize certain measurements.

7. Past, present and future impact of TEM in the global science landscape

As a most recent example, we recall that the 2011 Nobel prize in Chemistry was awarded to Dan Schechtman for his discovery of the quasi crystals, thanks to a comprehensive analysis of TEM electron diffraction patterns exhibiting an extraordinary fivefold symmetry [40]. Over the past decades, many other discoveries could also be quoted. Focusing on to the field of physics, chemistry and materials science, Fig. 6 is a personal selection of a few of them.

Using diffraction contrast in CTEM, the first observation of dislocations and other structural defects in crystalline solids was pioneered in the late 1950s at Cambridge (UK) by Hirsch, Howie and Whelan [41]. This was the starting point of the blooming TEM impact on microscopic studies and observations in metallurgy over decades and all around the world. The second example is the brilliant identification of the carbon nanotubes by Iijima in 1991 [42], based on a combination of HREM images with atomic resolution and microdiffraction. The last one is the live visualization of vortex lines in superconductors at liquid helium temperature and under dynamic magnetic field reported by Tonomura and colleagues [43].

What will be the next to emerge from the most recent developments in TEM described above? In which scientific domains will substantial progress in understanding and control of matter at the atomic scale be made? Prediction is a difficult exercise, but it is obvious that electron microscopy has become an indispensable tool in many domains of materials science, extending its input far beyond the standard structural characterization. Within this context, the success in the realization of aberration correctors at the end of the 1990s, has obviously played a key role. But they have been substantially enriched by the systematic association of imaging and spectroscopy and/or by the development of nanolaboratory environments which allow dynamic studies under constraints. TEM has thus moved from the traditional fields of metallurgy and semiconductors to brand new domains. Two of them have been selected for specific description here, as they are and will be involved in major fields of use and application. Furthermore, the new potentialities of TEMs presented in all the above mentioned papers, will form a very rich mine because of the “easy-access” to the atomic-level parameters. The first one deals with the carbonaceous materials, and in particular with graphene, by **Mangler and Meyer**. The second one concerns metallic nanoparticles involved in heterogeneous catalysis reviewed here by **Zhang and Su**.

This spectacular broadening of the field of application of modern instruments has generated a strong surge of motivated users in many different domains of research beyond its traditional ones. In parallel, the new possibilities in spectroscopy, holography, tomography, *in situ* measurements, require a wide range of expertise which is rarely to be found in a single laboratory. For these reasons, several initiatives have been stimulated and pursued over the past years to connect a few specialized centers into networks with several priority missions: training, open access to specific tasks, mutual exchange for continuous improvement of hardware and software, around a limited number of selected microscopes. This final contribution therefore reports three experiments of TEM networking presently run at national levels (AMMRF in Australia – see **Ringer and Apperley**, METSA in France – see **Épicier and Snoeck**) and internationally (ESTEEM supported as an Integrated Infrastructure Initiative–I3 – by the European Union, see **Snoeck and van Tendeloo**).

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