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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

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A B S T R A C T

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.

R É S U M É

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

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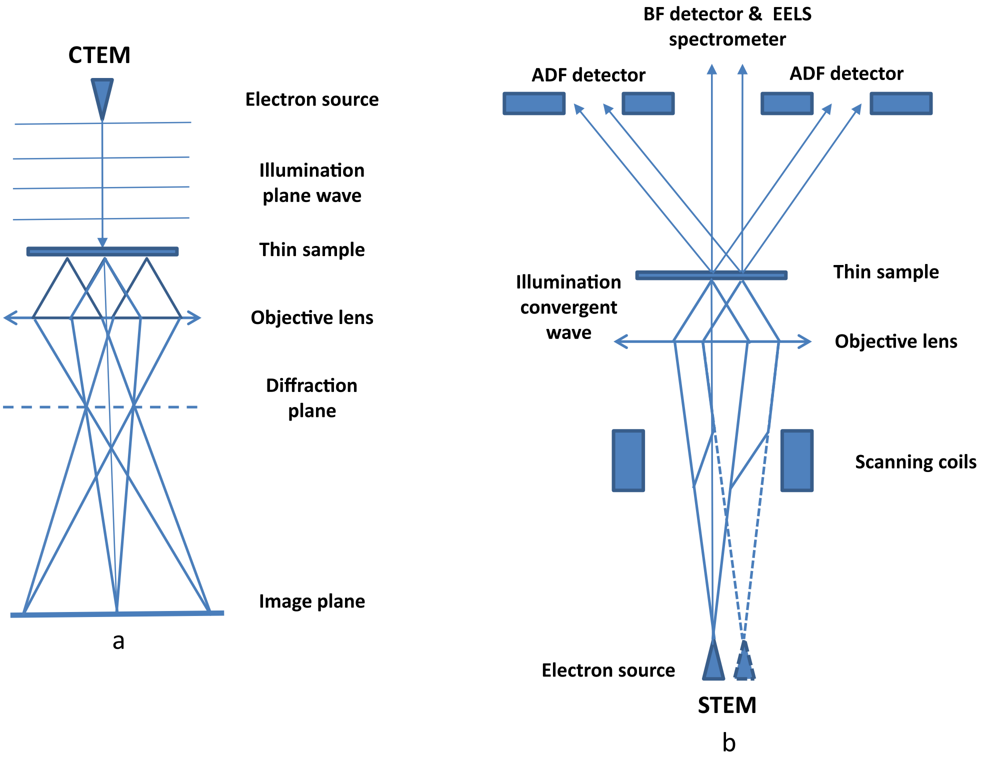

Fig. 1. (Color online.) Ray diagrams for imaging and diffraction in the CTEM (a) and in the STEM (b).

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