Transmission Electron Microscopy (TEM) Tutorial

AtomSolve
元析科技

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Introduction

Transmission electron microscopy (TEM) is a powerful imaging technique that uses a high-energy electron beam to probe the internal structure of materials at nanometer or even atomic resolution. In TEM, electrons are transmitted through an ultra-thin specimen, and their interactions with the sample generate detailed images, diffraction patterns, and spectroscopic data. TEM enables the study of crystal structures, defects, interfaces, and chemical compositions. Due to its extremely high spatial resolution, TEM is widely used in materials science, nanotechnology, biology, and semiconductor research.

0.1 EM lens

Figure (a) shows a **thin optical lens**, which refracts light to form images. A convex lens is depicted: a ray parallel to the axis (Ray A) passes through the front focus F_1 after refraction, while a ray passing through the lens center (Ray B) continues straight without deviation. The intersection of these rays determines the real, inverted image at point I. This setup obeys the lens equation $1/f = 1/v + 1/u$, where f is the focal length, u the object distance, and v the image distance.

Figure (b) illustrates an **electromagnetic (EM) lens**, which uses a magnetic field generated by a solenoid to focus an electron beam. Electrons emitted near point A spiral due to the Lorentz force, which acts perpendicular to their motion and the magnetic field lines. As the electrons spiral forward, their paths gradually converge along the axis to form an image at point B. Unlike optical lenses, which rely on refractive index changes to bend light, EM lenses control charged particles using magnetic fields. Though the mechanisms differ—refraction versus magnetic deflection—both lens types achieve focusing by altering trajectories and satisfy similar geometric relations between object and image positions.

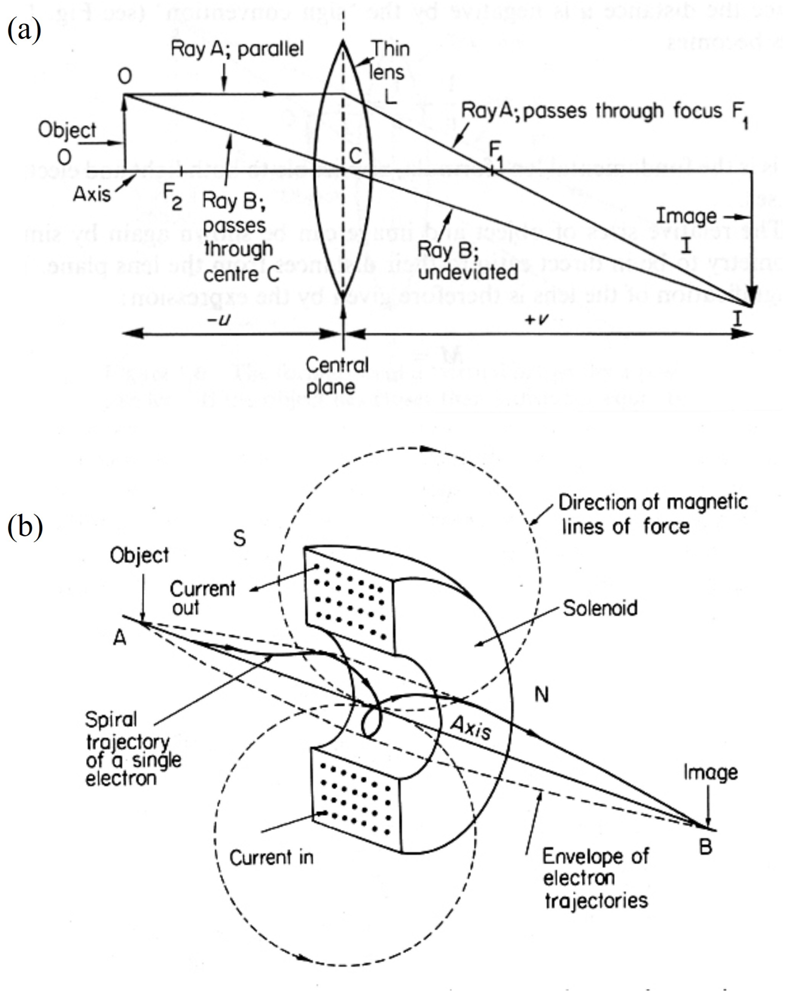

Figure 1: Schematic of (a) optical lens and (b) electro-magnetic lens.

0.2 Operation modes

(a) Imaging mode

In imaging mode, the Transmission Electron Microscope (TEM) is configured so that the objective lens forms a real-space magnified image of the specimen. The electron beam passes through the specimen and the objective lens focuses the transmitted and scattered electrons to form the initial image in its image plane. The intermediate lens further magnifies this image and relays it to the projector lens, which projects the enlarged image onto the viewing screen or camera. In this mode, the intermediate lens is adjusted to focus on the image plane of the objective lens. This configuration is used to observe the specimen's morphology, defects, interfaces, and thickness variations directly as a real-space image.

(b) Diffraction mode

In diffraction mode, the intermediate lens is adjusted to focus on the back focal plane of the objective lens, where the diffraction pattern forms. Instead of forming a real-space image, the microscope projects the pattern of diffracted beams resulting from the crystal lattice planes in the specimen. The projector lens further magnifies this pattern so it can be recorded or viewed on the screen. This mode provides information about the specimen's crystallographic structure, lattice spacings, and orientations. By analyzing the positions and intensities of diffraction spots or rings, users can identify phases and determine structural details. Switching between imaging and diffraction simply requires changing the excitation of the intermediate lens.

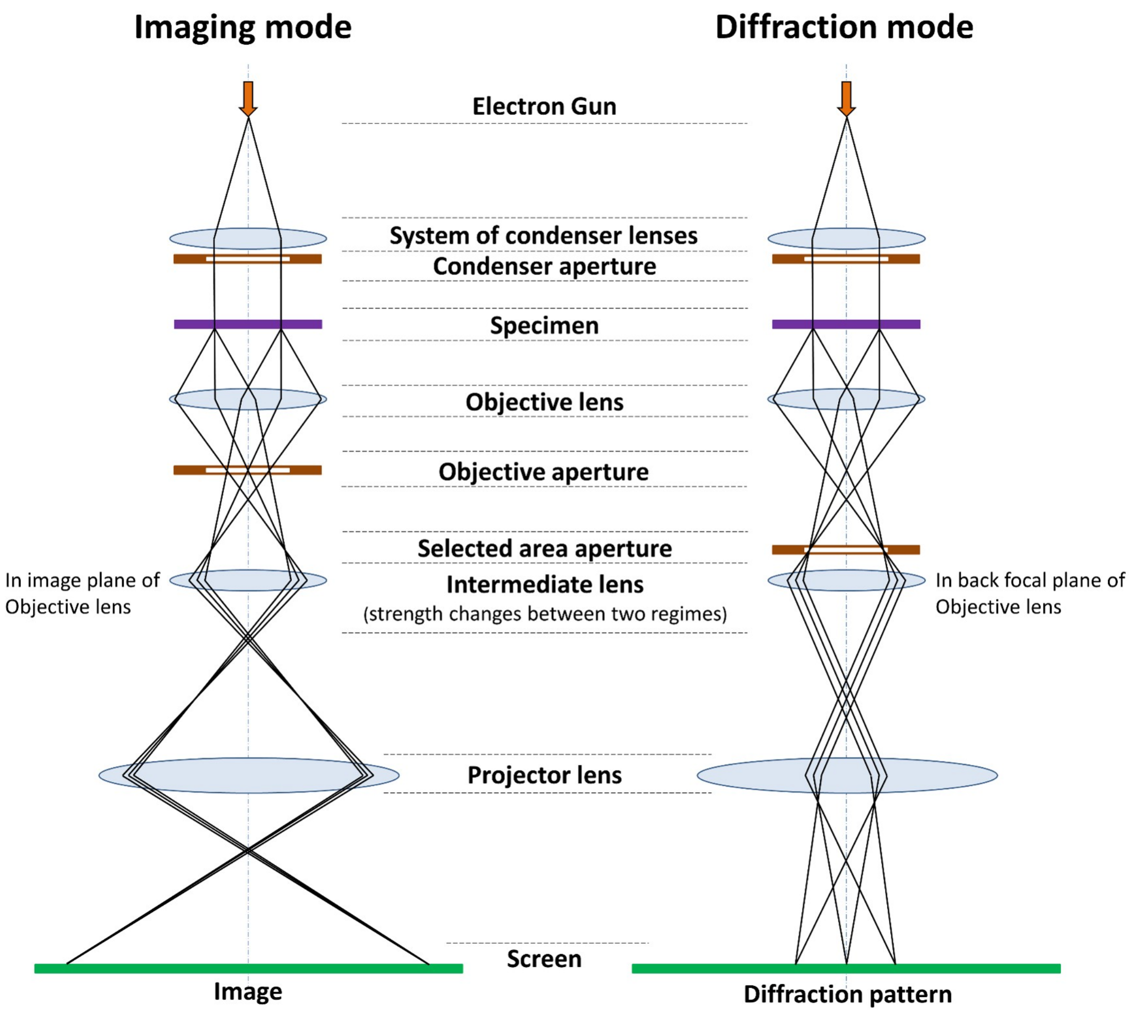

Figure 2: TEM imaging mode and diffraction mode. Image credit: Eric Kvaalen, wikipedia [1].

0.3 Diffraction pattern

This figure presents the electron diffraction patterns of four different materials, each corresponding to distinct crystallographic characteristics, as explained below:

(a) Single Crystal: The image shows regularly and uniformly arranged bright spots, representing diffraction spots produced by the periodic atomic arrangement within a single crystal structure. The diffraction spots are well-defined and symmetrically distributed, indicating a long-range ordered lattice. The electron diffraction pattern of a single crystal exhibits a sharp and regular spot array.

(b) Polycrystalline (Multi-crystal): The diffraction pattern appears as multiple concentric rings, formed by the superposition of diffraction spots from numerous grains with different orientations. Since the sample consists of many small crystallites, each with a random orientation, the diffraction spots form rings in reciprocal space. The ring-shaped pattern reflects the random orientation of the grains in a polycrystalline material.

(c) Amorphous: This pattern appears as diffuse and continuous rings without distinct spots, indicating the absence of long-range order and the lack of a periodic atomic arrangement. In amorphous materials, atoms are arranged without periodicity, and the electron diffraction pattern exhibits broad and diffuse ring-like scattering, reflecting short-range order.

(d) Quasicrystal: According to the classical crystallographic restriction theorem, crystals can possess only two-, three-, four-, or six-fold rotational symmetries. However, the Bragg diffraction pattern of quasicrystals shows sharp peaks with other symmetry orders, such as five-fold symmetry. In the image, the diffraction spots form a complex pattern that is symmetric but not completely periodic. Quasicrystals exhibit long-range order without translational periodicity. Their diffraction patterns reveal a non-periodic yet symmetric distribution of spots—e.g., 10-fold symmetry. Unlike the regular spot arrays of single crystals or the ring patterns of polycrystals, quasicrystals display intricate symmetric structures in their diffraction patterns.

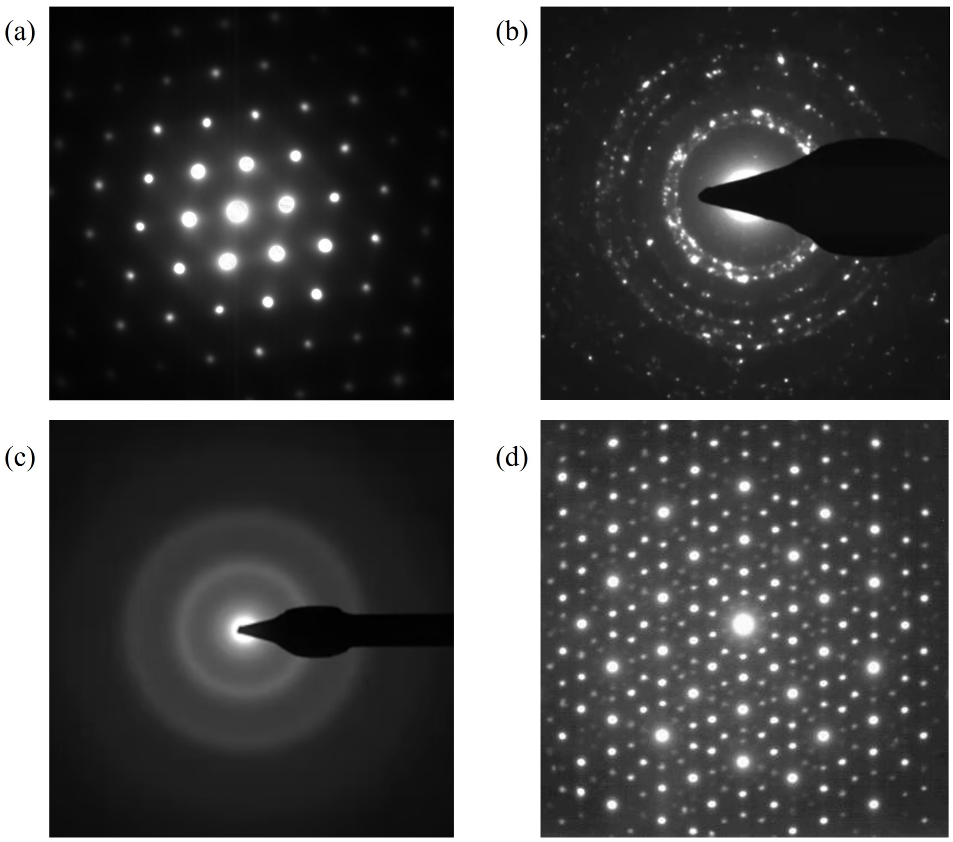

Figure 3: TEM diffraction pattern of (a) crystalline, (b) multi-crystalline, (c) amorphous and (d) quasi-crystalline materials [2].

0.4 Imaging cases

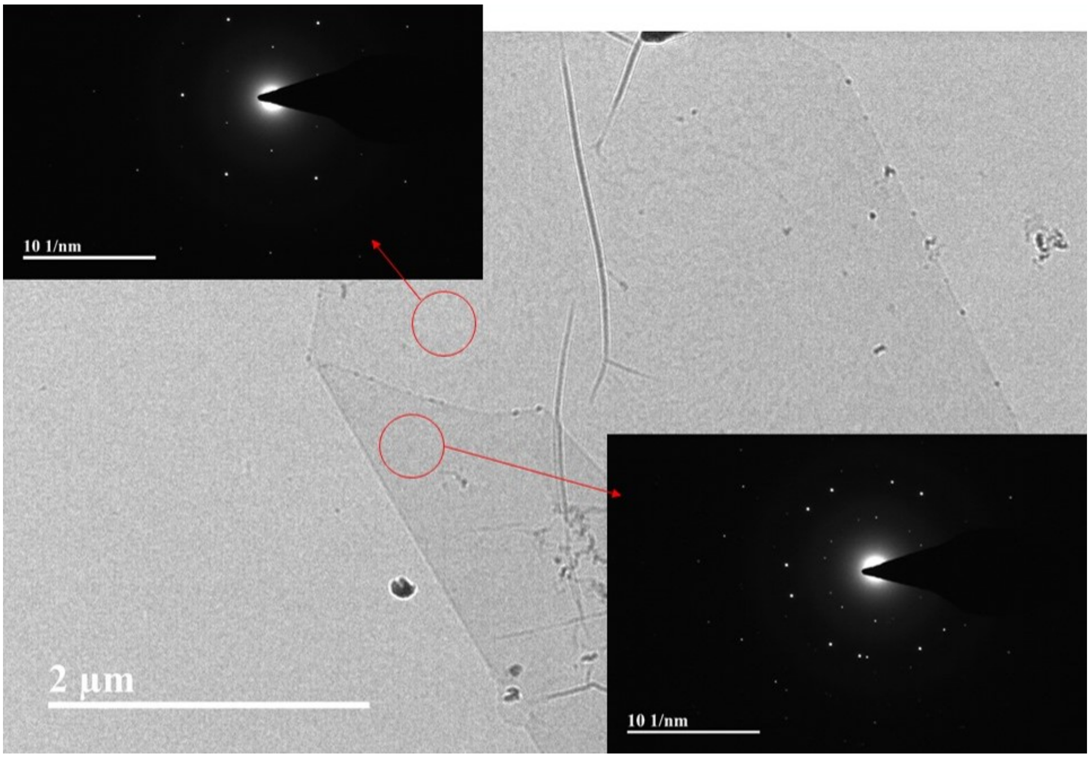

Figure 4: TEM image of ultra-thin material, the diffraction patterns show the single layer and folded bi-layer.

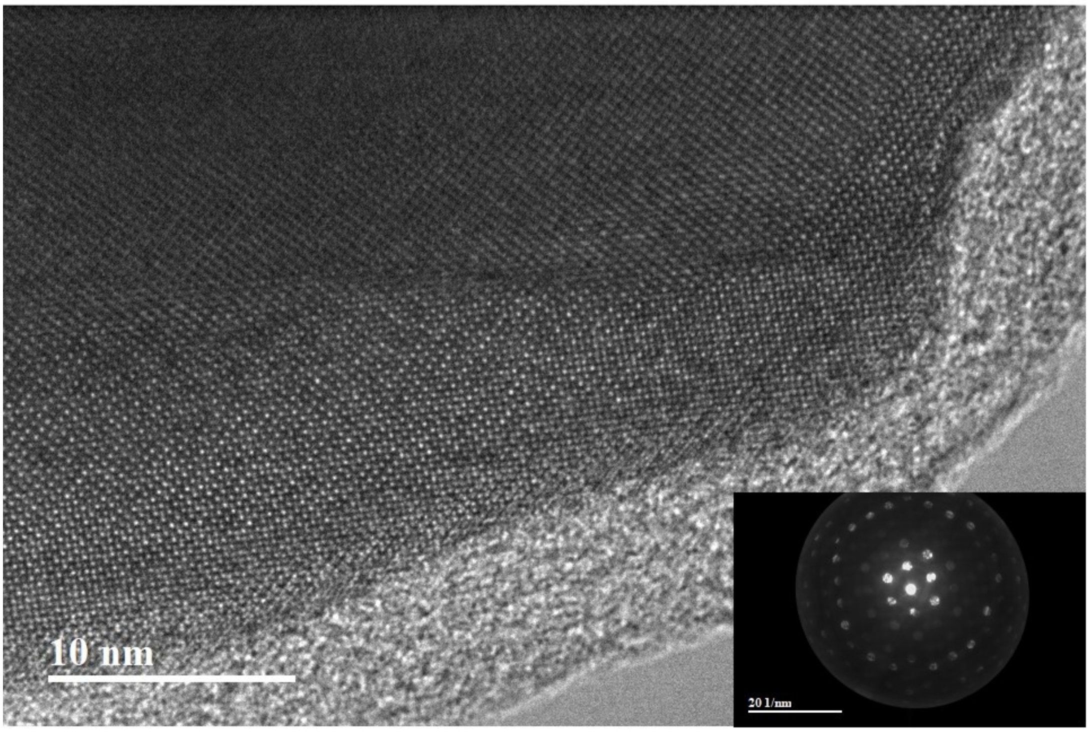

Figure 5: HRTEM image of a nanoparticle, where the atomic columns are clearly shown.

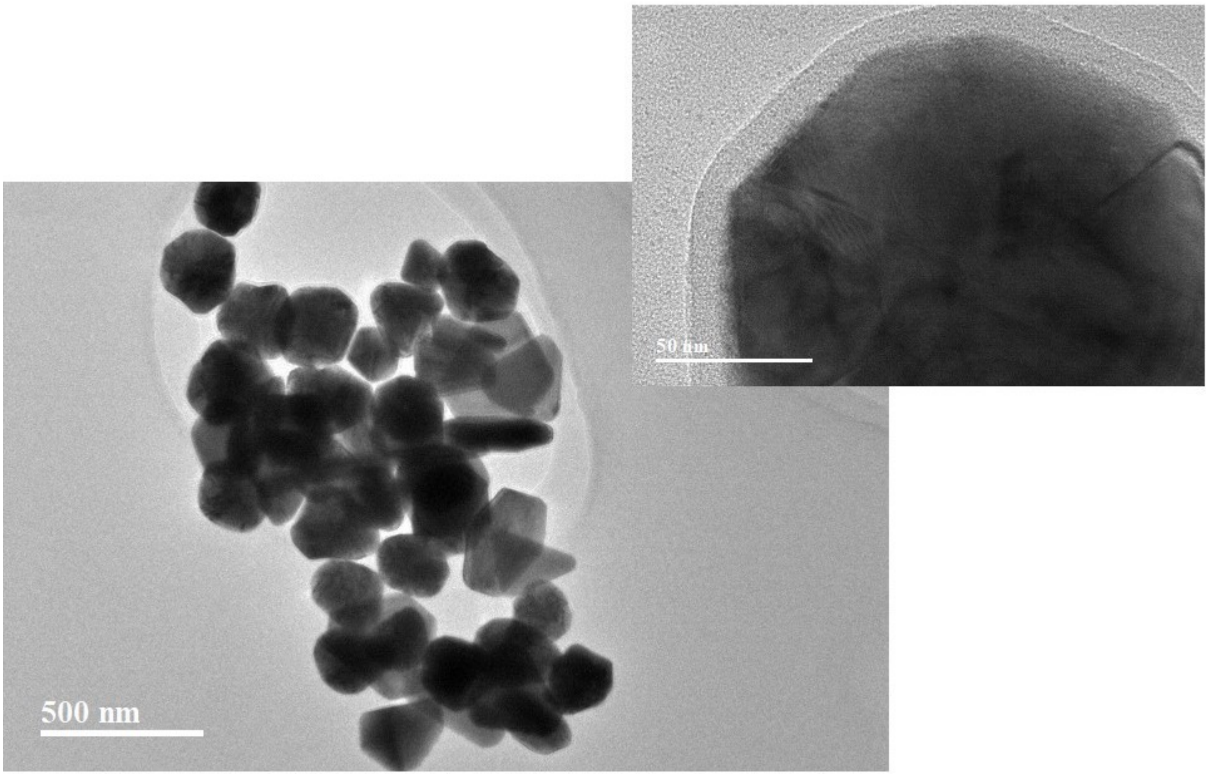

Figure 6: Bright-field image of metal nanoparticles with organic coating.

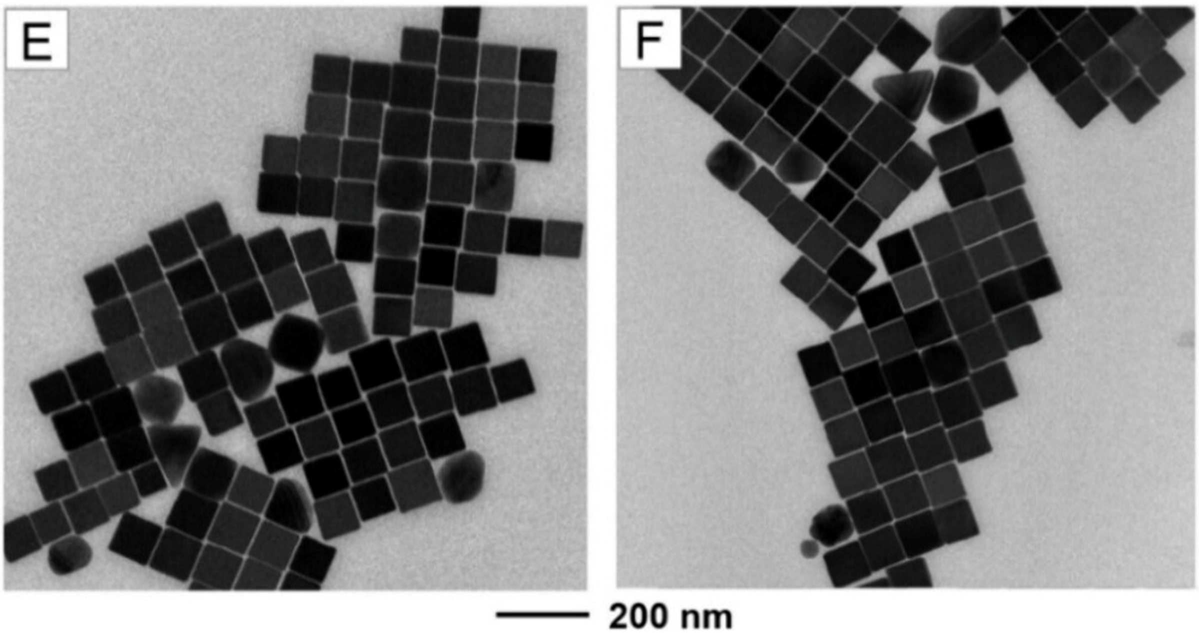

Figure 7: Bright field TEM images of metal nanocubes [3].

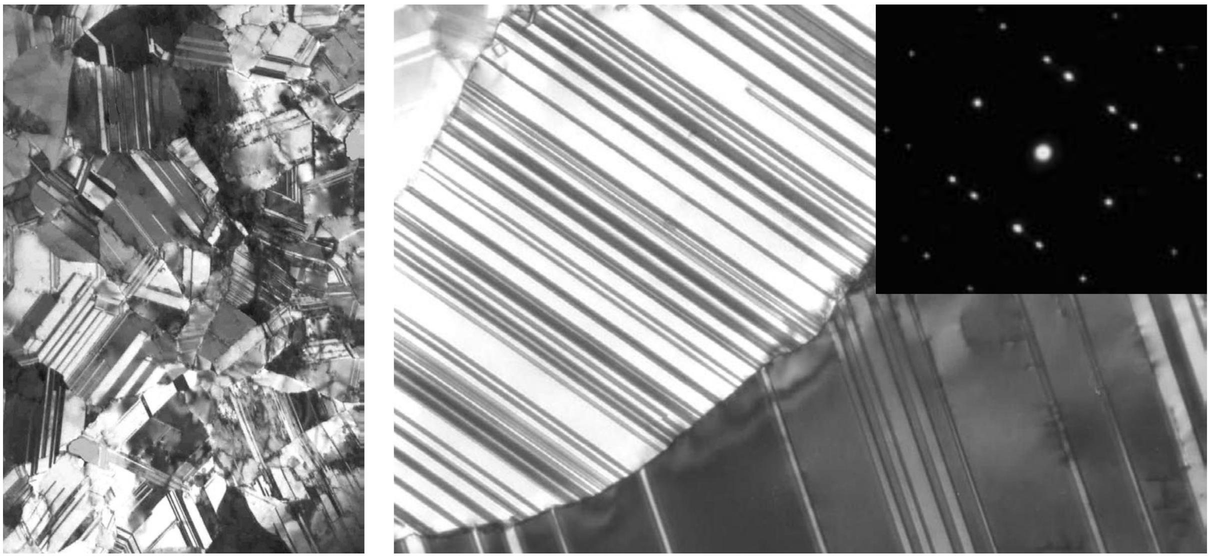

Figure 8: TEM images of nano-twinned Cu, the diffraction patterns shows the twinning [4].

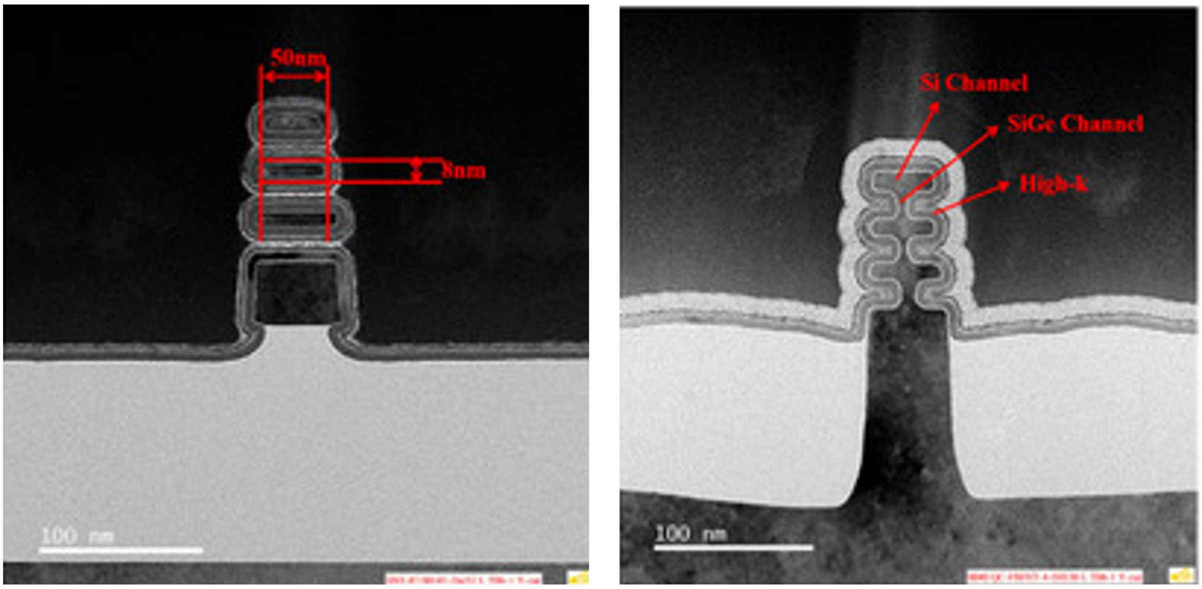

Figure 9: TEM images of semiconductor devices [5].

References

[1] *Transmission electron microscopy.* - Wikipedia. 2003.

[2] C Barry Carter and David B Williams. *Transmission electron microscopy: Diffraction, imaging, and spectrometry.* Springer, 2016.

[3] Qijia Huang et al. "Seeing Is Believing: How Does the Surface of Silver Nanocubes Change during Their Growth in an Aqueous System". In: *Nano Letters* 25.17 (2025), pp. 7115–7120.

[4] Lei Lu et al. "Ultrahigh strength and high electrical conductivity in copper". In: *Science* 304.5669 (2004), pp. 422–426.

[5] Xiaohui Zhu et al. "Low temperature (down to 6 K) and quantum transport characteristics of stacked nanosheet transistors with a high-K/metal gate-last process". In: *Nanomaterials* 14.11 (2024), p. 916.

Contact

T.J. Fang, Sales Manager
Email: tjfang@gmail.com
Tel: +886.932.186.234

Yuan Tu, Ph.D., Technical Sales Mananger
Email: ytujimmy@gmail.com

AtomSolve Technology Co., Ltd.
Address: No. 168, Lane 256, Yilin Road, Rende District, Tainan City 717, Taiwan (RoC)
Web: https://www.atomsolve.com

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