ATOMIC MAGNETISM FINALLY CAUGHT ON CAMERA

A REVOLUTIONARY ELECTRON MICROSCOPE enables the first imaging of an atomic magnetic field.

Transmission electron microscopes (TEMs) have been advancing our knowledge of the very small for nearly 100 years. Since their advent, they have helped scientists see structures as small as individual atoms. But they suffer from a fundamental drawback — to image individual atoms, samples have to be placed in strong magnetic fields. This makes it impossible to image materials that are strongly affected by magnetic fields, such as magnetic materials and steels.

Now, by developing a TEM that generates only very low magnetic fields at the sample, a team of researchers in Japan and Australia has succeeded in directly imaging an atomic magnetic field for the first time.

Instead of using light like optical microscopes, TEMs use beams of electrons to irradiate extremely thin samples. In a conventional TEM, the electrons are focused by electromagnetic lenses. As they pass through the sample, they are scattered before being picked up by electron detectors, which generate a visual representation of the sample. This technique can be used to scan a larger area of the sample or a specific point when using a scanning TEM (STEM).

SLASHING MAGNETIC FIELDS

In 2019, researchers at precision-instrument manufacturer JEOL Ltd. and the University of Tokyo, developed a magnetic-field-free atomic-resolution STEM (MARS). The instrument incorporates newly designed magnetic objective lenses as well as a higher-order aberration corrector.

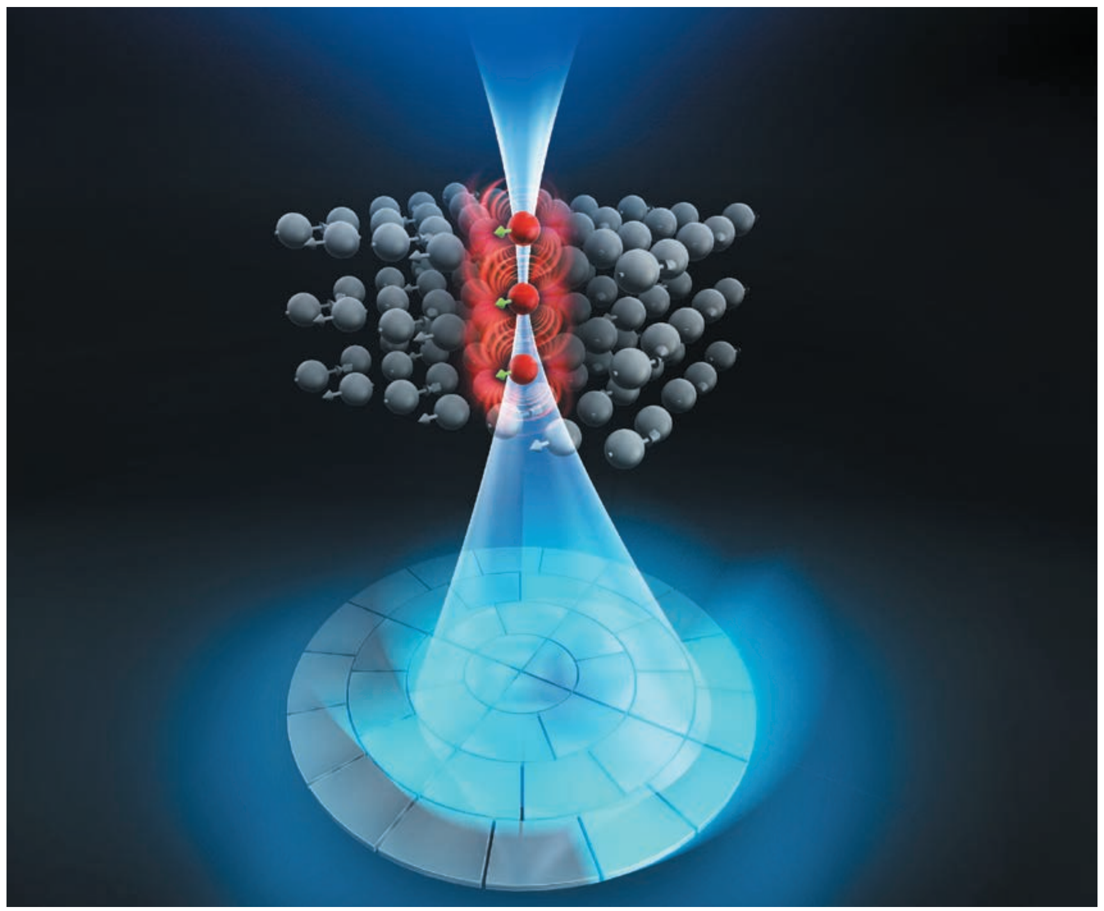
MARS can image individual atoms at a sub-angstrom resolution with a residual magnetic field of less than 0.2 millitesla at the sample. MARS allows for direct imaging, down to atoms, of magnetic materials such as silicon steels, which are important for motors and transformers.

The team consider it as a new stage in atomic-resolution electron microscopy.

"The very strong magnetic fields in TEM lenses can change or damage the structure of magnetic materials, preventing the observation of samples," says Naoya Shibata, a director and professor in the Institute of Engineering Innovation at the University of Tokyo, who led the development of MARS along with engineers from JEOL. "We wanted to overcome that limitation."

REPOSITIONING LENSES

The researchers hit on a relatively simple idea for creating a TEM without strong magnetic fields — they designed a new arrangement of lenses. Instead of using a single objective lens as in conventional TEMs, they placed two round lenses in front and behind the sample plane, forming a symmetrical arrangement of lenses. Because the magnetic fields in the two lenses have opposite polarities, they essentially cancel each other out at the sample plane. Even though the lenses are close enough to the sample to yield atomic-resolution imaging, the residual magnetic fields at the sample position are about 10,000 times smaller than those in conventional TEMs used for imaging atoms.



▲ Image depicting atomic-level, magnetic-field observation by MARS.

The team used MARS to image magnetic fields in iron atoms in a hematite crystal. In a colour-contrast image of the iron atoms, fuzzy groups of colourful blotches represent magnetic field orientation and strength. The results were the first such observations in the world.

"MAGNETIC-FREE OBSERVATION IS CRUCIAL FOR STUDYING QUANTUM MATERIALS."

"When we first saw the results, we were happy, but skeptical. We did a lot of analysis and experiments to prove that we were actually imaging magnetic fields," says Shibata. "We wanted to see magnetic fields emanating from iron atoms because the origin of magnets lies in the atoms. But to do that, we first needed to make magnetic-field-free conditions at the sample position." In addition, the team had to make an atomically sharp probe to measure the tiny magnetic fields.

Shibata credits JEOL engineer Yuji Kohno with the perseverance that made MARS work. Kohno had to take the prototype apart countless times to check that every single component was in order and perfectly aligned. Without that level of precision, atomic resolution observations would be impossible. But the payoff is a powerful tool that promises to be useful for a wide range of fields.

"Visualizing material at the atomic level is essential not only for observation and measurement but also for the development of new materials, such as evaluating their stability and quality," says Toyohiko Tazawa, director and senior executive officer at JEOL. "We feel this is key for developing industrial products to support the growth of society."

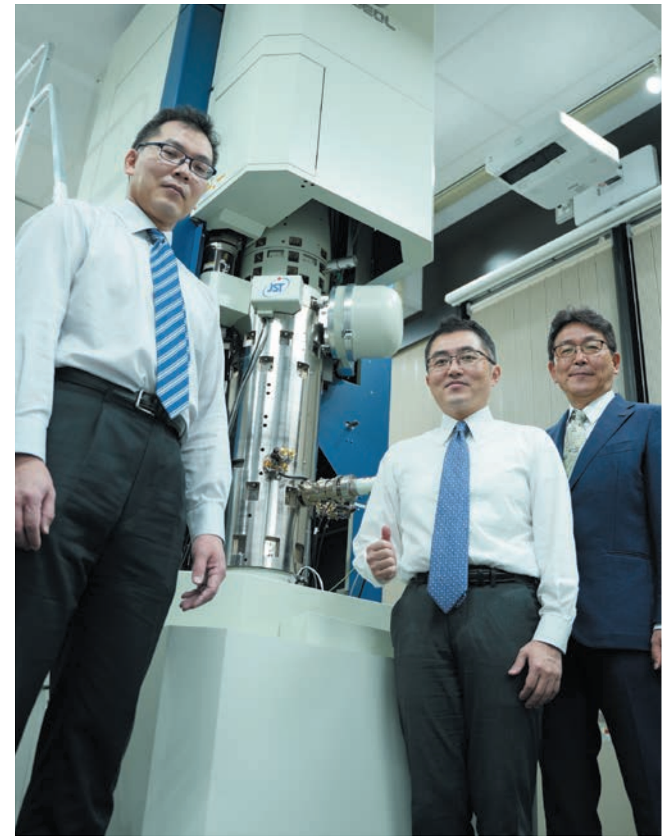
A LONG HISTORY IN ELECTRON MICROSCOPY

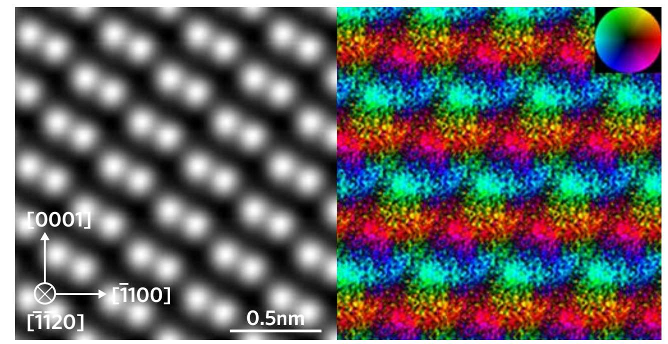
JEOL produced its first electron microscope in 1949, the year of the company's establishment. Today, under the philosophy of aiming for the world's most advanced technologies based on creative R&D, it manufactures scientific, metrological, semiconductor and medical instruments for customers around the world.

One part of the company's history is successful partnerships. Tazawa points out that the development of MARS is one result of a long collaboration between the University of Tokyo and JEOL. It began in 2005, when such industry–academia partnerships were relatively rare in Japan. Both sides embarked on a quest to reclaim the leading position in TEM that Japanese researchers and academics enjoyed from around the 1980s and 1990s.

WIDE APPLICATION

Manufactured by JEOL, MARS was recently commercialized and has already been sold to universities. Companies from steelmaking and other industries have also expressed interest in using the technology to refine products and develop new ones, says Shibata, who has been collaborating with Japanese companies in the steel, ceramic and automotive industries. MARS technology has drawn interest from scientists in fields that include superconductivity and memory device materials.





▲ Top: Researchers standing beside MARS. Bottom: Real-space images of antiferromagnetic alpha-Fe_2O_3. Atomic-structure image (left). Corresponding magnetic-field image (right).

"Magnetic-free observation is crucial for studying quantum materials," says Shibata. "I think our colleagues in the field of electron microscopy would really like to use these magnetic-field-free lenses to explore quantum materials. One of our next goals is to observe magnetic structures at atomic resolution and cryogenic temperatures."

By pursuing breakthrough scientific achievements such as magnetic-field-free atomic imaging with MARS, JEOL and its partners are committed to developing innovations that advance research and ultimately benefit society. ■

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