# World’s first observation of magnetic fields of individual lattice planes achieved using Hitachi’s atomic-resolution holography electron microscope

*Paving the way for practical use of high-performance materials and energy-saving devices to realize a carbon-neutral society*

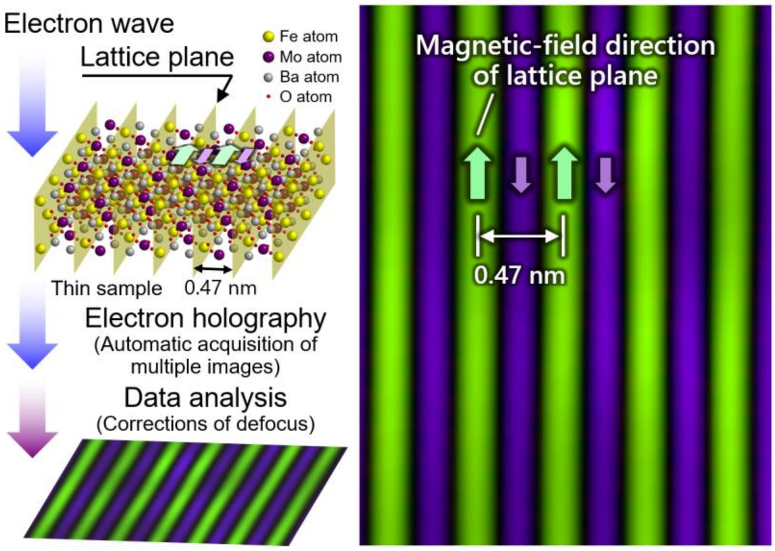


Figure 1. Schematic of observation method and observed magnetic field distribution of individual lattice planes

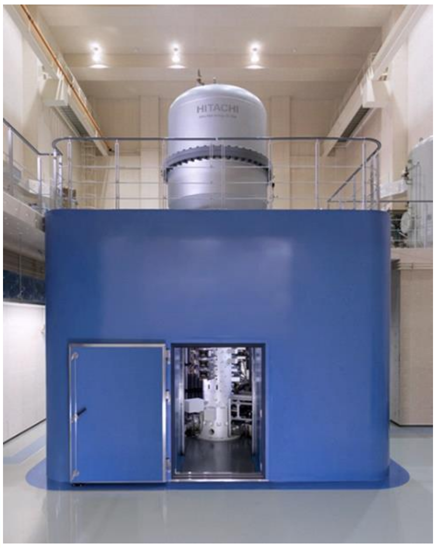

Figure 2. Hitachi’s atomic-resolution holography electron microscope

**Tokyo, July 4, 2024** --- Hitachi, Ltd. (TSE: 6501, Hitachi), Kyushu University, RIKEN, and HREM Research Inc. (HREM) today announced the world’s first observation of magnetic fields of individual lattice planes.*1 This was achieved by using Hitachi’s atomic-resolution holography electron microscope and a method enabling magnetic field observation of samples with uneven structures and compositions (hereinafter referred to as non-uniform samples)*2 such as magnetic multilayer films, which have been difficult to observe so far, in collaboration with National Institute of Advanced Industrial Science and Technology (AIST) and National Institute for Materials Science (NIMS).

Observation was accomplished by developing a technology with a higher degree of electron-holography precision and automated post-image-capture focus correction. With this, it is now possible to observe magnetic fields of the atomic-layer level at local boundaries between materials (interfaces), which greatly affects the physical characteristics of materials that include non-uniform samples and characteristics of electronic devices. In the future, we will contribute to the advancement of fundamental science by elucidating magnetic phenomena*3 occurring at the atomic-layer level and realization of a carbon-neutral society through the development of high-performance magnets and highly functional materials used in electrification for decarbonization as well as energy-saving devices for reducing total energy usage required in our daily life.

The research results have been published online in *Nature*, an international scientific journal, on July 4, 2024 (0 AM in Japan time).*4

*1 Atoms are the smallest stable particles which form objects. Objects are formed when atoms arrange in a three-dimensional manner. The two-dimensional arrangement of atoms in objects is called a “layer” or “plane.” A “lattice plane” is a structure in which atoms are orderly arranged on a two-dimensional plane in an object. It is an important factor as it determines the characteristics of an overall substance.
*2 Here, non-uniform samples are defined not only as samples with random structures such as amorphous but also as samples with different structures and compositions in a periodic structure.
*3 As for the examples of unique magnetic field states at interfaces, there are Malozemoff’s random field model, which treats magnetic fields of individual small areas as random models and assumes an average magnetic field in case interfaces have non-orderly arranged magnetic atom layers; and magnetic Friedel oscillation, in which atomic layers of non-magnetic and magnetic areas have variation in magnetic field strength in each atomic layer and are different from the magnetic field which has uniform state inside.
*4 Toshiaki Tanigaki, Tetsuya Akashi, Takaho Yoshida, Ken Harada, Kazuo Ishizuka, Masahiko Ichimura, Kazutaka Mitsuishi, Yasuhide Tomioka, Xiuzhen Yu, Daisuke Shindo, Yoshinori Tokura, Yasukazu Murakami, and Hiroyuki Shinada “Electron Holography Observation of Individual Ferrimagnetic Lattice Planes”, *Nature*, 2024, doi: 10.1038/s41586-024-07673-w

## ■ Background of the research

Electronic devices and motors are used in a variety of applications, including mobile phones, personal computers, cars, trains, and power plants, supporting our daily life. Many of those functions and performances are determined by the arrangement of atoms, which are the smallest unit of ordinary matter that forms material, and behavior of electrons. As such, to develop new functions and improve performance, there was a need for a technology enabling the ultra-high-resolution observation of matter at an atomic level. Since 1966, Hitachi has been developing the holography electron microscope as an instrument for the direct observation of electric and magnetic fields in extremely small regions, and in 2014, developed an atomic-resolution holography electron microscope with the support of the FIRST program (Figure 2). In 2017, Hitachi and RIKEN achieved a resolution of less than 1 nm,*5 which enables magnetic-field observation of a few atomic layers.*6 To achieve an even higher resolution, however, there were problems regarding improvement of microscope precision and correction of minute defocusing that occurs when images are captured.

Now, the collaborative research team solved these problems and developed a technology for realizing magnetic field observation of individual lattice planes for non-uniform samples such as magnetic multilayer films, which have been difficult to observe so far.

*5 Nanometer (nm): 1nm is equal to one billionth ($10^{-9}$) of a meter.
*6 News release on December 6, 2017, “Successful observation of a magnetic field with the world’s highest resolution of 0.67nm using an atomic-resolution holography electron microscope”.
https://www.hitachi.com/New/cnews/month/2017/12/171206.html

## ■ The main features of the developed technology

### (1) Technology for automated acquisition of large quantities of images for improving precision in electron holography

The precision of electron holography is increased by increasing the number of acquired image data. A technology for automated acquisition of more than 10,000 images over about 8.5 hours while sustaining ultra-high-resolution has been developed by adding automated control and tuning of the microscope during data acquisition and speeding up the imaging based on technology developed in 2017 for precisely separating electric field data and magnetic field data from the result of electron holography observation.

### (2) Technology for digital aberration correction that automatically corrects minute defocusing

To obtain high resolution, a technology to correct minute defocusing that remains in observed data is required. The idea of post-image-capture correction of aberrations is exactly the same as that which motivated Dr. Dennis Gabor to invent electron holography in 1948, and it is theoretically established. To date, however, there has been no technology for automated correction. In this research, automated correction was successfully performed by developing an original algorithm that reduced the impact of noises contained in the experimental data by applying the technique, which corrected defocusing by analyzing electron waves reconstructed from a focus series,*7 to the electron holography.

The developed technology was applied to the atomic-resolution holography electron microscope to observe magnetic materials ($Ba_2FeMoO_6$) with magnetic fields of different strength and directions in each atomic layer, and was used to successfully observe magnetic fields of individual lattice planes in the material at the resolution of 0.47 nm, which upon comparing the experimental results with the simulation results was concluded to be the highest in the world*8 for a method that enables observation of uneven samples.

Using this technology, detailed observation of the relationship between interface structures and magnetic fields in devices and materials has become possible, and the development of highly functional materials and energy-saving devices to realize a carbon-neutral society is expected to accelerate. Furthermore, supported by the Project for Promoting Public Utilization of Advanced Research Infrastructure of the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT), the atomic-resolution holography electron microscope will be used by various parties to contribute to the advancement of science and technology in a wide range of fields from fundamental physics to advanced devices.

*7 T. Tamura, Y. Kimura, and Y. Takai “Development of a real-time wave field reconstruction TEM system (I): incorporation of an auto focus tracking system”, *Microscopy*, 66, 172-181 (2017).
*8 Based on research by Hitachi in July 2024. Here, the resolution in magnetic field observation is defined as the minimum distance available to differentiate magnetic fields pointing in the same direction.

**█ Comment by Dr. Yoshinori Tokura, Group Director, Strong Correlation Physics Research Group, RIKEN Center for Emergent Matter Science**

This result is a novel electron microscopic technology that enables direct observation of magnetic fields at the lattice plane level and the advancement of materials science. I believe that this technology paves the way for innovative establishment of a principle for electronics and development of devices that drastically suppress power loss.

The development of the atomic-resolution electron microscope was supported by a grant from the Japan Society for the Promotion of Science (JSPS) through the “Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)” initiated by the Council for Science, Technology, and Innovation (CSTI). Further, a part of this research was also supported by the “Core Research for Evolutional Science and Technology (CREST)” program (JPMJCR1664) of JST.

**Introduction of Hitachi’s Atomic-Resolution Holography Electron Microscope**

- Overview: https://social-innovation.hitachi/en/topics/rd_electronic_microscope/index.html
- Movie: https://www.hitachi.com/rd/sc/video/2016/1603a.html
- February 18, 2015 news release:
  “Development of an Atomic-Resolution Holography Electron Microscope with the World's Highest Point Resolution (43 picometers)”
  https://www.hitachi.com/New/cnews/month/2015/02/150218.html

**About Hitachi, Ltd.**

Hitachi drives Social Innovation Business, creating a sustainable society through the use of data and technology. We solve customers' and society's challenges with Lumada solutions leveraging IT, OT (Operational Technology) and products. Hitachi operates under the 3 business sectors of “Digital Systems & Services” – supporting our customers’ digital transformation; “Green Energy & Mobility” – contributing to a decarbonized society through energy and railway systems, and “Connective Industries” – connecting products through digital technology to provide solutions in various industries. Driven by Digital, Green, and Innovation, we aim for growth through co-creation with our customers. The company’s revenues as 3 sectors for fiscal year 2023 (ended March 31, 2024) totaled 8,564.3 billion yen, with 573 consolidated subsidiaries and approximately 270,000 employees worldwide.
For more information on Hitachi, please visit the company's website at https://www.hitachi.com.

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