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From Early Days of Cold Field-Emission Electron Gun at Hitachi to Sub-Å Holography

Akira Tonomura

Advanced Research Laboratory, Hitachi, Ltd., Hatoyama, Saitama 350-0395, Japan
Advanced Science Institute, RIKEN, Wako, Saitama 351-0198, Japan
Okinawa Institute of Science and Technology, Kunigami, Okinawa 904-0411, Japan

The brightness or the luminosity of beams is very important for particle beams or electromagnetic beams especially when used as probes for investigating microscopic structures of matter. A most recent example is synchrotron radiation using light beams.

Efforts to increase the brightness of electron beams using field-emission mechanism began in the 1950s: several groups attempted to use a field-emission electron beam as an electron source for electron microscope, but they were confronted with technical difficulties. The first field-emission electron gun was successfully developed for scanning electron microscopes (SEMs) in 1968 by Crewe *et al.* [1] The brightness of the beam increased by a factor of three orders of magnitude, and the resolution of the scanning electron microscope improved from a few tens of nm to a few nm.

In 1972, Hitachi produced the first commercial scanning electron microscope (HSF-2) equipped with a field-emission electron gun under the guidance of Crewe (FIG.1). More than 5,000 microscopes have been manufactured up to now. Bright field-emission electron guns have made it possible to increase the resolution further down to 0.4 nm (Hitachi S5500). In 2009, Zhu *et al.* [2] succeeded in making a 0.1 nm probe by using a Cs corrector in a 200-kV field-emission electron microscope and obtained SEM images of individual heavy atoms!

Field-emission guns also contributed to transmission electron microscopes. In 1970, Crewe *et al.* [3] applied their field-emission gun to a scanning transmission electron microscope (STEM) to improve the resolution down to an atomic scale, and observed individual heavy atoms. Zeitler and Crewe [4] further tried to develop a 1-MV STEM to increase the resolution down to 0.1 nm making use of the shorter wavelength of the beam to observe even individual light atoms.

A field-emission electron beam was also proven to be suitable as a coherent beam for electron interferometry including electron holography [5, 6]. Holography was originally invented as a means to compensate for aberrations in electron lenses, but is now used mainly as electron phase microscopy with wide applications such as microscopic observations of electric and magnetic fields. In 2000, we developed a 1-MV field-emission transmission electron microscope and used to observe individual magnetic vortices in high-T_c superconductors trapped along columnar defects [7].

In 2010, we obtained a big funding of five billion yen as one of the 30 national FIRST projects to develop a holography electron microscope capable of observing quantum phenomena in atomic dimensions. (see http://www.first-tonomura-pj.net/e/index.html). Here FIRST stands for "funding program for world-leading innovative research and development on science and technology". The microscope to be developed is essentially 1.2-MV field-emission transmission electron microscope, which has a spatial resolution higher than ever (lattice resolution of 20 pm and point resolution of 40 pm) and a phase resolution in the order of 1/1000 of the electron wavelength. With this microscope, an object can be observed in atomic dimensions using the phase distribution, not using the intensity, of transmitted electrons. We aim at realizing this microscope by utilizing the bright, monochromatic, and short-wavelength of the cold field-emission electron beam, aberration-corrected lens [8] and holography principle [9], since atoms and molecules are pure phase objects, and their information is completely included in the "wave functions" of electrons but is only partially included in the intensity distribution obtained by image defocusing.

This will open a path to the dream of the observation of the microscopic world in atomic resolution with the "wave functions" of electrons, including the observation of electromagnetic-field distributions and the reconstruction of three-dimensional atomic arrangements, for example.

References

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FIG. 1. Albert V. Crewe at Hitachi Naka Works in 1972.

In the front row, from left to right, Y. Yamada, Y. Ohnuma, A.V. Crewe, I. Makino, T. Komoda, and B. Tadano; in the back row, from left to right, S. Inoue, K. Nakamura, Y. Umino, K. Inoue, S. Saito, T. Nagatani, and H. Akabori.