

Tonomura FIRST International Workshop on “Challenges to New Developments in Electron Microscopy”

Workshop Report

The recent and on-going revolution in electron optics over the successful correction of aberrations, which led to higher spatial resolution, and other developments with new detectors and electron tomography have made it very timely to hold an international workshop on electron microscopy to reappraise its present status and future prospects by bringing together the leading scientists and engineers in the field. The three-day discussion-based workshop, hosted by “Tonomura FIRST Project,” was held in Tokyo on November 8-10, 2010.

The meeting was attended by over 60 participants: 19 overseas invited speakers from the US (9), Germany (4), the UK (3), France (1), Denmark (1), and Belgium (1), and 15 Japanese invited speakers; 4 overseas participants and 24 Japanese participants.

The workshop was comprised of six discussion sessions and a wrap-up session. The following lists the session titles and summary of presentations of coordinators and panelists.

Session 1 “Can we detect electron phase shifts as precisely as 1/1000 of the electron wavelength? -- What can be seen with it? --”

Nano-scale electric fields and magnetic fields are not only very interesting research targets in leading-edge science, but also very useful in technological development once they are effectively used. Electron holography is the method to make this observation possible. Its full use on the atomic scale requires a phase detection precision on the order of 1/1000 of the electron wavelength.

This session on the future possibility of electron holography was coordinated by Hannes Lichte of Technical University of Dresden, who gave general discussion on the possible object of electron holography. Rafal Dunin-Borkovski of Technical University of Denmark discussed the optimization of phase resolution at $2\pi/1000$ level. Required technical conditions to achieve the $2\pi/1000$ phase resolution were discussed by Edgar Voelkl of FEI. Takayoshi Tanji of Nagoya University commented on the improvement of S/N ratio on the high phase resolution holography observation.

Session 2 “Cutting edges of electron holography - Electric and magnetic fields -”

Electron holography is a unique tool to visualize electric fields and magnetic fields inside

and outside the materials and has been extensively used in that capacity to study electro-magnetic behavior in ferromagnetic/ferroelectric materials and superconductors.

This session coordinated by Daisuke Shindo of Tohoku University comprised five presentations. Shindo reported on the progress in electromagnetic field analysis by electron holography and Molly McCartney of Arizona State University discussed nanoscale imaging of electric and magnetic fields by off-axis electron holography in quantification of electrostatic and magnetic fields in and around quantum dots and patterned nanomagnets. Tsukasa Hirayama of Japan Fine Ceramics Center profiled Li or hydrogen distribution in Li-ion batteries through electric potential distribution. Yasukazu Murakami of Tohoku University reported analysis of magnetic domain structures in ferromagnetic memory alloys in relation to domain walls and anti-phase boundaries. Yoshio Matsui of National Institute for Materials Science reported direct visualization of Skyrmion lattices in $\text{Fe}_{0.5}\text{Co}_{0.5}\text{Si}$ by low-temperature Lorentz-TEM.

Session 3 “New applications of electron microscopy and electron holography”

High-resolution electron microscope and electron holography are expected to be applied to wide areas of science and engineering. Without these applications, these instruments lose their identity. The following new applications are going to be considered to expand our technologies: plasmonics in thin films, damage-free measurements, lattice defect measurements, electron vortices, and electronic dynamics in nanostructure materials.

This session on innovative technologies, methodologies and, uses of electron microscopy and electron holography was coordinated by Christian Colliex of CNRS. Colliex discussed mapping of electric fields at nanoparticle surfaces with inelastic electrons by using EELS with light optics and electron energy gain spectroscopy. Non-invasive electron microscopy via interaction-free quantum measurements was suggested by Mehmet Yanik of MIT. Gustaaf Van Tendeloo of University of Antwerp presented ideas of using electron vortex beams with angular momentum to study magnetic and spin structures of materials on atomic scales. Hirotaro Mori of Osaka University presented the results of new application of the 3-MV electron microscope, for example, in situ TEM imaging at voltage up to 3MV and at temperatures from 16 to 290 K. Nester Zaluzec of Argonne National Laboratory discussed prospects for electronic dynamics in nano-structured materials via combined electron and optical spectroscopy. Archie Howie of University of Cambridge proposed to consider the following subjects for the future development of electron microscopy: cryogenic, holographic phase imaging, diffraction contrast phase information, effect of the phonon-scattered

component in HREM images, decoherence in electron holography and longitudinal coherence holographic studies.

Session 4 “What can we observe at sub-angstrom resolution and how far can we increase the point resolution?”

Realization of aberration correction technology made it possible to improve the electron microscopy resolution so that it became possible to directly observe atoms. Is there a technological and fundamental limit to the resolution? When we realize higher resolution, what can be observed?

Further improvement of spatial resolution was discussed in this session coordinated by David Smith of Arizona State University. Smith discussed the determining (dragging) factors of high resolution observation in terms of microscope, specimen, and environment. Kunio Takayanagi of Tokyo Institute of Technology reported the efforts towards imaging of hydrogen atom and proton. Kazu Suenaga of National Institute of Advanced Industrial Science and Technology discussed single atom spectroscopy with reduced delocalization effect at a low acceleration voltage of 30 kV by STEM. Current progress of electron microscope hardware was discussed by JEOL and Hitachi engineers: development of chromatic aberration correctors using combination concave lens system by Yukihiro Kondo of JEOL and atomic resolution imaging by secondary electron using aberration corrected electron microscope by Hiromi Inada of Hitachi Hi-Technologies. Harald Rose of University of Ulm, who had inspired and led the subject of aberration correction for decades, insisted on the harm of electron irradiation damages and presented prospects of the sub-angstrom low-voltage electron microscopy of the SALVE project in Germany. Maximilian Haider of CEOS, a former co-worker of Rose, presented a new production plan of the spherical aberration corrector for the 1.2-MV electron microscope.

**Session 5 “Can we observe atom shape and atom bonding?”
- in relation to electron diffraction -**

Recent research targets have been to capture atoms and molecules, and now their behavior renders important information in leading-edge scientific and technological developments. It is no longer satisfactory to approximate atoms simply as points or spherical objects. The following questions are raised: “Can we observe asymmetric forms of atoms and bonding characteristics?”, “Is higher point resolution needed for this purpose?”, and “Does phase microscopy help to do it?”

This session is concentrated on discussion of the imaging of atomic bonding and real atomic shapes coordinated by John Spence of Arizona State University. Spence insisted on the importance of the observation of atomic bonding of electrons showing that how small changes in electron density led to large changes in the character of materials. Yimei Zhu of Brookhaven National Laboratory discussed various methods to measure the atomic non-spherical electron orbital and reported his result. Gustaaf Van Tendeloo of University of Antwerp discussed results achieved by using precession diffraction method. Archie Howie of University of Cambridge described the routes to mapping of atomic bonding in solids by pointing out various disturbing effects such as excited secondary electrons and surface charge dipoles.

Session 6 “Can we dispense with films and image-pick-up tube?”

-- high-resolution and high-quality image sensors --

Detectors are very important, especially in biological microscopy where radiation damage limits the observation accuracy. Electron holography requires sensitive and high resolution sensors because we want to detect all the electron-carrying information of objects without any loss. We have been using photographic films and image-pick-up tubes to observe images in electron microscopes for a long time. New devices including high-quality two-dimensional image detectors and CCD cameras have been developed.

This session, coordinated by Keiichi Namba of Osaka University and Mark Ellisman of University of California at San Diego, was devoted to discussion on electron detectors. Necessary requirements of detectors were discussed by Namba from the biological electron microscopy viewpoint, especially of 3D reconstruction of protein molecules. Ellisman reported advanced image recording systems, especially development of large array lens-coupled scintillator-based systems and direct electron detectors designed for biological 3D reconstruction. Nobuyuki Osakabe of Hitachi, Ltd. discussed needs for detection system, in particular specifications of the CCD camera for the 1.2-MV electron microscope. Paul Mooney of Gatan reported on development of a high-speed direct detection camera for high-resolution TEM, and Greg McMullan of MRC-Laboratory of Molecular Biology reported on the challenging subject entitled “Can darkroom finally be retired?” and discussed feasibility of CMOS based monolithic active pixel sensors (MAPS) and FEI Falcon detectors.

Session 7 “Can we observe atomic arrangements in three dimensions?”

Properties of materials are determined by three-dimensional arrangements of atoms, for example, DNA. If we can capture these 3D atomic arrangements by using a leading-edge electron microscope with ultra-high resolution, it becomes an exceptionally useful and important measuring tool in addition to X-ray diffraction and electron diffraction methods. We are getting close to that target step by step.

In this session, coordinated by Paul Midgley of University of Cambridge, 3D imaging at atomic resolution was discussed. Midgley discussed present status and future prospects of six possible methods for 3D atomic resolution imaging: tilt series, discrete tomography, model fitting, single atom STEM imaging, through-focus TEM, and reconstruction of aperiodic objects. Gustaaf Van Tendeloo of University of Antwerp brought up an important question: “Is the 3D atomic resolution achievable?” and answered “yes” by increasing S/N ratio and using electron tomography. Kenji Kaneko of Kyushu University discussed ten required factors to achieve atomic resolution in three dimensions in electron tomography by showing the result on CeO₂. Christoph Koch of Max Planck Institute for Metals Research insisted on superior potential of inline electron holography on the 3D reconstruction to the conventional off-axis electron holography. Hiroshi Jinnai of Kyoto Institute of Technology reported on successful attempts of 3D imaging of complicated composite soft material using electron tomography.

Wrap-up Session

This wrap-up session was coordinated by Archie Howie of University of Cambridge who acted as the workshop coordinator. Session coordinators and organizing committee members summarized what were discussed in Sessions 1-7 and reported on future prospects of electron microscopy and electron holography.

Attached is the Workshop Coordinator’s Report by Professor Archie Howie of University of Cambridge on behalf of all the invited coordinators and panelists.