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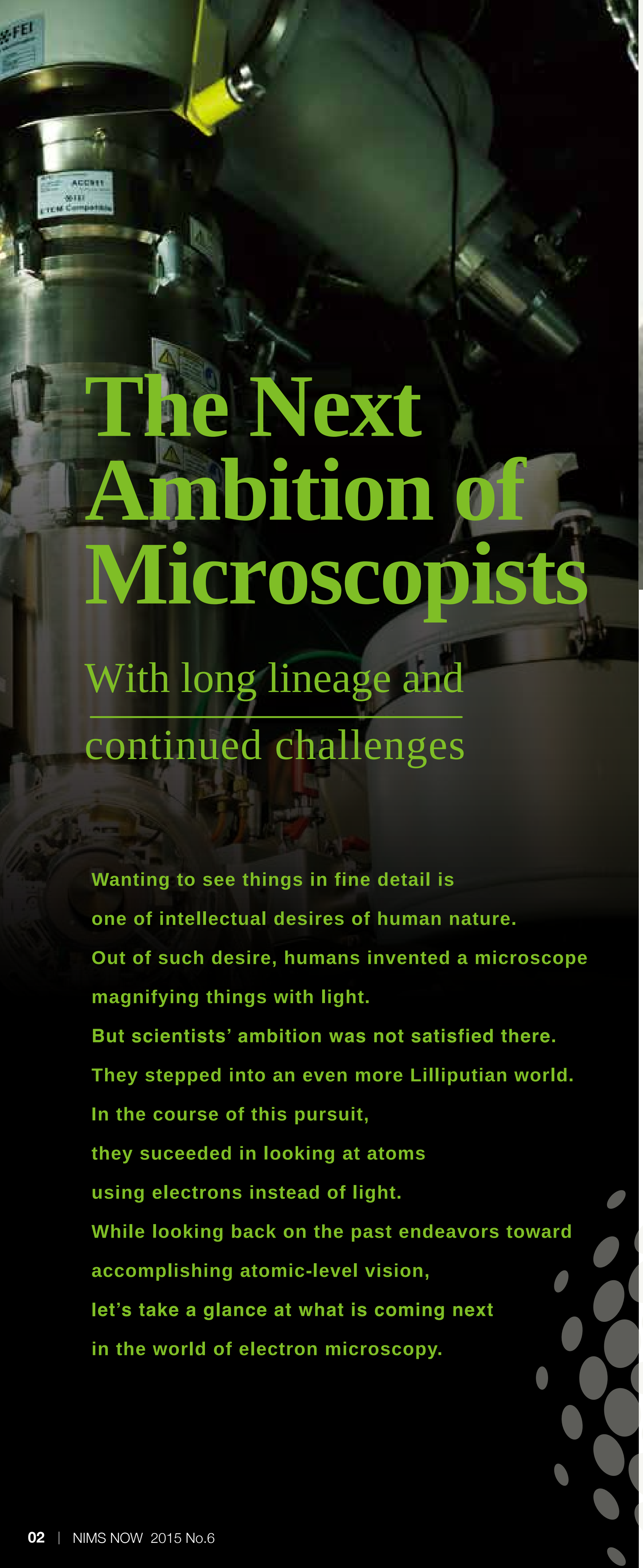
The Next Ambition of Microscopists

With long lineage and continued challenges



The Next Ambition of Microscopists

With long lineage and continued challenges

Wanting to see things in fine detail is
one of intellectual desires of human nature.
Out of such desire, humans invented a microscope
magnifying things with light.
But scientists' ambition was not satisfied there.
They stepped into an even more Lilliputian world.
In the course of this pursuit,
they suceeded in looking at atoms
using electrons instead of light.
While looking back on the past endeavors toward
accomplishing atomic-level vision,
let's take a glance at what is coming next
in the world of electron microscopy.

Koji Kimoto
Director of the Surface Physics and Structure Unit,
Advanced Key Technologies Division,
NIMS

Nobuo Tanaka
President of The Japanese Society of Microscopy,
Professor Emeritus of Nagoya University

Special interview

History of the advancement of the electron microscope as viewed from Japan

Today, the resolution of electron microscopes has reached the sub-atomic level of 50 pm*. How was this accomplished?
The key terms are "high voltage" and "aberration correction."
Here, the two scientists in a teacher-student relationship—Nobuo Tanaka, President of The Japanese Society of Microscopy, and Koji Kimoto, a NIMS unit director, who has been working on materials research using a cutting-edge electron microscope—will discuss the history of the development of the electron microscope.

* 1 pm (picometer) is one-trillionth of 1 m.

Humankind's ambition to see more minute details

Kimoto: I would like to begin our talk on the subject of the invention of the electron microscope. I have noticed that people who see an electron microscope for the first time often look surprised due to the huge differences in size and shape between an electron microscope and the optical microscopes which they are familiar with from science classes at school.

Tanaka: The optical microscopes commonly seen in school science classes magnify small samples using glass convex lenses through which the light illuminating the sample travels to form enlarged images. The first optical microscope was invented in the 17th-century in the Netherlands. On the other hand, looking into the history of electron microscopes, we ultimately arrive at the 1923 account by the French physicist Louis de Broglie, who said that electrons are also waves. Before that, electrons had been considered as particles. Electron microscope originated from the idea that if electrons are waves, then it must be feasible to observe magnified images of small samples using electrons in a similar way to how an optical microscope works.

Wavelengths determine resolution. When visible light, with wavelengths ranging between 380 and 800 nm (1 nm [nanometer] is one-billionth of 1 m), is used, the maximum possible resolution attained is about 100 nm. In comparison, when electrons with wavelengths much shorter than those of visible lights are used, observation of atomic-level objects is possible in theory.

However, there was a problem in realizing an electron microscope; the image of a specimen formed by electrons couldn't be magnified using glass lenses. Amid this situation, the German physicist Hans Busch suggested in 1926 that magnetic fields generated by running electric current through a donut-shaped coil could be used to direct electron beams in a way analogous to the way that glass convex lenses direct light in an optical microscope. Then, in 1931, the German physicist Ernst Ruska successfully created the world's first electron microscope.

Early development in Japan

Kimoto: I believe that the development of electron microscopes in Japan began when the subcommittee of the Japan Society for the Promotion of Science (JSPS) was founded in 1939. Is that correct?

Tanaka: The news that the first electron microscope was invented in Germany quickly reached Japan. Then, based on the idea that Japan should manufacture its own electron microscopes, the 37th subcommittee for research on electron microscopes was organized in the JSPS with Shoji Seto, professor of The University of Tokyo, appointed as a chairman.

Kimoto: I also heard that in addition to researchers from universities and research institutes, engineers from manufacturers joined the subcommittee.

Tanaka: Some manufacturers such as Hitachi, Ltd., Shimadzu Corp., Tokyo Shibaura Denki (currently Toshiba Corp.) and Yokogawa Electric Corp. indeed took part. When World War II broke out, the subcommittee no longer had access to information from Germany. However, the subcommittee continued its own development activities, and succeeded in the manufacture of Japan's first commercial product in 1941. I was once told by my mentor, late Professor Ryoji Uyeda, that when the war ended in 1945, he didn't feel that Japan was behind in the electron microscope science & engineering at all, based on the information that started to come in from abroad again. Japan Electron Optics Laboratory Co. Ltd., a precursor of JEOL Ltd., which is one of the major electron microscope manufacturers today, was established in 1946. And in 1949, the Japanese Society of Electron Microscopy was launched. I am currently serving as a president of the society, and it is one of the older scientific societies in Japan.

Strategy involving high voltage

Kimoto: Electron microscopes are capable of achieving atomic-level resolution in theory, but their initial resolutions were lower than their potential.

Tanaka: The electrons that pass through the periphery of a lens contribute to a blurred image, as they deviate from the focal point. This effect is called a spherical aberration, which reduces a microscope's resolution. Since the time when the electron microscope was invented, this aberration has been a cause of problems. In addition, achieving electrical stability had been a challenge for many years.

Kimoto: Even if aberrations are not fully corrected, resolution can be improved by shortening the wavelengths of the electrons. To achieve this, an ultra-high voltage electron microscope was developed in which the wavelengths of electrons were shortened by accelerating the electrons by applying high voltage to them. Atomic resolution was nearly achieved as early as around 1990 when I was a university student. Only Japanese manufacturers were producing ultra-high voltage electron microscopes at that time, and they were also exporting the microscopes overseas.

Tanaka: Ultra-high voltage electron microscopes once dominated around the world, but a limitation was reached in terms of further shortening the wavelengths of electrons by increasing the acceleration voltage. According to Einstein's special theory of relativity, as the speed of electrons nears the speed of light, the mass of the electrons increases. So, eventually the effort to increase the speed of electrons reached a plateau. Due to this situation, the resolution of ultra-high voltage electron microscopes remained unimproved for a certain period.

Lineages surrounding electron microscopes: Germany and Japan

Kimoto: In the meanwhile, Germany was trying to correct spherical aberrations. This effort was led by Harald Rose, Maximilian Haider and Knut Wolf Urban who won the 2015 NIMS Award. You know them very well and you were closely following their research in progress. How did they develop the aberration correction technology?

Tanaka: To start with, you might be wondering why the aberration correction technology was developed in Germany, not Japan. That is because Germany had a sound academic foundation that developed with the creation of electron microscopes, and was supported by a long lineage of researchers. In regard to aberrations, German physicist Otto Scherzer began basic research from the 1930s. In 1970s, Rose was an associate professor working at Scherzer's laboratory. And Haider was Rose's student. For more than 60 years until mid-1990s when they succeeded in correcting aberrations, they continued research through generations under an unsatisfactory environment. Unfortunately, such a long lineage of researchers does not exist in Japan. There were a few researchers in Japan who created prototypes of fundamental parts based on literature review, but the effort is no match for the lineage of researchers in Germany.

Kimoto: I learned that if you go back in history to the time before Scherzer's era, you will find that the lineage begins with Arnold Sommerfeld who pioneered quantum mechanics. Japan also has a long continuous tradition in different aspects of electron microscopy and diffraction research, and I personally am proud of it.

Tanaka: Roughly speaking, the lineage of electron diffraction researchers in Japan goes back to Torahiko Terada at the beginning of the 1900s. Shoji Nishikawa was his student, and Shizuo Miyake, Seishi Kikuchi and Ryoji Uyeda were Nishikawa's students. Professors Miyake, Kikuchi and Uyeda respectively pursued study on X-ray diffraction, atomic nuclei and electron microscopy, respectively. There are some other lineages of researchers through which many outstanding discoveries were made. Nevertheless, in the aspect of aberration correction, the German lineage was superior to its Japanese counterpart.

Challenge the impossible

Tanaka: There are aberrations in optical microscopes, too, but that can be cancelled by combining convex lenses with concave lenses. On the other hand, in electron microscopes, Scherzer proved in 1936 that concave lenses do not work properly in an axially symmetric magnetic field. Later in 1947, Scherzer suggested that aberrations can be corrected by combining non-axially symmetric magnetic fields generated by multipole lenses consisting of several magnetic poles. Rose and others aimed to correct aberrations using the proposed method.

Kimoto: After the theoretical basis of the aberration correction method was proposed, it took many years to achieve its practical use. When those researchers gave lectures, they often spoke of "mission impossible."

Tanaka: I heard from Haider in person that the toughest time he underwent during the development of an aberration correction device came around the end of the 1980s, just before the device was successfully developed. He said that at that time, he thought he may not make it because people around him told him that that is an impossible task and there was no research funding available to him. One reason for having taken so long to realize aberration correction was that peripheral technologies could not catch up with his work.

Kimoto: In order to correct aberrations, it is necessary to measure the amount of aberration and adjust multipole lenses. However, up until the 1990s, it took a long time to measure aberrations because the general practice at that time was that electron microscopy images were taken by film cameras and the film needed to be developed. During the film processing, the condition of the microscope might change, so it was difficult to correct aberrations using film.

Tanaka: It was the early 1990s when various technologies, such as CCD digital cameras capable of in-situ aberration measurements and software capable of high-precision control, became fully available. Also, the aberration measurement method proposed by Friedrich Zemlin in the late-1970s was helpful. And finally, applying aberration correction, enhanced resolution of an electron microscope was achieved for the first time in the world in the mid-1990s by Rose, Haider and Urban with Urban taking charge of actual observations.

There was another path in the development of an aberration correction device. Ondrej Krivanek of the University of Cambridge, a successor of Albert Crewe who invented the scanning transmission electron microscope (STEM), developed a STEM-compatible aberration correction device. He also succeeded in improving the resolution of STEM in the end of 1990s.

The reason behind a decision on the first installation of aberration correction devices to Nagoya University

Kimoto: Unlike the method of Rose and others, Japanese researchers were pursuing the method of inserting a thin film in a lens and applying voltage to it, as well as the method to correct aberrations by processing recorded images. Since an ultra-high voltage electron microscope gave us fine images, many researchers appeared to be satisfied with the results and thought that it might be unnecessary to acquire the aberration correction device at that time.

Tanaka: Since I was an applied researcher, it was meaningless to merely prove that a method can correct aberrations. Rather, my profession required stable acquisition of clear, high-resolution images of various materials. So, I visited Haider more than five times to decide whether it was really worth equipping the aberration correction device.

Kimoto: You acquired the device as the first person in Japan around 2000. What made you come to that decision?

> **Further advancement of TEM is necessary through developing the capability to measure various physical properties.**
>
> Nobuo Tanaka

Tanaka: I was deeply impressed by Haider as a committed engineer. When he tested the sample I brought, the device wasn't good enough for my applied research purposes at that time. After I explained to him the problems, he brilliantly fixed them in three months. He was an outstanding engineer, a wonderful person and very reliable. In addition to the performance of the device, our relationship of trust was also vital.

Kimoto: Since Haider gave his all to the development of the device, he probably would only have sold the device to people who could use it properly. I suppose that he decided to sell it to you as he knew you well.

> **Japan also has a long lineage in electron microscopy research, and I am proud of it.**
>
> Koji Kimoto

The benefits brought by aberration correction

Kimoto: The use of the aberration correction device dramatically improved the resolution to the current 50 pm (0.05 nm) or less. This value is less than the radius of a hydrogen atom which is 53 pm. In addition to the improvement of resolution, the emergence of the device had expanded the variation of objects to be observed. For example, the use of an ultra-high voltage electron microscope, which employs high-energy electron beams, damages one-atom-thick nanomaterials such as graphene and nanotubes. But the use of the aberration correction device has allowed high-resolution observation without destroying the samples due to the use of low acceleration voltage. This was a great news for materials researchers.

Tanaka: Also, we used to intentionally obtain slightly unfocused images as a means to obtain contrast. Since this operation is no longer necessary with the current technology, research on interfaces has made significant advancements. In addition, this correction technology also reduced the measurement time, for instance, from one hour to one minute. This reduction is important especially from the perspective of industrial use such as semiconductor production management.

Moving forward from the stage of "merely capturing images"

Kimoto: Aberration correction devices have been becoming popular these days, but the currently available commercial products are capable of correcting only third-order aberrations called spherical aberrations, which had been the most serious issue. Since there are higher order aberrations, it is necessary for the development of correction technology to continue. While Japan was left behind in the commercialization of spherical aberration correction devices, do you think Japan can compete with other countries this time?

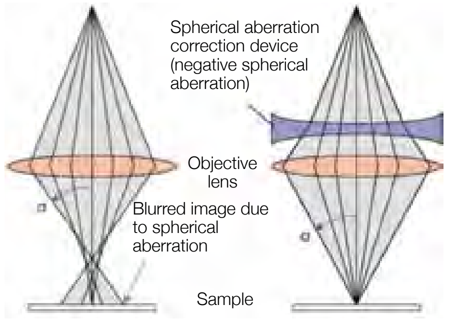
Tanaka: Two or three countries have launched aberration correlation projects such as the Transmission Electron Aberration-corrected Microscope (TEAM) Project initiated by the United States in 2005. Japan, too, has been carrying out two similar projects since 2004 and 2006, respectively. In these efforts, JEOL created an electron microscope equipped with aberration correction device, which achieved resolution of 50 pm or less. Furthermore, Japan developed its own aberration correction device, and succeeded in correcting fifth-order aberrations. Japan is also working on the correction of chromatic aberration. At present, only two or three countries are able to manufacture transmission electron microscopes (TEMs) equipped with aberration correction devices. I believe that Japan definitely has caught up with leading countries in this field.

Kimoto: In the future, what kind of electron microscope technologies do you think need to be developed?

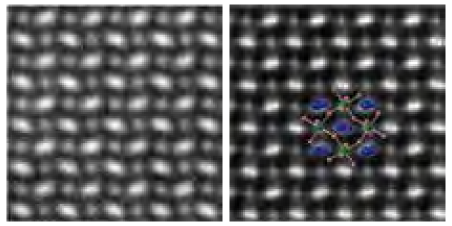
Tanaka: It is true that we now have means to observe atoms directly, but in most cases, we are seeing a column of vertically overlapped atoms in a crystal. So, one goal would be to make individual atoms visible three-dimensionally. Also, in addition to capturing atomic images, further advancement of TEM is necessary through developing the capability to locally measure various physical properties. As for the need to distinguish different types of atoms, the electron energy loss spectroscopy which you are working on has taken care of the issue. As the second goal, I would like to see "limbs" of atoms or bonds between atoms. Some western countries have begun putting efforts into the measurement of scattering due to inelastic scattering. If Japan doesn't work on these subjects right away, it will be left behind again. So I would like to send my encouragement to young Japanese researchers including yourself.

Kimoto: We will do our best.

(by Shino Suzuki, PhotonCreate)



The principle of aberration correction

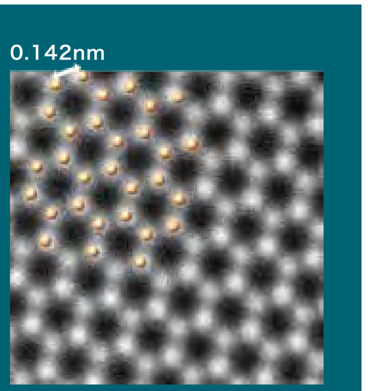


Improved resolution by the application of an aberration correction device

The white dots represent atoms. The conventional TEM is incapable of separating two adjacent atoms, showing them as a white oval (left). The TEM equipped with an aberration correction device is capable of separating two adjacent atoms (right).

Observing atoms, recognizing elements

Koji Kimoto succeeded element-selective imaging at atomic resolution, in addition to visualizing individual atoms in crystals, first in the world.



Graphene observed using an aberration-corrected STEM

If you look at atoms using an electron microscope……

Electron microscopy enables you to look at atoms. But what exactly do they look like?

The scanning transmission electron microscope (STEM) forms an image by scanning a tightly focused electron beam across the sample and using electrons that pass through the sample. The resulting image is monochromatic and shows rows of white dots representing atoms (Fig. 1, left). Because we observe electrons scatter as they interact with atoms in the specimen, the positions of atoms show up as bright dots in the image. An element with a greater atomic number causes the interacting electron beam to scatter more intensively, resulting in a brighter dot in the image. However, it is very difficult to distinguish elements of individual atoms solely based on monochromatic images.

“Visualizing atomic arrangements is a remarkable accomplishment and it is exciting to look at them,” says Kimoto. “But to use the results of electron microscopy analysis for the development of materials, it’s important to recognize the arrangements of elements. And for this purpose, it’s necessary to identify the different types of elements by examining individual atoms.”

Visualizing atomic arrangements in different elements

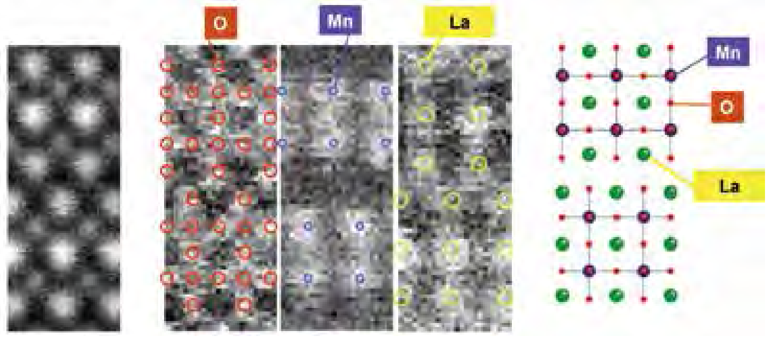
Kimoto has been carrying out research since 2003, aiming at the discrimination of elements. He paid attention to the energy that is lost when interaction occurs in the specimen between the transmitted electrons and the atoms. An atom consists of a nucleus at the center and surrounding electrons forming shells. The amount of energy lost due to interaction between the transmitted electrons and the electrons in the atoms’ inner shells is unique for each element. As such, one can identify which atom is associated with which element by measuring the energy of the captured interacted electrons. “This method is called electron energy-loss spectroscopy (EELS), and it was proposed in the 1980s that a combination of this method with STEM would allow discriminating different types of elements due to the element-specific spectra. But the theory had not yet been realized at the level of atomic arrangements.”

In order to distinguish different elements, it is necessary to measure electron energy loss for individual atoms. And to accomplish this, the electron beam must be narrowed to a width of 0.1 nm, which is close to the diameter of an atom, before penetrating a single atom. That is really a challenge.

Kimoto began to enhance an existing STEM. First, he improved the STEM’s mechanical and electrical stability by about 10 times to prevent the electron beam from missing the targeted atom. Then, he set up the improved STEM in a special vibration-proof experimental building. Moreover, he eliminated as much external disturbance—such as change in temperature—as possible by cutting and pasting insulation material around the STEM.

Later, in 2007, he succeeded in visualizing atomic arrangements in different elements for the first time in the world by combining STEM and electron energy loss spectroscopy, and published the study in the scientific journal Nature (Fig. 1). The commentary article in the journal was dominated by positive opinions and pointing out the significance of Kimoto’s accomplishments. At the same time, limitations of the experimental device, such as the fact that it took one hour to obtain the image, were also pointed out. “I knew that if I had access to a STEM that was equipped with a device capable of correcting aberrations, I could have obtained clearer images more quickly. But we didn’t have such equipment at NIMS at that time, although I didn’t want to use that as an excuse,” says Kimoto. “In addition to the improvement made to the STEM, I searched for other ways to address these issues without using aberration correction devices by simulating and studying quantum-mechanical effects such as the propagation and the scattering of electrons by atoms in a crystal.”

Three months after Kimoto’s publication, researchers in the United States published a paper in Science documenting their success in discerning different elements by examining individual atoms using both an aberration-corrected STEM and EELS. “Their image quality was almost similar to mine, but their images contained many more pixels, were taken with a wider field of view, and were produced in 30 seconds. It was utterly surprising to me, and I realized that my method was inadequate for materials evaluations as it allowed us to look at only a very limited area of a material at a time and it took us one hour to take measurements. But the fact that I produced positive results in this endeavor before anyone else in the world was of great significance.”



STEM image | Images showing the distribution of different elements | Crystal structure

Fig. 1. STEM image of manganese oxide and the identification of different elements.

In STEM images, while the positions of elements can be identified as white spots, it is not feasible to distinguish different types of elements (left). With combined use of STEM and EELS, atomic arrangements in different types of elements can be identified (right).

Fig. 2. Aberration-corrected STEM

Spatial resolution that matches atomic radius

NIMS finally acquired a STEM equipped with an aberration correction device at the end of 2010 (Fig. 2). To minimize the effect of external noise and vibration on STEM operation, the STEM was set up in the basement of a building most distant from a major road on the NIMS campus. In addition, to avoid the impact of floor vibration, the STEM was set on an active anti-vibration table, and to prevent rapid change in atmospheric pressure, temperature and air flow in the microscope room, the door to the room was doubled. After setting a specimen, the rest of the STEM operations were remotely conducted from the next room with an insulated double paned window connected to the microscope room. “Even though the STEM is equipped with an aberration correction device, it is still necessary to thoroughly eliminate external disturbance so that atoms can be observed with high precision,” says Kimoto. The current spatial resolution is 50 pm (0.05 nm), which is nearly the same as the radius of the smallest atom, the hydrogen atom (53 pm).

“We don’t use the STEM with the default specifications set by the manufacturer. We make improvements to it and develop our own measurement system control software. These modifications allow us to enhance the performance of the STEM beyond the level preset by the manufacturer’s guaranteed specifications. Through these efforts, we try to see things that cannot be seen by others.”

The image of graphene (beside the title of this article) demonstrates the high performance of NIMS’ STEM. Graphene consists of carbon atoms arranged in a hexagonal lattice and is only a single-atom thick. “It is difficult to produce a graphene image as good as this one. People from the microscope manufacturer even asked us to give a copy to them for use in presentations.”

Kimoto produced this image using the auto measurement function of his own software, which had been developed since the time when NIMS did not possess an aberration correction device, and combining 300 images into one.

Koji Kimoto

Director of the Surface Physics and Structure Unit,
Advanced Key Technologies Division,
NIMS

Discrimination of lightweight elements become achievable

The research group including Kimoto analyzes not only samples from NIMS but also those from universities, research institutes and private companies in Japan. A bismuth (Bi) high-temperature superconductor is one of them. This material was developed in 1988 at NIMS, and consists of stack layers of Bi, strontium (Sr), calcium (Ca) and copper (Cu). There are several different types of superconductors developed in terms of the number of layers they include, and each type has a different transition temperature to a superconductive state. The research group succeeded in the visualization of atomic arrangement in each element using the STEM and EELS (Fig. 3). This study related to the relationship between atomic arrangements and physical properties, and the information is expected to be useful in the development of practical materials.

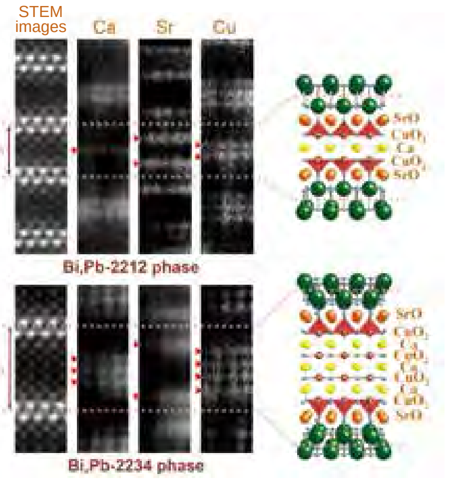


Fig. 3. Images showing the distribution of different elements in a bismuth high-temperature superconductor.

The group also receives frequent requests to analyze lithium (Li) battery-related materials. “Li is a difficult element to analyze because of its small atomic number,” says Kimoto. But the STEM at NIMS is capable of analyzing Li because it is equipped with a device called a monochromator which converts electron beams into monochromatic electron beams. The use of this device has greatly increased the energy resolution from 1 eV (electron volt) to 70 meV. As a result, it is now feasible to analyze elements with small atomic numbers and discern two different elements with similar energy levels.

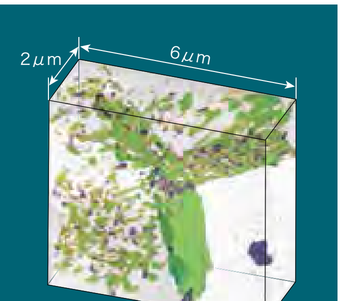
Kimoto’s ambition never ends as he says, “I also want to study soft materials. For example, I want to look at molecules in amino acids. Most specimens we are analyzing now are crystals consisting of numerous atoms. It would be great if we can increase the STEM’s spatial resolution and detection sensitivity. Then, I would like to place a molecule on graphene and look at it while preserving its functions.”

His challenge to observe things no one has seen before using an electron microscope will continue on.

(by Shino Suzuki, PhotonCreate)

A perfect match of manufacturer's new technology and researchers' needs

It all started from one manufacturer came up to Toru Hara, asking for advice.Hara tells us the story behind the development of an electron microscope capable of high-precision three-dimensional structure analysis.



Three-dimensional image reconstructed by extracting only precipitates from tomographic images of heat-resistant steel

Electron microscope was just for a supportive function.

"Actually, FIB-SEMs existed for many years. The key point of the recent development was the invention of orthogonally-arranged FIB-SEM," says Hara. But to begin with, what is FIB-SEM?

The instrument consists of two parts: an FIB and an SEM. FIB stands for "focused ion beam." It is used to process the surface of a specimen by scanning a finely focused ion beam to sputter atoms from the surface. FIB has been used since around the mid-1980s for microfabrication of semiconductor devices. SEM stands for "scanning electron microscope," which enables image production and observation of the surface roughness by scanning a finely focused electron beam across the specimen and capturing back-scattered electrons, secondary electrons emitted from the specimen and other matters.

In the 1990s, needs to observe and process the surface of a sample at the same time, were increasing. In response to these needs, the FIB-SEM was developed. "From the beginning, processing was the primary purpose of the FIB-SEM, and as such, the SEM was considered a secondary device supporting the processing performed by the FIB," explains Hara.

Improvements made by the 30° difference

"Around 2008, I was consulted by an engineer at Hitachi High-Tech Science Corporation. He said that they had a technology with strong potential, and he wondered if I had any good ideas as to what to apply it to," says Hara, looking back on the conversation. Hara learned that the technology would enable an FIB and an SEM to be positioned at right angles (Fig. 1, right). Conventionally, the FIB and the SEM were positioned so that their optical axes intersected at about 60° (Fig. 1, left). After hearing the engineer's explanation, Hara thought that this technology might help enhance the precision of three-dimensional imaging by an FIB-SEM.

"My area of expertise is metal materials including steel. Like many other materials and like organisms, steel materials have a three-dimensional hierarchical structure. Many researchers in this field had been trying different methods, including FIB-SEM, that might work to internally visualize the three-dimensional structures of materials for precise structural studies."

If you thinly cut the surface of a sample using an FIB and observe it using an SEM, you can obtain a tomographic image at a certain depth. Then, if you repeat this process and reconstruct an image based on the serially produced tomographic images obtained using a computer, you can produce a three-dimensional structure of the sample. However, there was also some inconvenience using FIB-SEM for three-dimensional structure analysis because the instrument was basically designed for surface processing.

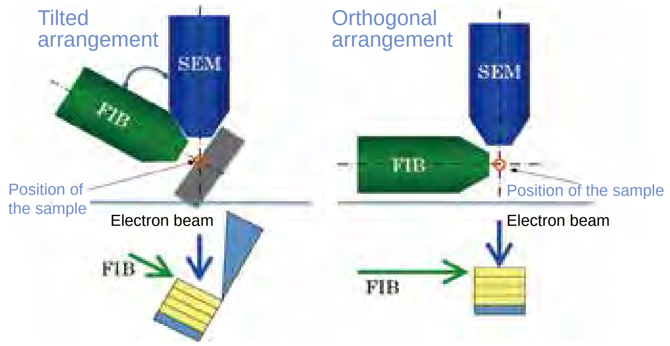


Fig. 1. Positioning of the FIB and the SEM in an FIB-SEM.

Fig. 2. Orthogonally-arranged FIB-SEM.
An FIB-SEM operator, Nakamura (right), says, "Analyzing a skull in a chicken embryo was memorable. I was able to obtain clean thin pieces of the specimen for STEM." "By obtaining both a three-dimensional image using FIB-SEM and STEM images from the same specimen, you can performed more detailed analysis. But that can be achieved only by experienced operators," says Hara.

The positioning of the FIB and the SEM was the biggest problem. For the purpose of simultaneous observation and processing, it is ideal to position the FIB and the SEM so that their optical axes intersect at about 60°, as this arrangement allows the FIB and the SEM to view the same point at the same time. However, due to the slanted placement of the SEM with respect to the surface of the sample, when tomographic images were produced in succession while surface processing was repeatedly performed, there were problems such as occurrence of drift among SEM images. "If our purpose is to analyze the sample's three-dimensional structure at high precision, the best approach is to arrange the FIB and the SEM perpendicularly. It seems easy to do, but in fact no one had succeeded in achieving that. And I found that Hitachi High-Tech Science knew how to do it."

Matching the manufacturer's new technology and researchers' needs

Hara wasted no time taking a sample to be observed under the FIB-SEM prototype Hitachi High-Tech Science created. "It was amazing. I expected that the precision of the prototype would be higher than that of the conventional FIM-SEMs, but what I actually saw was beyond my expectation." They soon started joint R&D toward commercialization of the new FIB-SEM. "The prototype still needed a lot of improvements. We—materials researchers who often use FIB-SEM—made various requests to improve the product, and engineers on the manufacturer made the improvements according to our requests."

One of their requests concerned the size of specimens to be observed. The prototype was created assuming the size of a specimen being about 0.1 mm, but Hara pointed out that the size was too small. "There is a wide range of steel materials in terms of size, from the nanometer level to the millimeter level. We insisted that the FIB-SEM should enable us to observe samples in this size range." After holding discussions and revising the prototype over and over, we finally created a product with the capacity to observe samples that are as large as 4 mm square and 2 mm thick.

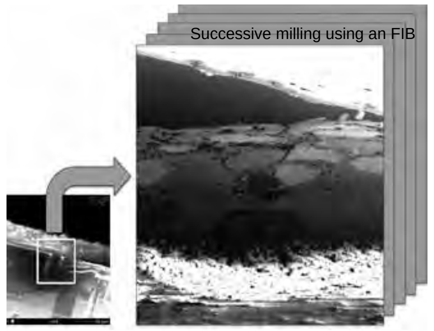


Fig. 3. Observation of a skull in a chicken embryo, from the surface layer to the deeper section.

Hara also did not compromise on his assertion to create a multipurpose FIB-SEM, saying, "I want to gather many types of information in one scan." As a result, the final product was made compatible with several detectors such as an energy dispersive X-ray spectrometer capable of identifying element composition in a sample, an electron backscatter diffraction analyzer capable of identifying crystal orientation, and a scanning transmission electron microscope (STEM) capable of observing the final remaining thin fragment of sample after a series of sample slicing.

The first FIB-SEM product was completed in 2011 and was delivered to NIMS (Fig. 2). When NIMS researchers observed heat-resistant steel using the product, it captured the distribution of interfacial precipitates in a three-dimensional image (beside the title of this article). "During the development of the orthogonally-arranged FIB-SEM, the interests of the highly-skilled engineers at the manufacturer and the needs of the materials researchers who were accustomed to using FIB-SEM perfectly matched."

From battery materials to biological samples to pigments

Hara receives requests from external researchers to analyze a variety of samples using the orthogonally-arranged FIB-SEM.

This instrument has high demand for the analysis of battery materials. Electrodes of rechargeable batteries and fuel cells need to contain pores through which electrons and ions can travel. In order to understand the size and the arrangement of pores, it is ideal to use the orthogonally-arranged FIB-SEM capable of performing precise three-dimensional structure analysis.

While most requests to Hara involve material samples, observation of biological specimens is also carried out sometimes. When asked about the most impressive specimen he has analyzed, Hara answered, "I have analyzed a skull of a chicken embryo, a dental material and an ancient pigment." In the study of the skull, he analyzed from its surface to the deeper layers, and observed the bone tissue formation process (Fig. 3).

Toru Hara
Chief Researcher,
Electron Microscopy Group,
Surface Physics and Structure Unit,
Advanced Key Technologies Division,
NIMS

Excellent operators and rich know-how are the strengths

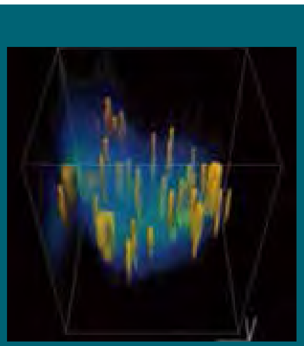
There are presently almost 10 orthogonally-arranged FIB-SEMs in use in Japan. No overseas manufacturer has pursued the development of similar products. "I am pleased that the product, whose development I was involved in, is now widely used, but it's a little sad knowing that the one we are using is now the oldest," says Hara with smile. "Even so, we have excellent FIB-SEM operators at NIMS and have acquired considerable technical know-how. So, our analytical skill level is superb."

Going forward, Hara is planning to place more emphasis on steel materials research, his original profession. "The microstructure of steel hasn't yet been identified at all, and there are many other materials I would like to see in terms of three-dimensional structure," says Hara with a twinkle of interest in his eyes. "If there are things I want to visualize, I will take an approach of developing new devices and techniques in collaboration with manufacturers' engineers. That said, I hope to keep a balance between materials research and device development."

(by Shino Suzuki, PhotonCreate)

Revolutionary idea of “moving a specimen” in STEM

NIMS invented a new technology enabling high-resolution, three-dimensional observation of a specimen’s internal structure. A research group led by Masaki Takeguchi and Ayako Hashimoto played a central role in this accomplishment.



Reconstructing three-dimensional structures of platinum nanoparticles on carbon nanostructures

Three-dimensional imaging using STEM

With their extremely high resolution and due to their atomic-level observation capability, scanning transmission electron microscopy (STEM) is widely used in a range of situations including basic research and practical purposes. However, Takeguchi was not satisfied with the status of the STEM at that time. “In scanning transmission electron microscopy, a finely focused electron beam scans across a sample, and an image of the sample is produced using the electrons that passed through the sample. Due to this imaging principle, STEM images are likened to shadow projection. For example, if you detect a defect in the sample using a STEM image, you cannot tell whether the defect is located in the upper or lower part of the sample. I had been hoping to somehow observe the three-dimensional internal structures of samples using STEM.”

In optical microscopy, three-dimensional imaging had already been realized by means of a technique called confocal microscopy. By focusing on a specific depth of a specimen, and removing all transmitted light out of the focal position, you can obtain an image of that focal position alone. After acquiring several sectional images while refocusing on different depths of the specimen, you can reconstruct these images into a three-dimensional structure using a computer. Since around 2004, Takeguchi had carried out full-fledged R&D in order to realize three-dimensional imaging by applying the principle of confocal microscopy to the STEM.

Moving specimens, not the electron beam

At the same time, Argonne National Laboratory in the United States also had been conducting R&D to realize confocal imaging using STEM since several years before Takeguchi began his study. Because the Argonne group did not have the technology to move the electron beam along an optical axis, they had not succeeded in acquiring the three-dimensional structures of specimens.

On the other hand, Takeguchi had a brilliant idea. “Instead of moving the electron beam, I thought perhaps we could move specimens three-dimensionally by the specimen holder. I named this movable specimen holder a “scanning specimen holder” and carried out basic experiments while making the holder by hand.”

In 2007, Hashimoto joined Takeguchi’s R&D project. “I was utterly surprised when Dr. Takeguchi asked me to create an aperture. Up until that time, my thinking was that an electron microscope was a tool to observe a sample and an aperture was a part of a microscope that could be acquired through purchase,” says Hashimoto, looking back on those days.

Takeguchi had his reasons for being insistent on making microscope-related devices by hand. “Making devices ourselves makes it easier for us to fix problems and add new functions. This approach may appear to be time-consuming, but in reality, research progresses more quickly in this way. And above all, it’s fun to make devices while seeking creative solutions.”

In 2008, Takeguchi and Hashimoto’s group successfully developed a scanning specimen holder. Soon after that, researchers at the University of Oxford in the United Kingdom inquired if they could jointly carry out research with the group. They were also working on three-dimensional imaging using confocal STEM, but their progress was slow. They had come to the conclusion that the employment of a scanning specimen holder was critical for successful development of their product. Takeguchi thought that the joint research would be beneficial for his group as well.

At that time, there was no appropriate electron microscope equipped with aberration correctors at NIMS. But it was available at the University of Oxford. “The University of Oxford was viewed as a leading institute in the field of electron microscopy. I thought that the collaboration between them and us would be like the formation of a dream team,” says Takeguchi. Consequently, a two-year joint research project began from fiscal 2009.

Improving depth resolution using scattered electrons

There was another issue to be resolved in order to realize three-dimensional imaging. “To capture the three-dimensional internal structure of a sample in detail, it was necessary to increase the resolution in the depth direction. But we were beginning to find that it would be difficult to apply the method to produce images using electrons that passed through the specimen, based on both experimental results and theoretical predictions,” explains Hashimoto. “So, we tried to increase resolution in the depth direction using a different method called annular dark-field imaging, in which images are produced using scattered electrons in the specimen.”

The research group repeated the process of creating and testing apertures to be used for annular dark-field imaging. “We greatly improved our skills and speed in aperture making as we created many of them,” says Hashimoto smiling. “As we improved the quality of the aperture, the resolution in the depth direction gradually increased. I really felt the advantage of the hand-making approach as we were able to quickly repeat testing and revision steps.”

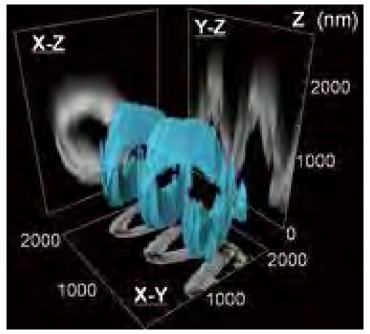


Fig. 1. Reconstructing a three-dimensional structure of a carbon nanocoil
The three-dimensional structure was reconstructed using 27 tomographic images taken at an interval of 100 nm by a STEM without aberration correction.

Masaki Takeguchi
Director,
Transmission Electron Microscopy Station,
Research Network and Facility Services Division,
NIMS

Ayako Hashimoto
Senior Researcher, Electron Microscopy Group,
Surface Physics and Structure Unit,
Advanced Key Technologies Division,
NIMS

Visualization of internal structures became reality

Takeguchi and others finally succeeded in three-dimensional imaging employing a confocal STEM equipped with a scanning specimen holder and an annular dark-field imaging device. They were able to actually observe carbon nanocoils made of coil-formed carbon fiber and reconstruct their three-dimensional structures.

The image of the carbon nanocoil in Fig. 1 was produced using STEM without aberration correction. To get further increased depth resolution, the group combined the aberration-corrected STEM at the University of Oxford and the technologies developed by the Takeguchi’s group. Then, the group observed a sample of carbon nanostructures with platinum (Pt) nanoparticles, and reconstructed the sample’s three-dimensional structure (the figure beside the title of this article and Fig. 2). You can see how Pt nanoparticles are dispersed in the carbon structures. In these images, Pt nanoparticles looked elongated in the vertical direction due to insufficient depth resolution. However, by the time the project was completing at the end of fiscal 2010, the depth resolution was increased to the level at which a single atom was discernable.

In-situ three-dimensional observation

In 2011, NIMS acquired an aberration-corrected electron microscope (Fig. 3), and the research group continues studies today with the goal of more clearly observing specimens’ internal structures. “Actually, our research hit a wall when we found that it was difficult to bring the depth resolution to less than 10 nm, even with the aid of the aberration-corrected STEM. Only recently, a key technology for further improving depth resolution was developed. We are now aiming to reach the atomic level resolution of 0.5 nm,” says Takeguchi enthusiastically. Hashimoto continues with excitement, “In reality, materials consist of atoms arranged in a lattice pattern. But what we are seeing using the electron microscope currently available are vertically overlapping atoms. If depth resolution increases, we should be able to distinguish individual atoms that are aligned vertically. I really hope that will happen.”

Takeguchi’s group is also developing a new specimen holders. The inside of the electron microscope is maintained in a vacuum condition to prevent the emitted electron beam from scattering due to effects from molecules in the atmosphere. However, requests to make “in-situ observations” are increasing these days. In in-situ observations, materials of interest are observed under simulated real-world conditions in terms of high temperatures, the presence of gases, optical illumination and other factors. To meet these demands, the research group is developing a specimen holder enabling in-situ observation under a variety of environments.

Lastly, Takeguchi said, “An electron microscope is like a living creature. It tells you such things as how it is feeling—good or not good, and what it wants from you when it is operated. Unless you carefully listen to these voices, you won’t be able to capture good images. Moreover, it gets angry if you fail to take good images. I would like to continue to capture images of the microscopic world unknown to science using my own ideas and hand-made devices.”

(by Shino Suzuki, PhotonCreate)

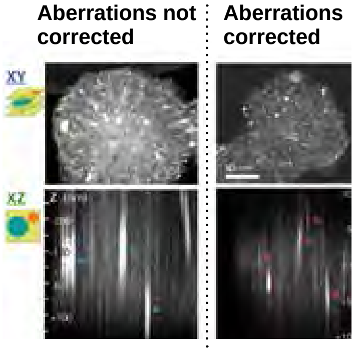


Fig. 2. Observation of platinum nanoparticles on carbon nanostructures.
When an aberration-corrected STEM was used, the nanoparticles looked less elongated vertically in the X-Z images than they did when a STEM without aberration correction was used. The characteristics of the scanning specimen holder also include the ability to capture X-Z cross-sectional images. The figure beside the title of this article (P.10) shows a three-dimensional structure reconstructed using 15 sectional images taken at an interval of 25 nm. Blue indicates carbon nanostructures while yellow indicates platinum nanoparticles.

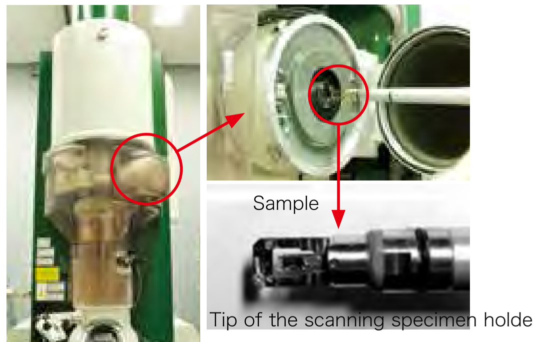


Fig. 3. Scanning-specimen-type confocal STEM.

TALKING WITH THE BIG THREE

Prof. Knut Wolf Urban

Born in 1941. After receiving his PhD from University of Stuttgart, conducted research at the Max Planck Institute of Metals Research, and served as a professor at University of Erlangen-Nuremberg, Tohoku University, etc. Now Julich Aachen Research Alliance Senior (Distinguished) Professor of Peter Gruenberg Institute (PGI-5), Research Center Juelich

Prof. Harald H. Rose

Born in 1935. After receiving his PhD from Technical University of Darmstadt, he conducted his research at The New York State Department of Health, University of Chicago, University of Darmstadt, Lawrence Berkeley National Laboratory, etc. He has been Senior Guest Professor of University of Ulm since 2009.

Prof. Maximilian Haider

Born in 1950. After receiving his PhD from Technical University of Darmstadt, he conducted his research at the European Molecular Biology Laboratory. He founded Corrected Electron Optical Systems (CEOS) GmbH with Joachim Zach in 1996. He is now Honorary Professor of Karlsruhe Institute of Technology, Senior Advisor of CEOS.

Realizing the Impossible

Development of the world’s 1st aberration-corrected electron microscope

A trio of eminent scientists - Prof. Maximilian Haider, Prof. Harald H.Rose and Prof. Knut Wolf Urban – recognized for their revolutionary work involving high resolution electron microscopy gave speeches upon being presented the NIMS Award 2015.

Soon after the invention of the electron microscope by Ernst Ruska in 1931 (the TEM) and by Manfred von Ardenne in 1937 (the STEM) it became clear that the resolution of these new instruments is limited by the aberrations of the electron lenses. These lenses are formed by magnetic fields, and there is a fundamental law in physics which prevents correction of these aberrations by conventional means. So the task left by Ruska and von Ardenne to the next generation was nothing less than to overcome a fundamental law of nature. Although there were some intelligent theoretical ideas and smart attempts to realize these experimentally in Germany, in England and in the U.S., the right way toward the realization of aberration-corrected electron optics had not been found yet by the early 1980s. At about the same time, based on his earlier systematic work, Harald Rose came up with a novel theoretical concept avoiding the problems of all the earlier approaches. That he together with Maximilian Haider and Knut Wolf Urban succeeded to realize his ideas experimentally, the three scientists attributed largely to their team concept: a theoretician (Rose), an experimental physicist with outstanding experience in electron optics (Haider) and a materials scientist (Urban). This enabled realization of the world's first aberration-corrected transmission electron microscope between 1991 and 1997. This was tantamount to breaking the "sound barrier" as to atomic resolution in materials. Today more than 500 commercial aberration-corrected instruments are installed world-wide. With few exceptions, independent of whether these are TEMs or STEMs, all employ the double-hexapole corrector principle developed by the three scientists.

Q: The NIMS Award 2015 selection committee emphasized your contributions to the advancement of materials research...

Prof. Rose: It is appreciated that the selection committee acknowledges the advances in materials science that are enabled by the new corrected electron optics. We consider it a privilege that we became the first in the world to successfully develop an electron microscope capable of atomic-level imaging through the use of aberration correction technology. Nevertheless we would like to offer a nod from our side to the work that had been done in Germany, in England and in the U.S. between the 1940s and the early '80s. That it was not successful underscores the extraordinary complexity of the problems to be solved. It was clearly a premature conclusion when many "experts" believed that this earlier work had shown aberration correction to be impossible by principle. Having worked in the field for decades I always firmly believed that aberration correction is possible. We are grateful to the Volkswagen Foundation that at a time where no other funding agency worldwide was prepared to invest in the advancement of electron optics trusted us and in the universality of our concept for the correction of both TEM and STEM optics by the hexapole based principle, which we then were able to realize between 1991 and 1997.

Prof. Haider: Indeed, it was hard work where each of us had a respective role. It started with the theory, then the realization and afterwards the demonstration of the advantages of this development for the materials science community. We had different backgrounds but were able to work together at different stages in setting up an aberration-corrected electron microscope with enhanced resolution and higher contrast. The device also enabled not only to at last see the atoms in matter but also to measure very precisely their positions. If this achievement led to further progress of various research activities, in particular in materials science, then I am really satisfied!

Prof. Urban: With respect to the application I should like to emphasize that the atomic world is a special world governed by quantum physics. This is often not appreciated when people look at the atomically resolved images which today - thanks to aberration-corrected optics - are part of our daily life. The common saying of "seeing is believing" does in fact not apply to the atomic world's microscopy. That superficially regarded the images are fitting so well to our simple-minded ball-and-stick models trivializes things dramatically. Understanding what we are actually seeing is one of the great challenges after we are now able to penetrate with these new optics into the world of atoms. Is an atom really there where we see a "dot" in the image? Can we really trust a contrast-related or a spectroscopic signal localized at the atom position? I really would like to emphasize at this point the enormous progress in computer-based understanding of atomic images in both TEMs and STEMs. This is the obverse side to the “gold medal” of aberration-corrected atomic-resolution electron microscopy. Yes, it is true, by the atomic-resolution studies we are now able to contribute to nano-scale materials science and to the improvement of materials for our daily life. But it is important to realize that this is done "in tandem" by improved optics and improved quantum physical understanding of our images.

Prof. Rose: Yes, being able to look into the atomic dimensions has opened up a new world. One should not underestimate the changed paradigm; a new mindset is now available, people are thinking "atomic." I understand that one of the reasons for our award selection this year was "popularization" of optical aberration correction for electron microscopes, and of the application as to the new electron optics to materials science and other fields. Let me add that aberration correction has opened up new research opportunities in a number of fields. One of these is electron-energy spectroscopy. Also, to mention recent advances, the electron microscopy of biological materials, biomolecules and cells which are suffering from electron-radiation damage appreciates substantial increases in specimen lifetime under the electron beam employing lower electron energies and aberration-correction technology.

Prof. Urban: In the past scientists had to be content with looking at structures. Please note that a structure is a “collective property” and not a single-atomic one. Today we measure single-atomic lateral coordinates and shifts at the extraordinary precision of better than 1 picometer. This is just one hundredth of the diameter of the smallest of all atoms, the hydrogen atom. This is where the physics happens. And in these dimensions modern electron optics meets the modern ab-initio theoretical computation techniques. These two are teaming up for state-of-the-art materials science. Furthermore we can analyze the energy of the imaging electrons with such a high precision that characteristic energy losses originating from interaction with sample electrons can be probed and used for elemental identification. This is one of the reasons why STEM is so successful today. In STEM the sample is rasterized by a fine electron beam of atomic-scale lateral extension. This permits atom-by-atom elemental analysis.

Q: How did your collaboration all start?

Prof. Urban: Having been responsible over many years for a large electron microscopy installation at Stuttgart I was familiar with electron optics and also the challenges of electron-optics technology. On the other hand, my real “home” was materials science. I had done extended experimental work in many modern fields like superconductivity and quasicrystals, the prominent research topics of the 1980s. And I was in the process of building up a new electron microscopy and materials research group at Juelich. I was aware of the urgent need for atomic resolution in materials research, and I was very pleased that Prof. Rose and Prof. Haider invited me to join the team.

Prof. Haider: In my case, this was before I founded the company CEOS together with Dr. Joachim Zach in Heidelberg, because I knew Prof. Rose since many years and on many occasions at conferences we discussed the possibility to start an aberration-corrector

> ***we knew what we were doing, and this formed the basis of our optimism***

right conviction, strong will and the enthusiasm turned this project into a story of success

project. In summer 1989 at a conference at Salzburg/Austria all three of us met and discussed the possibilities of getting such a project funded which was at this time the main obstacle. However, with the clear scientific justifications and requests by Prof. Urban we could finally convince the Volkswagen Foundation to get for this project the requested financial support.

Prof. Rose: We all used Prof. Haider's in-depth knowhow of electron optical engineering. On this platform, Prof. Urban brought forth invaluable applications of the aberration-corrected TEM by obtaining atom-resolved images with a precision of several picometers based on his expertise in the materials sciences field. This was the starting point for the electron optical industry to develop the new generation of TEMs and STEMs with the all-time record resolution of about 45 pm permitting better than 1 pm precision.

Q: What do you attribute as a specific key to your success?

Prof. Rose: The key was teamwork: we as a team took a look from the materials science perspective, applied modern electron optical engineering methods and attained the required mechanical and electronic stability of the new instrument. With all due modesty please allow me to mention also the new construction principles presented in my 1981 (for STEM) and 1989 (for TEM) papers. We knew what we were doing, and this formed the basis of our optimism which never left us.

Prof. Haider: "Teamwork for an applicable TEM" might be a good slogan for us! Each of us had to fulfill our own tasks at the various stages of this project. My role was more at the mid-term of this development when the theory was clear and the TEM not yet ready for applications. It was sometimes hard work when it took more time to find out and to solve a hidden problem but with the right conviction, strong will and the necessary enthusiasm not to give up - even if the problems are seemingly unsolvable - it was possible to turn this project into a story of success for us three together. And our 1997 success in obtaining about 120 picometers resolution with aberration-corrected imaging opened the gate into a whole new world.

Prof. Rose: The Volkswagen Foundation's funding was a "condition sine qua non" in order that Prof. Haider could acquire the necessary equipment and manpower. As the old Romans noted, not only "Virtute" (being virtuous, hardworking and having the potential) but also "Fortuna", or to paraphrase Prof. Haider, "luck" are essential prerequisites for successful research. If Prof. Haider allows me to continue to speak on his behalf I would like to add that the acquisition of the financial means and the formation of a group of engineers required for setting up a successful company, CEOS, for production of parts, for licensing and for the continuation of the R&D was another essential key to success.

Prof. Urban: I would like to add that what we achieved is nothing less than a change in paradigm in the sense of Thomas S. Kuhn. Nobody is prepared for it, and we have to understand the hesitation of the funding agencies to commit themselves (after decades of world-wide fruitless attempts) to fund "the impossible". Therefore another key to our success was that we spared no effort to convince the materials research community and the funding agencies that the project was doable and promising scientifically and economically.

Q: What do you expect for the future of electron microscope and science?

Prof. Rose: In electron microscopy, I expect more advances in actually utilizing it for tasks like manipulations at the atomic level. Moreover, I expect the revival of electron microscopy in biology and other radiation-sensitive objects due to the availability of high-resolution low-voltage electron microscopes operating at voltages below the threshold for atom displacement. This is an area I am now focusing on at Ulm University.

Prof. Haider: I'm sure we can look forward to a brighter world due to enhanced collaboration between Japan (via NIMS) and the world. There are still many goals to be achieved for ultra-high resolution electron microscopy of imaging of all kind of objects. The research of new materials as well as the understanding of macroscopic properties at the atomic level requires new approaches of imaging and analytical techniques.

Prof. Urban: The future of science will see a continuation of its exponential growth due to new insights and an increase in the availability of new theoretical and experimental tools. We have been able to enrich science by one of these, a very universal one, atomic-resolution electron microscopy. Science will also see an exponentially growing need for science-based solutions. All the great challenges of our time, health, environment, climate change, energy, and not to forget personal and public safety require science-based solutions to very, very difficult problems. Seeing and understanding atoms in condensed matter from biomolecules to engineering materials will play a prominent part in these.

(Interview: C. Pomeroy)

what we achieved is nothing less than a change in paradigm

Science is even more amazing than you think (maybe…) 9

Nobel Prize winners à la carte

Written by Akio Etori

Title lettering and illustration by Shinsuke Yoshitake

Every October, Nobel Prize winners are announced. Last year, all of Japan got excited over the news that three Japanese scientists—Profs. Isamu Akasaki, Hiroshi Amano and Shuji Nakamura—received the prize for their accomplishments in the creation of blue LEDs. This year, too, Prof. Satoshi Omura won a Nobel Prize in Physiology or Medicine and Prof. Takaaki Kajita earned a Nobel Prize in Physics, resulting in Japanese winners for two consecutive years.

Exploration of the minute world has always been a fascination to humankind since ancient times. Several contributors to the development of microscopes, which helped realize such interest, also have won Nobel Prizes.

Dutch physicist Fritz Zernike invented the phase contrast microscope, and collected a Nobel Prize in Physics. His invention enabled people to clearly observe cells, microorganisms and tissues, which were previously difficult to see, as well as plastics, oils, fibers and other materials. The microscope was widely used not only in medical science and practice but also in the industrial sector.

In 1931, German engineer Ernst Ruska succeeded in the development of a microscope that employs an electron beam instead of light. His accomplishment enabled people to look at more micro objects. However, the Nobel Prize was not given to him until 1986—55 years after he developed the microscope! Since the first electron microscope was developed, huge technological advancement had been made. As a result, the electron microscope today enables perceiving objects as small as 50 picometers, which are even smaller than a single atom.

Concurrent with Ruska's Nobel Prize reception, two other contributors to the development of electron microscopes won the prize: Profs. Gerd Binnig and Heinrich Rohrer at the IBM Zürich Research Laboratory, who developed a scanning tunneling microscope (STM). The STM was capable of visualizing the surface of a specimen using tunneling current, and discerning objects as small as 0.1 ångström. Binnig and Rohrer received the prize only four years after the development of the STM in 1982.

I imagine that Dr. Ruska was really patient for 55 years, waiting until his Nobel Prize reception at the age of 80. As you might know, only living people are qualified to receive the prize.

Speaking of waiting a long time until being awarded with the prize, Prof. Yoichiro Nambu, who passed away this year, was another person with a similar experience. In the 1960s, he developed a basis for the Kobayashi-Maskawa theory which predicted the existence of six types of quarks." When he received a Nobel Prize, together with Profs. Makoto Kobayashi and Toshihide Maskawa, in 2008, Nambu was 87 years of age.

I would like to mention one more person who earned a Nobel Prize decades after his accomplishment was recognized. While the current age of information technology is supported by the advancement and popularization of computers, it was initially driven by the invention of the transistor and integrated circuit (IC). The inventors of the transistor were honored with the Nobel Prize within 10 years after their research was recognized. However, the inventor of the IC, Jack Kilby, waited for 42 years before his Nobel Prize reception. He invented the IC in 1958 and was awarded the prize in 2000, making him the last Nobel Prize winner in the 20th century.

In contrast, there also are very fortunate scientists who won a Nobel Prize only a year after they announced their research accomplishments: Profs. Alex Müller and Georg Bednorz at the IBM Zürich Research Laboratory, who were the recipients of the prize in physics in 1987 for their discovery of high-temperature superconductors.

Going back to the subject of microscopes, Profs. Harald Rose, Maximilian Haider and Knut Wolf Urban, who developed aberration correction technology for electron microscopes, have been named as Nobel Prize candidates several times, and so have many other world-renowned scientists. It is expected that many interesting episodes, both joyful and sad, will continue to emerge as winners of this world's most reputable prize are announced every year.

Akio Etori: Born in 1934. Science journalist. After graduating from College of Arts and Sciences, the University of Tokyo, he produced mainly science programs as a television producer and director at Nihon Educational Television (current TV Asahi) and TV Tokyo, after which he became the editor in chief of the science magazine Nikkei Science. Successively he held posts including director of Nikkei Science Inc., executive director of Mita Press Inc., visiting professor of the Research Center for Advanced Science and Technology, the University of Tokyo, and director of the Japan Science Foundation.

NIMS NEWS

1 NIMS signs CCA with National Cheng Kung University, Taiwan

(September 24) NIMS has concluded Comprehensive Collaborative Agreement (CCA) with National Cheng Kung University (NCKU), inviting President Professor Huey-Jen SU at NCKU and Director Dr. Lu-Sheng HONG at Science and Technology Division, Taipei Economic and Cultural Representative Office in Japan. NCKU was founded back in 1931 as Tainan Technical College by Governor-General of Taiwan, and it became the current name in 1971. NCKU has been a pioneering university in engineering and science from the foundation. One of the biggest features is to adopt close collaborations with industry for promoting fundamental researches. NCKU recently has received glowing reviews in medicine and biology as well, and they have conducted enthusiastic research activities in both fields. The central government designates NCKU as the most important university to aim at internationalization with National Taiwan University. NIMS and NCKU had collaborated with each other in specific themes and individual level researches until now; however, the closer and stronger collaboration and relationship between the two institutions than ever are highly expected in interactive researches by this CCA.


Prof. Su (left) and Prof. Ushioda (right)


The attendants focusing on the presentation

2 The 1st NIMS-IMRE Workshop held at NIMS

(October 21-22) The 1st NIMS-IMRE Workshop on Materials Science was held at Namiki Site of NIMS. IMRE, which stands for Institute of Materials Research and Engineering, is a research institute affiliated with the Agency for Science, Technology and Research (A*STAR), Singapore. The workshop consisted of seven technical sessions such as characterization, superconductivity, soft materials and so on. A total of 17 researchers from NIMS and IMRE presented their most up-to-date research results. The researchers also closely discussed possibilities of research collaborations in the individual discussion session, and participants from IMRE attended the lab tour to observe NIMS's cutting-edge facilities and equipments. This WS has surely offered an excellent chance to promote the collaboration between the two institutes.

Hello from NIMS

Hi, I'm an ICYS researcher from Ireland, a small island west of England that is famous for Guinness, beautiful green scenery and ceoil, cainte agus craic (Irish for music, talking and having fun). I first experienced NIMS as a visiting intern during my PhD student on two occasions. During these stays I was exposed to the excellent research facilities available at NIMS as well as the fantastic structures in place for international researchers. These experiences made me determined to return to NIMS in the future. A further incentive for returning to NIMS was the opportunity provided by the International Center for Young Scientists (ICYS) to initiate my independent career. As an ICYS fellow I have my own research budget and the freedom to pursue my own research without restriction. Currently I am focused on a new line of research that branches out from my main expertise – organic solar cells, where I am looking to answer many questions that are not possible from conventional approaches, which typically study bulk materials, thin-films or complete devices. When I'm not in the lab or at the desk, my son is educating me about Japanese trains or *Anpanman* and his friends.


My son brought me on a field study to the Railway Museum in Saitama.


The Ryan family on trip to Izu for some sun, sand and *onsen*(hot springs).

James W. Ryan (Irish)
February 2015 - present
ICYS-GREEN Researcher

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