What is Nanotechnology?

Nanotechnology is attracting an increased attention in the world today. Encouraged by the National Nanotechnology Initiative (NNI) established by former US President Clinton in 2000, research and development on nanotechnology has accelerated as a national strategy of many countries.

The author attended the Micro & Nano Engineering (MNE) Conference 2001 in Grenoble, France, in September 2001. Since the first meeting held at the University of Cambridge in 1975, this annual meeting has been held in various European countries and marked the 27th last year. At the meeting, more than 450 scientists from around the world discussed and exchanged information on nanoscience and nanoelectromechanical systems. Researchers also presented numerous reports on the creation, analysis, and evaluation of nanostructures. In October 2001, the author attended the 14th International Microprocesses & Nanotechnology Conference 2001 in Matsue, Japan, which drew more than 300 participants from throughout the world. Researchers here have also presented and exchanged information on nanotechnology. Although the word “nanotechnology” has become popular recently, it is not an entirely new field as one can see from these conferences.

What is meant by “nano”? “Nano” is a prefix that means one billionth of something like a second or a meter. One nanometer is one billionth of a meter ($10^{-9}$ m). Figure 1 shows the scale of lengths. We can see how small one nanometer is.

We often use a phrase used to express an industrial trend by referring to a specific field. As an example, “the information technology (IT) revolution” is a revolution in communication technology. In contrast, the word “nano” does not refer to a specific field. This means that everything in the cosmos can be the target for nanotechnology. “Nanotechnology” means nanostructure engineering, research, and development in creation of useful materials, devices, and systems at nanometer-size scale.

The smallest unit of substances known to us is the atom, but it is not functional by itself. We may say that nanotechnology produces the smallest functional unit (approximately one nanometer in size) by building groups of atoms.

Approaches to nanotechnology: “Bottom up” and “Top down”

Approaches to nanotechnology research and development are grouped into two categories, “bottom up” and “top down”. The bottom-up approach ingeniously controls the building of nanoscale structures. This approach shapes the vital functional structures by building atom by atom and molecule by molecule. The bottom-up approach researchers are working to find the mechanism of “self-assembly”. “Self-assembly” is like the most basic ingredients of a human body reproducing the most basic structures by themselves. “Self-assembly” covers the creation of the functional unit by building things using atoms and molecules, growing crystals and creating nanotubes.

“Top down” is an approach that downsizes things from large-scale structures into nanometer-scale structures. As an example, vacuum tubes yielded to transistors, they then gave way to ICs (integrated circuits) and eventually LSIs (large scale integrated circuits). The way of creating things by downsizing from millimeter size to micrometer size is called “microtechnology”. The top-down approach is an extension of microtechnology. The narrowest line pattern on a semiconductor device is now coming to the 50 nanometer level. This is an achievement of the top-down approach.

The word “micro electro mechanical system” (MEMS) is not so popular as nanotechnology, but is well known to nanoscience and nanotechnology researchers. MEMS is a system composed of micrometer-size by a combination of electrical and mechanical technology. MEMS technology has already provided many things of practical use to society. Figure 2 shows an example of MEMS. It is a scanning electron microscope (SEM) micrograph showing part of a gear wheel made using lithography technology (field of view: 300 micrometers).

In my understanding, the final goal of MEMS is to create nanoscale structures (NEMS: nano electro mechanical system). There are, however, many hurdles to overcome in its research and development, and many scientists around the world are continuing to make hard efforts.

Nanotechnology will make our life more comfortable

Why is nanotechnology so important? Former President Clinton said, “In the future, all information in the Library of Congress can be stored in the size of one sugar cube”.

There are many practical issues to overcome before reaching this target even if it is theoretically possible.

Thinking of our daily life, for example, since the outer diameter of a gastroscop is 15 mm in the past, was downsized to 2 to 3 mm, the patient’s pain has been greatly decreased during a stomach examination. Let us recall the 1966 movie “Fantastic Voyage”. This is a science-fiction movie in which four miniaturized doctors entered a human body to conduct a brain surgery. Today, a technique similar to this movie, called a “drug delivery system”, has become a reality. This application of nanotechnology delivers medicine to a specific body part, allowing us to use the minimum amount of medicine necessary. Nanotechnology makes our life more convenient and comfortable.

ICs are already incorporated in most of our daily-use appliances and exhibit a variety of capabilities. ICs and LSIs are greatly downsized and multifunctional, making our daily life more efficient. These chips enable us to use handy cellular phones, and automatically pay for train tickets and commodities. Microtechnology has brought about such achievements.

Now, nanotechnology has emerged. In the upcoming years when practical applications of
nanotechnology prevail, our daily life will become much more convenient and comfortable.

### Development of Nanotechnology

**Nanomaterials are in the production stage**

The following is a comment made by a professor at Nagoya University when the author visited him in August 2001. “We have nanomaterials, but no nanotechnology”. “We have techniques to produce nanomaterials like carbon nanotubes (CNT: carbon tubes 1 nm in diameter and several micrometers in length) and nanofullerene (spherical carbon approximately 1 nm in diameter) with a production yield of approximately 90%, but we have no techniques to cut and assemble these nanomaterials”.

Scientists engaged in materials research have been using the transmission electron microscope (TEM) for more than 30 years to observe nanometer-size materials. The professor pointed out that observing nanomaterials is not new, but the technology needed to manipulate and control nanoscale substances is not yet fully developed.

The author will introduce two examples of nanomaterials research. **Figures 3a to 3c** are TEM images that show the creation process of xenon (Xe) nanoparticles. When injecting Xe ions into an aluminum (Al) substrate, Xe microcrystals combine with each other to form Xe nanoparticles. Figure 3a shows the state before the microcrystals combine: **Figure 3b** shows the state during the microcrystals merge; and Figure 3c shows the state after the microcrystals have combined. The resulting Xe nanoparticles are arranged in the Al substrate in the form of solid octahedrons. When viewed from a certain direction, they look hexagonal. The two microcrystals isolated from each other (Fig. 3a) combine with each other to form a single large solid octahedron (Fig. 3c). The TEM images clearly visualize a nanoscale change of a nanomaterial.

The next example is a nanowire. **Figure 4** shows a schematic diagram of a helical multi-shell gold nanowire and a micrograph taken with a TEM (magnification: 20,000,000). This micrograph shows the gold nanowire approximately 1 nm in diameter.

We have great expectations for the fabrication and creation of nanodevices, which will contain nanotubes, nanoparticles, nanowires, and other materials.

**Nanotechnology is in the development stage**

The suggestion of the professor at Nagoya University has provided a hint to what instrument suppliers must do. Namely, we have to meet the demands from top-level researchers engaged in nanotechnology. To achieve this objective, we have to further improve the performance and capabilities of our products by enhancing our technology. After attending several meetings on nanotechnology, the author also recognized that in addition, scientists have many issues for the creation of nanostructures.

A leading industry employing the top-down approach is the semiconductor industry. Integration of semiconductor devices is an application of nanotechnology. The narrowest line pattern of a semiconductor device now reaches below 100 nm; therefore, controlling the patterns at the nanometer level is essential. In addition, the semiconductor roadmap (International Roadmap for Semiconductor Technology) projects the miniaturization of the semiconductor design rule in the future.

However, many difficulties confront us, and research and development are being pushed...
forward aggressively to solve these problems. When downsizing a large substance, the function of this substance also changes. Therefore, we must overcome many challenges that take place.

From the viewpoint of the bottom-up approach, research and development efforts are made based on the following mechanism: A single atom has no function on its own, but when atoms gather together to become the size of DNA (approximately 1 nm), they suddenly have novel functions. In research on metals, ceramics, semiconductors, polymers, and biology, scientists are now evaluating physical properties of aggregates of atoms and molecules. However, we still have a wide range of unknown obstacles, which have to be overcome.

**Nanotechnology is making progress in various fields**

Nanotechnology is now regarded as the core scientific technology. Many researchers have reported that ceramic, metallic, and other materials enhance their physical properties when created using nanoscale control. We can expect that materials can be improved in many ways, and large devices become compact while improving their capabilities. For example, many people are tackling the creation of single electron devices using a single CNT. Utilizing nanotechnology, we can downsize and enhance devices. Nanotechnology is expected to progress in various fields, including information/communication, life science, environmental conservation, energy saving and medical care.

Figure 5 shows an example of the applications of “nanotube tweezers” that are created by means of CNTs. The schematic diagram at left shows the construction of a molecular device using the nanotube tweezers, and the SEM micrograph at right makes the nanotube tweezers visible. The tips of the nanotube tweezers can be opened and closed by switching on and off a voltage between the two CNT probes. Nanotube tweezers are expected to be applied in various fields of research and development on nanoscience and nanotechnology, in terms of the bottom-up approach.

In biological studies, TEM and SEM have contributed to the progress of medical care by offering imaging of virus particles several nanometers in size. Worldwide efforts are being made to create artificial human organs including eyes and ears. We may say that good news will be brought to people with visual or hearing difficulties in the near future.

Many efforts in leading research and development start with the development of new technology and products. This is where JEOL’s challenge to nanotechnology lies ahead.

**JEOL’s Challenge to Nanotechnology**

**JEOL’s continuing challenge to nanoscience and nanotechnology**

Figure 6 shows a composite of a TEM micrograph (replica of a single crystal aluminum surface) and a photograph of mountain climbers, taken in the 1960s. This photograph is a message depicting JEOL’s challenge to the microworld. Since its establishment, JEOL
has been actively engaged in research and development of products for research at the micro and nano level. Our variety of products has contributed to nanoscience research around the world. Many JEOL customers have been awarded the Nobel Prizes, and six Nobel Prize laureates planted commemorative trees when they visited our company. The information boards placed at these trees convey their outstanding accomplishments.

The author will explain some examples of applications of JEOL products related to nanotechnology.

“Characterization”: Observation of nanomaterials and nanostructures

Figure 7 shows a defect-review SEM (DRT-SEM) micrograph of nanostructures of an LSI. JEOL’s DRT-SEM is used as a tool for monitoring processes and detecting defects in the semiconductor production lines. This is an example of the image of surface nanostructures. Accurate observation of nanoreas is the starting point to understand substances, just as “seeing is believing”. JEOL’s TEM, SEM, scanning probe microscopes (SPM), electron probe microanalyzers (EPMA) and other instruments can observe and analyze nanostructures of materials. These instruments are used for structural characterization and materials research at the micro- and nanoscale.

“Nanometry”: Metrology and analysis of materials at the nanoscale

We use a ruler to measure the size or length of visible substances. If the substance to be measured is too small, we cannot measure it with our eyes or using an optical microscope. The TEM, SEM, and SPM are powerful tools for measuring such small substances.

Our EPMA, nuclear magnetic resonance spectrometers (NMR), mass spectrometers (MS), and other instruments are used for the analysis of substances. Professor Noyori at Nagoya University, the Nobel Prize laureate in 2001, used JEOL’s NMR in the development of catalysts and evaluation of synthesis results, as an important tool in his research of asymmetric synthesis. NMR is used in three-dimensional structure analysis and molecular movement evaluation at a molecular level. The NMR allows us to evaluate the distance between atoms at the 0.1 nm level and the movement of atoms inside molecules. This clarifies the three-dimensional structures of proteins.

JEOL’s MS is an effective tool for mass analysis and chemical structural analysis of trace components at the picogram (pg) or femtogram (fg) level. The picogram level or femtogram level is below the nano level. In recent years, the mass spectrometer combined with electrophoresis has been used for structural and functional analysis of genes, genomes and proteins.

“Fabrication”: Creation of nanostructures and nanodevices

One of the cutting-edge technologies for “creation” in the nanoworld is pattern writing using a SPM. Figure 8 shows a “nanopanda” figure fabricated by moving atoms one by one on the silicon substrate surface, using an ultrahigh-vacuum scanning tunneling microscope (UHV-STM). Nanotechnology offers such fine fabrication and creation.

Semiconductor-device fabrication is a leading technology for creating nanodevices. To produce semiconductor devices, 200 to 300 processes are necessary. The production of photomasks is very important in the front-end process. JEOL has been supplying electron beam lithography systems (EBX) that are indispensable tools for the fabrication of photomasks. These systems are also used for writing micropatterns for MEMS and system on a chip (SOC). In the ultra-microscopic world, defects or foreign matter of nanometer scale can cause fatal defects in semiconductor devices. JEOL also offers systems that detect, classify and analyze defects that occur in the semiconductor fabrication process.

Today, large-volume information, including images and motion pictures, is being transferred via networks at high speed. Conventional electronic-transfer becomes difficult at such large volume and high speed. As a replacement, optical communication technology that utilizes the high speed of light is being developed. In developing a variety of optical communication devices such as band-pass filters, highly sophisticated deposition technology is required to form thin films on surfaces of glasses and metals at the nanometer level. JEOL’s high-density reactive ion plating systems (HDRIP) can meet this requirement and contribute to the creation of nanoscale, high-quality, multi-layer thin films.

JEOL’s contribution

On the basis of “Creativity” and “Research and Development”, JEOL positively challenges the world’s highest technology, thus forever contributing to the progress in both Science and Humanity through its products.

This is JEOL’s company philosophy. Based on strong determination, our challenge continues to offer advanced technologies and products, which are useful for characterization, metrology, and fabrication of nanomaterials and nanostructures. JEOL’s integrated technology of “Characterization, Nanometry and Fabrication” will contribute to a variety of solutions in nanoscience and nanotechnology.

References:

The author has written this paper by referring to the following articles.

1. Nanotechnology (Shaping the world atom by atom): National Science and Technology Council of USA.
2. Nanotechnology Research Directions: M. C. Roco, R. S. Williams and P. Alivisatos