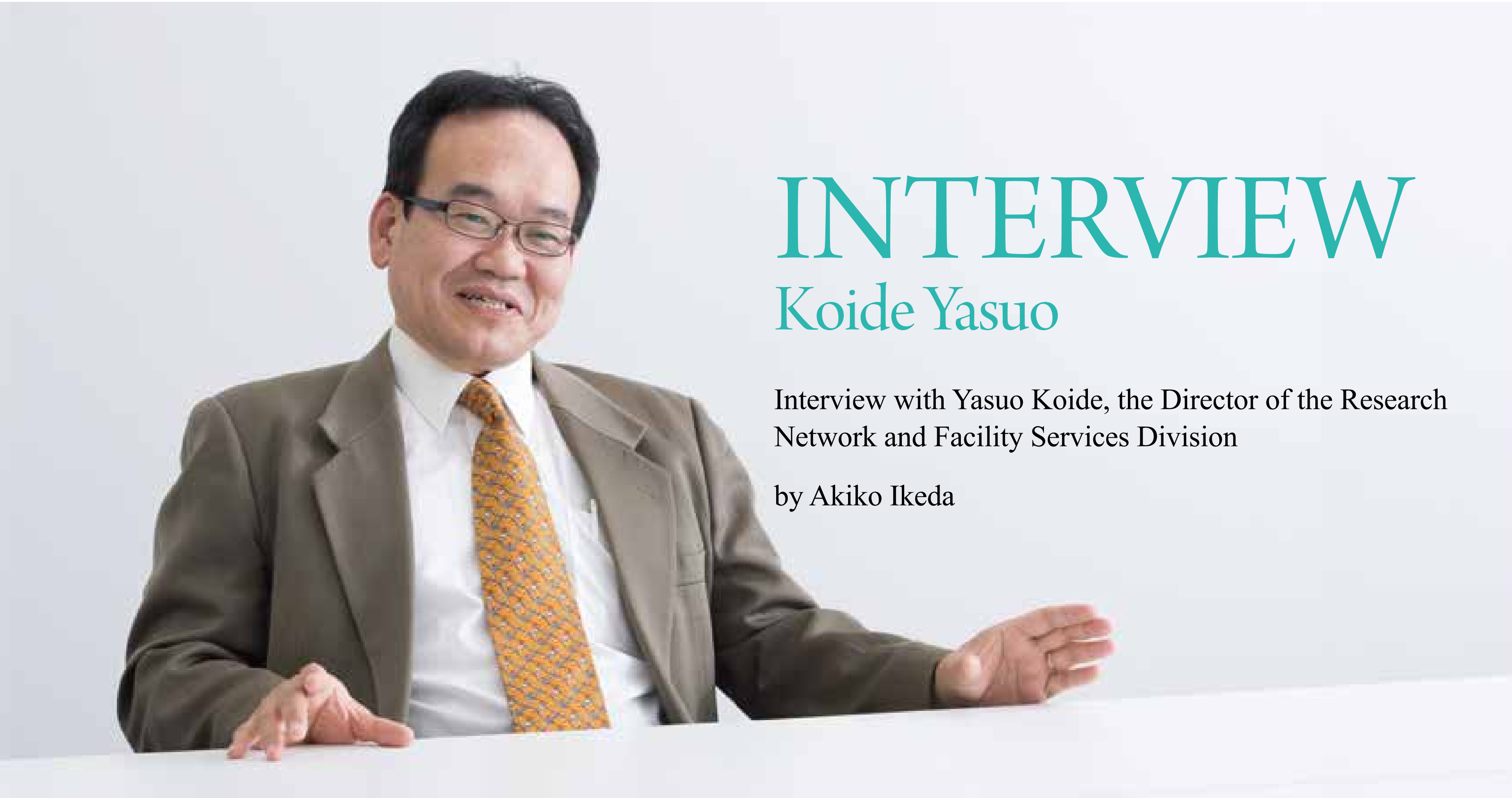


INTERVIEW
Koide Yasuo

Interview with Yasuo Koide, the Director of the Research Network and Facility Services Division

by Akiko Ikeda

Blue light shines after years of adversity

Yasuo Koide at NIMS runs wide-gap semiconductor research at the forefront. Due to their properties, wide-gap semiconductors are expected to promote energy saving in power devices and shortening wavelengths in light-emitting devices. Familiar examples of their practical use include blue light-emitting diodes (blue LEDs). As a graduate student, Koide witnessed firsthand the historical development of blue LEDs.

Assembly of MOVPE Apparatus No. 1

Q: You belonged to the laboratory run by Professor Isamu Akasaki who developed blue LEDs, correct?

Koide: In 1984, when I was a first-year doctoral student at Nagoya University, I joined the Akasaki Laboratory (Photo 1). At that time, Professor Hiroshi Amano was also a member of the laboratory as a second-year master's student. My first assignment from Professor Akasaki was to build an apparatus that would allow us to carry out the metal-organic vapor phase epitaxy (MOVPE) method. MOVPE is a method to grow compound semiconductor single-crystal thin film on a substrate by flowing a gas containing a mixture of substances such as hydrogen, nitrogen and organometallic compounds onto the substrate. I had previous experience assembling a MOVPE apparatuswhen I was a master's student at the Toyohashi University of Technology. Since there were no commercially available MOVPE apparatus then, Professor Akasaki asked me to build one using my experience so that his team could grow gallium nitride (GaN) crystals.

Q: Isn't GaN a material used for blue LEDs, the invention for which the last Nobel Prize in Physics was rewarded?

Koide: Yes. At that time, Professor Amano was planning to create blue LEDs using GaN, which nobody had accomplished before. LEDs emit light when electrons from an n-type semiconductor recombine with electron holes in a p-type semiconductor. To achieve this, we needed n-type and p-type GaN single crystals of high quality. So, Professor Amano and I took the initiative in building a MOVPE apparatus.

Photo 1. Members of the Akasaki Laboratory during a trip, August 1985

I was in a position somewhat like master carpenter, so to speak, who was taking charge of building a house. I drew schematic diagrams and made a list of all the necessary parts. Due to a shortage of funding, I procured secondhand parts and equipment, and asked the staff of Matsushita Electric Works, Ltd., where Professor Akasaki previously worked for many years, to create some necessary parts.

Three months later, we completed the MOVPE Apparatus No. 1. Today, a part of that is exhibited at the Akasaki Institute on the Nagoya University campus (Photo 2).

Taking turns for experiments

Q: I understand that great accomplishments were made using the MOVPE Apparatus No. 1.

Koide: Using this apparatus, Professor Amano and I respectively attempted to grow crystals of new materials containing GaN (Amano) or AlGaN (Koide). The new material I developed was later used in LEDs, but back then, there were no data about its materials property. So, at first, I studied its physical properties. Since we had to share this apparatus in two-week shifts, both of us felt that we had to make every second count. Professor Amano said that he carried out crystal growth experiments, with each experiment taking two to three hours, more than 1,500 times in two years.

Q. What specifically did you do during the experiments?

Koide: Both of us attempted to grow crystals of our target materials on a sapphire substrate. However, it was very difficult to create high-quality crystals due to the great difference in the lattice constant value, or interatomic spacing, between the sapphire substrate and the material to be crystalized on the substrate. Then, one day, Professor Amano came up with the solution to this problem, which was to place a "zabuton" (a Japanese sitting cushion) between the sapphire and the material.

Q: A zabuton?

Koide: That is my way of saying it (laugh). It is officially called a buffer layer. We created a buffer layer with a lattice constant value that is in-between those of the substrate and the material, and crystalized the intended material on top of it. Specifically, I created a buffer layer using aluminum nitride. When I tried the buffer in my crystal growth experiment as advised by Professor Amano, I knew at a glance that I succeeded in creating a high-quality crystal. While low-quality crystals with uneven surfaces become cloudy in appearance, high-quality crystals have mirror-like surfaces. Upon examining the physical properties of the crystal, we found that its quality was world-class from crystallographical, electrical and optical perspectives. Crystallographically, it had ideal orientation and excellent specularity as single-crystal thin films. Electrically, it had low residual electron density and high electron mobility. And optically, it emitted extremely strong light near the photonic band edges (i.e., exciton emission). Crystals that meet these conditions are said to be world-class quality crystallographically, electrically and optically. This accomplishment was the first breakthrough in the development of blue LEDs, and was a great contribution of the MOVPE Apparatus No. 1. Both Professors Akasaki and Amano said that the success in growing high-quality GaN crystals was the most vital step.

Professor Akasaki's conviction

Q: What was Professor Akasaki's character like?

Koide: At the laboratory, Professor Akasaki did not give overly detailed instructions to us, as he trusted us and allowed us to do experiments freely on various ideas. As for the fundamental direction of overall research, he was the one to make the decisions. At that time, GaN was receiving much attention as a potential blue LED material. However, because GaN was a difficult material to crystalize, many researchers shifted their focus to zinc selenide (ZnSe) when it was found that ZnSe emits blue light. Even so, we stuck with GaN because of Professor Akasaki's strong conviction. Although it is more difficult to crystalize hard materials such as GaN than soft materials such as ZnSe, he did not give up on GaN because, as he has said, GaN crystals are very strong. In fact, ZnSe, which emits blue light, eventually collapses as more and more defects appear in its crystal structure. The strength of the crystals was critical as they emit high-energy blue light.

True innovation

Q: After the successful crystallization of GaN, did the material once again attract much attention?

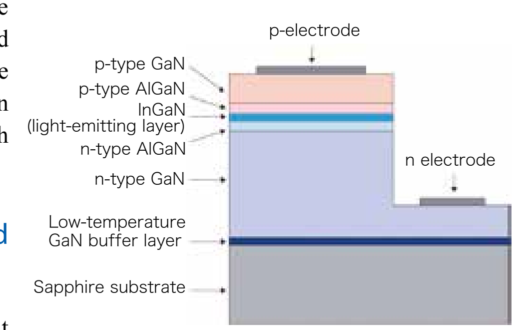
Koide: Actually, that wasn't the case. After we succeeded in crystallization of GaN in 1985, we joyously and actively presented this innovative finding at international conferences. However, the responses of the audiences were negative, and some people even left our presentations halfway. Given this reality, we decided to actually create a blue LED using the material. To achieve this, Professor Amano first doped GaN with various Group II elements in order to create a p-type semiconductor which nobody had developed before. Then, in 1989, he discovered the method of generating p-type conduction in magnesium-doped GaN that was treated with electron beam irradiation.

Q: I presume that breakthrough led to today's huge blue LED market.

Koide: At that time, my expectation was that blue LEDs wouldn't become available for practical use until the 21st century. However, in 1993, Nichia Corporation, where Professor Shuji Nakamura was working at that time, suddenly made an announcement that it would begin mass producing blue LEDs. The successful development of blue LEDs in turn made the production of white LEDs possible as the combination of a blue LED with a yellow phosphor makes white light. I thought only Nichia Corporation, which had been producing phosphors used in fluorescent lamps, could come up with such a brilliant idea. Since white LED lighting became a reality, it has grown into a twenty billion dollar market. That is what I call true innovation.

Professor Nakamura, another Nobel Award recipient, also made great contributions. His first contribution was the discovery that p-type GaN can be created by adding magnesium to GaN and heating it, in addition to the established method in which GaN is treated with electron beam irradiation. This discovery facilitated mass production of blue LEDs and allowed the reduction of their production

Photo 2. MOVPE Apparatus No. 1 displayed at the Akasaki Institute, Nagoya University



Structure of blue LED

costs. His second contribution was that he used a solid solution of GaN and InN (InGaN) as a light-emitting layer in blue LEDs (Figure 1). This method increases the indium concentration in a certain part of the crystal. This part is energetically low compared to the surrounding parts, and have the property of attracting and recombining electron holes and electrons, which leads to light emission. Light emitted from InGaN has slightly less energy than that from GaN, and is more truly blue than light emitted from GaN. Furthermore, the use of InGaN prevented electron holes and electrons from falling into defects in the crystal, resolving the issue of crystal collapse. These two improvements led to the commercialization of blue LEDs. I am so pleased that achievements made by these three researches were recognized internationally.

Of course, I am also proud of my accomplishment in creating high-quality GaN crystals using the MOVPE Apparatus No.1 at the very early stage of this whole endeavor.

Yasuo Koide
the Director of the Research Network and Facility Services Division, NIMS

Evolution of wide-gap semiconductors

What are wide-gap semiconductors?

A wide-gap semiconductor literally means a semiconductor with a wide band gap. Given that the band-gap energy of silicon (Si), the most standard semiconductor material, is about 1.1 eV*1, a semiconductor material with band-gap energy greater than 2.2 eV, double the value for Si, is considered to have a wide band gap.

Since some wide-gap semiconductors have outstanding crystal binding strength, they are physically and chemically very stable, and are able to withstand a severe environment such as exposure to high temperature and high electric current. Thus, they are used to produce highly efficient (energy-saving) and long-lasting light-emitting devices and electronic devices.

Diamond semiconductors

"Among available diverse wide-gap semiconductor materials, application of diamond is particularly challenging," says Koide. While most research conducted around the world is focusing on common wide-gap semiconductor materials such as gallium nitride (GaN) and silicon carbide (SiC), NIMS has been conducting research using diamond. Diamond has an exceptionally wide band gap of 5.5 eV. If this energy level is translated in terms of the electromagnetic spectrum, it falls under deep ultraviolet (UV) rays (wavelength: 190-280 nm) which carry enormous energy.

Diamond is a promising material to be used in optical and electronic devices due to its thermal conductivity, which is 12 times greater than that of SiC, excellent dielectric strength, and chemical stability. Application of diamond, of course, would require the fabrication of p-type and n-type diamond semiconductors. However, such attempt, especially of synthesizing n-type, was challenging as it was difficult to recover doping-generated crystal defects through heat treatment (that is because heat treatment denatures diamond for the reason that the most stable phase of carbon-based material is not diamond but graphite). Today, n-type diamond semiconductors have been successfully developed by doping diamond with phosphorus based on the method of microwave plasma gas-phase synthesis.

Success in the development of deep UV sensor

Deep UV rays are a type of invisible light. If a technology is available to sense this ray in the open air during daytime, it can be used to rapidly detect fire and harmful substances in a highly sensitive fashion. Thus, Koide developed this small device, a solar-blind UV sensor*2, using high-quality diamond semiconductors (Figure). The use of diamond semiconductors was advantageous as they are mechanically strong, have superior thermal conductivity, and are exceptionally stable thermally and chemically. Koide will continue to develop diamond-based sensors and electronic devices.

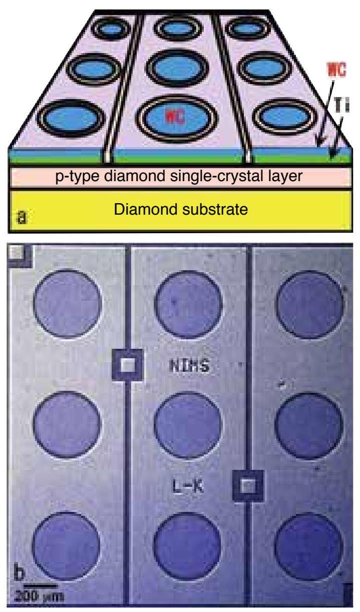


Fig. 1. Schematic diagram and the top view of the Schottky diode-type diamond deep UV sensor which Koide developed (left), and packaging elements (right)

*1:1 eV corresponds to the amount of energy given to an electron by accelerating it through 1 volt of electric potential difference.
*2:A solar-blind UV sensor refers to an optical sensor capable of detecting UV light having a wavelength equal to or shorter than 280 nm without being influenced by sunlight.

Sciense is even more amazing than you think (maybe…) 4

Sketch of light

Written by Akio Etori
Title lettering and illustration by Shinsuke

Nothing moves faster than light. It moves at the rate of 2.99725×10^{8} meters per second in a vacuum. In other words, light can travel around the Earth 7.5 times in 1 second.

According to the dictionary, light is defined as perceivable brightness to the eye, or a physical cause that stimulates the eye leading to visual sensation. The true nature of light is electromagnetic radiation with its wavelengths ranging from about 1 nanometer to 1 millimeter including visible light, infrared rays and ultraviolet rays. (You might be wondering what electromagnetic radiation is. For now, let's just think of it as a general term for light, radiation and radio waves.)

After all, without light, we are unable to see anything. What is the source of light that travels to the Earth? Needless to say, the answer is our mother star, the Sun. Nuclear fusion reactions occurring in the core of the Sun generate light that reaches the Earth.

Light exhibits the interesting property of being both waves and particles. Sunlight is a combination of lights of different wavelengths and is called white light. The mechanism of vision involves light reflecting off of objects which then travels to our eyes and stimulates them.

If a prism is used to break down sunlight, it separates into seven colors ranging from red to violet. The wavelength of violet light is 400 nanometers and that of red light is 700 nanometers. Light in this wavelength range is called visible light because this is the light by which humans are able to see things.

Sunlight that reaches the Earth also includes other types of light besides visible light. Electromagnetic radiation within a range of wavelengths longer than the wavelength of red light is called infrared rays. The key function of infrared rays is to transfer heat. Far-infrared heaters and saunas employ this principle to generate warmth.

Electromagnetic radiation with wavelengths longer than the wavelengths of infrared rays is generally called radio waves. This means that the types of radio waves such as millimeter waves and centimeter waves used in communication are related to light.

Sunlight also comprises a type of light that has wavelengths shorter than the wavelength of violet light. This type of light is detrimental to organisms since the shorter the wavelength, the higher the level of energy the light holds. Ultraviolet rays damage human skin and cause cancer. Furthermore, extensive exposure to X-rays or radiation (e.g., alpha rays, beta rays and gamma rays) can be life-threatening. Cosmic rays, which are useful in studying the structure and history of the universe, are also a type of light.

We know that there are mysterious objects called black holes that exist in the universe, which swallow everything, even light. A black hole is an enormously massive object that was formed through a steady accumulation of atoms (protons and neutrons), basic building blocks of matter. The massive gravitational force of a black hole even traps light with the speed of 300,000 km/s, within its boundary. It might be difficult to visualize such phenomenon unless you can relate it to something more familiar to you for comparison. For example, when a rocket is launched into space against the gravitational pull of the Earth, it needs to be propelled at the speed of 16.7 km/s. Supposing that the Earth is downsized to the size of a pachinko ball without changing its mass, its gravitational force would increase to an extreme extent. This example might help you to understand the existence of objects, like black holes, that suck light in and never allow it to escape. Moreover, in modern astronomy, even more massive forms called dark matter and dark energy are believed to exist and comprise much of the universe.

Overall, light is essential for our survival. ~~electronic paper that consumes a small amount of electricity~~.

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.