NATIONAL INSTITUTE FOR MATERIALS SCIENCE
NIMS NOW INTERNATIONAL
No. 2
2015

The Future of Smart Mobility

Nano-Electronics Materials

THE FUTURE OF SMART MOBILITY

Nano-Electronics Materials

Taking on the Challenge of Developing Nano-Electronics Materials

In 1886, the first gasoline automobile was invented in Germany.*
German Kaiser Wilhelm II said,
"I believe in the horse. The automobile is only a passing phenomenon."

However, in today's society, automobiles are a major means of mobility.
In the near future, we will believe in the automobile, and be riding
in autonomous automobiles.

To achieve automated driving, the demand for computerized technologies
such as electronic control of vehicle-to-vehicle communication and
obstacle detection has grown rapidly.
Power-saving technology is also important in view
of global interest in environmental concerns.
In efforts to address these issues,
the automotive device industry has taken an unprecedented
initiative to innovate technologies involving the automotive industry,
IT industry and electronic parts industry.

In this issue, we shed light on the technologies derived from
nano-electronics materials research which contributes to miniaturization of
automotive devices, high integration and reduced power consumption,
and present the latest R&D activities at NIMS in such fields.

In pursuit of a sophisticated driving experience,
NIMS has taken on the challenge of creating new nano-electronics materials.

* Karl Benz acquired a patent for the world' s first gasoline automobile in 1886.

NIMS NOW Special Dialogue

When Vehicles Understand Humans

Automotive Technology to Come into Reality in Five Years and New Materials that Support It

Talk on smart mobility of the future between Tsuguo Nobe (Intel), a leading expert in in-vehicle information systems, and Toyohiro Chikyow (NIMS).

Tsuguo Nobe (Intel)
Director, Intel Corporation
Also a Visiting Associate Professor at Nagoya University

Toyohiro Chikyow (NIMS)
Unit Director,
Nano-Electronic Materials Unit
Nano-Materials Field, MANA

Online Games Accelerated the Development of the IoT (Internet of Things)

Chikyow : Mr. Nobe, you are currently working around the world to develop automated driving technology. We went to the same university at the same time although we belonged to different departments. Your career after university is very interesting. Could you tell me the circumstances behind it?

Nobe : I studied Applied Physics at the university. After graduation, I worked in the PC business at NEC Corporation because I found that the concept of "Computer and Communication (C&C)," which NEC had been advocating since the 1970s, matched my idea of integrating computers and communication devices. At that time, NEC had a popular PC product line called PC-98, and my first job was to expand the market of NEC PCs overseas. The products, however, were not compliant with the international standard and thus were not accepted in the U.S. market. So, as an overseas strategic planner, I proposed to release IBM-compatible PC lines to meet the international market needs, based on my long belief that the advancements of IT products would be realized on international standards. With support from people sharing the same view, I played my assigned role in a full-fledged manner based on this philosophy and NEC introduced IBM PC compatible products in the US and resulted in quite a success.

Then, in 1995, Windows 95 was released and the use of the Internet was popularized across offices and homes. I said to myself, "This is it!" After stationed at Microsoft in Redmond for two years, I quitted NEC at the end of 2000. Around that year, Mr. Masayoshi Son of Softbank launched Yahoo BB! Based on ADSL, a communication line with wider network bandwidth. At that time, ADSL was well accepted in South Korea. Mr. Son thought that online game was a driving force for the expansion of ADSL, decided to make a joint venture with the world's largest online game company, and I was appointed as the CEO of the joint venture. The game was of a type called a "massively multiplayer online role-playing game (MMORPG)." To play the game, many users access game servers from their PCs, and make virtual friends and players encounter various types of monsters backed up by artificial intelligence.

Furthermore, in the world of MMORPG, the location data of all the players are plotted on a virtual map, which is basically a database, or a game field, and activities and statuses of players are analyzed, updated and disseminated back to each player within 1/30th of a second. To achieve this, it was necessary to use ADSL, because it provides low network latency, has wide bandwidth, is always connected, and is offered at a flat rate. Many kinds of services had been made possible by ADSL and the MMORPG game contained origins of recent high-end technologies such as Big Data Analysis, SNS, Target Marketing, Virtual Money and Artificial Intelligence. Then, I considered these technologies will be valuable social assets and should not be confined only for games. For example, if we analyze all kinds of data from vehicles on real map, we would be able to detect very useful information, such as traffic jam information, for our daily life. For additional example, if we detect an area where the windshield wipers of many cars are moving quite quickly within a small spot, we could assume that there would be a local torrential downpour. Thus, we could use vehicle as sensors and make weather information, for example. This total system was functioning like what is now called as IoT.

IoT for Electric Vehicles

Chikyow : Then you moved to Nissan Motor Corporation, correct? From around that time, you often said in your lectures, "The Internet should be used in the telematics of the next-generation automobiles." That was how I discovered what you are doing now after college. I find your idea of perceiving automobiles as mobile communication devices connected with the Internet very innovative.

Nobe : That's right. When I came to think about the necessity to implement "IoT"-like solutions for vehicles, by chance, I got opportunity to join Nissan in 2004 and have worked on this area as I hoped. We integrated electric vehicles (EVs) with IT solutions with connection to the Internet via a mobile telephone network, thereby connecting EVs located in Japan, USA and Europe via global data center just like connecting dispersed PCs to MMORPG servers. That was a particularly innovative project and, in 2011, we won the Best Mobile Innovation Award for Automobiles and Transportation from GSMA, a world-leading mobile communication industry group. Specifically, we created a system that enables detecting deterioration of car batteries and monitoring traffic conditions using this IT system with sensors installed in EVs. We also launched an information service in which we analyze big data collected from vehicles to help drivers find new charging stations and estimate how far the EV can go based on many parameters including outside temperature, estimated traveling speed and inclination of roads.

Artificial Intelligence

Chikyow : That stirs my imagination. How will IT-equipped vehicles evolve from now on? For example, instrument panels (the gauge board in front of the driver's seat in cars) now have a speedometer, rev counter and a car navigation system as well. Will it be something like a big display that can be customized any way you like? (see related article on page 12)

Nobe : I think so. But rather than "any way you like," it would be more likely that necessary information will be displayed in a proper location at proper timing to accurately and safely provide information to the driver. If a driver exceeds a speed limit of, say, 80 km/h, the vehicle recognizes the road signs and displays a warning in most visible and relevant place of display to surely alert the driver without driver distraction.

Chikyow : To realize that, image sensors that capture the surrounding traffic situation are the key. But the only image sensor that is currently installed in vehicles is a drive recorder that memories driving trace. Do you expect that multiple image sensors will be installed inside and outside the vehicles to collect information in the future?

Nobe : Radar and cameras are particularly important. Radar measures the distance between vehicles, and high-resolution cameras such as 4K and 8K capture the surrounding images and recognize text based on the positional information of road signs pre-stored in the 3D map. Thus, only the necessary portion of an image will be recognized to save the processing power of computer. Furthermore, artificial intelligence will be involved and make proper decision to accelerate, decelerate and turn a car on behalf of human brains, then automated driving is achievable.

Chikyow : Speaking of automated driving, there is also an approach to install various transmitters in social infrastructures, such as

TSUGUO NOBE

roads and traffic lights, from which signals are sent to vehicles.

Nobe : Such studies had been conducted in the past. But implementation of automated driving that relies on locally unique communication infrastructure, especially when that is not compliant with the international standards, is not realistic when we think about overseas expansion. On the other hand, mobile phone networks have rapidly spread around the world and are becoming more reliable and sophisticated. I think it would be a better approach for us to develop automated driving technology using those networks to even make connections between vehicles and the Cloud, vehicles and pedestrians, and among vehicles themselves. So, this is one of the examples how I believe that international standardization of automotive IT is necessary and this is why I moved to Intel in 2012.

Material Development, a Key to Success

Chikyow : I believe that innovation is certainly occurring in the world of automobiles. But if an electric vehicle without power-generating capability has to control all the devices and carry out communications within the limit of the electrical capacity of the battery, doesn't it need to be equipped with power-saving devices such as highly efficient inverters (electrical AC/DC converters)?

Nobe : Exactly. The air conditioner actually consumes about 30% of the battery power in mid-summer and mid-winter. When advanced image sensors are installed in the future and high-speed computers identify, analyze and judge various situations while driving, those functions will consume much power as well. Furthermore, it will be necessary to install an in-vehicle network capable of functioning faster than the currently used Controller Area Network (CAN). So, the use of power-efficient devices is immensely critical in every aspect.

Chikyow : At NIMS, we are developing compact and high-performance next-generation power devices using such materials as gallium nitride (GaN), silicon carbide (SiC) and diamond. Also, in consideration of the fact that high-performance and low-power-consumption image sensors need to be installed in limited in-vehicle space, we are also working on structural improvement which is called 3D lamination of devices (see a related article on page 10). We are also envisioning developing devices that will function stably even in an extreme in-vehicle environment in terms of temperature changes and vibration (see a related article on page 8).

Nobe : All of what you mentioned are important. In an automated driving system, artificial intelligence will drive a vehicle on behalf of humans. In order to make the artificial intelligence work, we need to install a computer that has a capacity equivalent to the supercomputers developed 10 years ago. The size of and heat generated by the computer are issues that need to be addressed. Supposing that we downsize the computer to the size of a single chip assuming the current power consumption rate, it is predicted that its temperature will be as high as that on the surface of the sun. Obviously, development of automated driving technology will not be possible without major technological advancement in this area.

Chikyow : At NIMS's Nano-Electronic Materials Unit, we are developing materials for next-generation micro-MOSFET, interface control technology, and new evaluation methods for developing energy-saving functional devices. These technologies may contribute to the future smart mobility.

Fun to drive

Chikyow : By the way, many people think that automated driving will deprive drivers of enjoyment. But that is not the case, right?

Nobe : It depends on how you define enjoyment. But for example, you might enjoy driving in the following way. If you choose the "Ayrton Senna" option from the automated driving mode, Senna-like driving is implemented. If you do so at a race track, you could feel like you are an F1 racer within the performance limits of your vehicle. But whether the driver can endure the velocity is another story. The automated driving will make a long trip more enjoyable because you don't have to concentrate on driving all the time. I expect that popularization of automated driving will provide a totally new way of enjoyable driving. And I believe that we are presently in a transition phase toward such a new era.

Chikyow : I would like to ask you a question concerning the even more distant future. The fictional cars that played a central role in the Japanese animation "Super Jetter," which I passionately watched as a child, and in the American TV series "Knight Rider" were capable of coming to pick up their owners at the request. These cars were even able to exchange jokes with the owners. Is there a chance that vehicles with such capability will be created in the future?

Nobe : I believe that such feats are technically achievable. At that point of time in the future, I imagine humans and computers can co-exist in harmony. The development of automated driving technology could serve as a first step to define the new relation between humans and computers.

When Vehicles Understand Humans

Nobe : The U.S. National Highway Traffic and Safety Administration (NHTSA) classifies the automation of vehicles into five levels from 0 to 4. At level 4, complete unmanned driving is assumed. Automated driving could be very useful, for example, to provide a means of transportation to elderly people living in depopulated areas. It may be important for such vehicles to be more than mere machines and capable of performing human-like functions such as gently talking to elderly passenger. Indeed, it is very important that vehicles can understand various situations associated with drivers and passengers.

Chikyow : Japan is aiming at commercializing a semi-automated driving system (level 3) in the early 2020s and a full-automated driving system (level 4) in the late 2020s.

Nobe : Level 3, one level below full automation, is very important. At this level, artificial intelligence learns the habits of the driver. For example, it can learn the situation-specific driving patterns of a given driver and use that information to provide comfortable automated driving patterns similar to how the driver drives a car. It is also possible to program the vehicles so that they assist drivers to correct their driving habits. Of course, such innovation will require the collection of vast amounts of data on real roads and machine learning and deep learning to analyze the collected data. The ideal form I am envisioning is that vehicles understand the needs of drivers and passengers and offer a pleasant on-board experience. Of course, as I mentioned earlier, to achieve this, drastic technological advancement including material development is required.

Chikyow : Expectations are high for the development of automated driving systems as a new social infrastructure. It was a very productive talk for me to learn that NIMS's material development is contributing to this technology. Thank you very much.

(by Akiko Ikeda)

TOYOHIRO CHIKYOW

Examples of Automobile Related R&D at NIMS

Our contribution to the development of automobiles through material innovation

I.

II.

III.

I. Defect characterization and material assessment of next generation semiconductors.

SiC is a potential candidate for next generation power semiconductors. The power loss of SiC is more than 10 times smaller than that of Si, and SiC works at high temperatures as 200 °C. Although SiC power device is expected to be installed in HVs and EVs, SiC wafers still contain some crystalline defects which limit the performance. Thus, the defect characterization and control is necessary for the improvement of SiC devices. The photo shows an EBIC/CL (cathodoluminescence) system for this purpose.

II. Lithium air battery

To promote popularization of electric vehicles and solar cells in the pursuit of reducing carbon emissions, it is necessary to drastically reduce the size and price of secondary batteries. The lithium air secondary battery is the ultimate secondary battery with the highest energy density on a theoretical basis. The use of this battery is expected to drastically improve electric storage capacity and reduce costs. At NIMS, we conduct comprehensive R&D, from basic research on lithium air battery materials and electrode reactions to cell design and creation of prototypic products, to establish fundamental technology for practical batteries.

III. Energy-saving magnetic material

At NIMS, we are developing magnetic materials and next-generation devices that will greatly contribute to energy saving. They include hard and soft magnetic materials for HVs and EVs, energy-saving magnetic recording media using high-density hard disks, magnetic resistance elements for read heads, new non-volatile memory that contributes to energy conservation in the information technology field and next-generation nano-devices. We are also developing highly coercive neodymium magnets without using the heavy rare-earth element dysprosium.

Sector-1 Power Saving & Safety

For One-Chip Electronic Devices

Materials Contributing to Reduction of Power Consumption of Vehicles

Takahiro Nagata

Semiconductor Device Materials Group,
Nano-Electronic Materials Unit,
Nano-Materials Field, MANA, NIMS

For Safe Driving Control

It is expected that drastically increased number of electronic devices will be mounted on vehicles for automated driving. In order to integrate information obtained from these devices and to deliver safe driving control, it is essential to have electronic devices on "one chip" and to have "wireless" communication devices. MANA Scientist Takahiro Nagata studies and develops materials necessary to achieve this goal under the project in collaboration among industries, universities, and national institutes.

Make It Simpler

Automated driving for vehicles is underway. To achieve this, we will need to mount various sensors to monitor engine, generators, tire conditions, and emission of exhaust gas, radars and cameras to measure distance between vehicles, let alone communication devices, and highly sophisticated computer that integrates and processes information obtained from these electronic devices and optimally controls driving.

However, with the number of mounted electronic devices increasing and frequent information exchanges inside the vehicles, it is inevitable that systems and wiring will be complicated. Low power consumption and low cost of devices are also necessary. For this reason, research and development for mounting all the electronic devices on “one chip” to share functions of electronic devices, and making the communication “wireless” are currently underway all over Japan. The objective is not to make it complex, but to make it simpler.

Under such circumstances, Takahiro Nagata, a MANA scientist, is working on the research and development of “film capacitor material” for sensors that function normally even in high-temperature environment, and “epitaxial wafer” that lowers the cost of power semiconductors. This research and development is intended for Hybrid Electric Vehicles (hereinafter HEV).

The time when we can check battery and parking instructions on your smartwatch is coming. Mounting electronic devices on one chip is essential in promoting computerization of vehicles. BMW i Remote App for the Smartwatch Samsung Gear S. (Photo courtesy of BMW)

Resistance to High Temperature

Currently, the trend is shifting from gasoline-fueled vehicles to ecologically-friendly vehicles represented by electric vehicles (EV) and fuel-cell vehicles. Among these vehicles, HEV is a bridging option. However, the demand for HEV is expected to grow continuously and to account for about 50 % of the ecologically-friendly vehicles in 2030.

For automated driving of HEVs, we will need sensors and circuits to monitor engine combustion and exhaust gas, power semiconductors to control power, and capacitors which are the elements to charge/discharge power to be stable against temperature fluctuation. In addition, it is desirable to make these devices compact and light, and have them mounted on a single chip.

Nagata is working on the development of thin film capacitor material that functions normally even at high temperature of 250 to 400℃ .

“In order to mount capacitors on a chip for HEV, they must be reliable against temperature fluctuation and be compact. For this purpose, we worked on development of a thin-film process of ‘relaxor ferroelectric material’ the team of the University of Tokyo suggested in the collaborative project among industries, universities, and national institutes,” says Nagata.

The relaxor ferroelectric material is a material that shows distinctive dielectric relaxation phenomenon (relaxor phenomenon) and can maintain high permittivity in wide ranging temperature and frequency. Until now, these materials often contained toxic lead. The team from the University of Tokyo has discovered that adding oxide material containing bismuth (Bi) to barium titanate ($BaTiO_3$), a lead-free oxide material, produce relaxor phenomenon.

But this is a bulk material. On the other hand, to stack this relaxor ferroelectric material on a power semiconductor substrate which uses silicon carbide (SiC) and to make it work as a thin-film capacitor, we needed to thin this material and control its structure and composition at the atomic level.

Nagata focused on two points in thinning this material: Finding out how much Bi needed to be added to obtain necessary permittivity in the wide ranging temperature, and how to prevent Bi from diffusing inside and coming up to surface during high-temperature treatment in thinning process and to suppress degradation of the characteristic.

NIMS made it possible

As for the first point, Nagata used the “combinatorial method,” one of the important methods in exploring materials and NIMS is very good at. This method efficiently explores the material composition that demonstrates unique functions to several types of elements. For example, we use two types of elements: A and B to explore material composition that demonstrates the desired ability. Using some methods such as sputtering method, an inclined film is formed in regard to the thickness of the element A. Then, the inclined film of the element B is formed from the opposite side (Fig. 1). This allows us to make materials of various composition ratio in a sequence at once.

“Using this method, we found out that adding 7 % more Bi than the target composition produced the most stable permittivity,” Nagata explains.

As for the second point, he thought that Bi diffusion could be suppressed by highly controlled thin-film layered structure. Nagata used the world’s largest database on bulk material characteristics NIMS has accumulated over many years, and its application system called “Metal segregation prediction system”.

“Using these databases, we found out that Bi is hard to diffuse when Bi layer was sandwiched by layers of oxides to which a great amount of titanium (Ti), tantalum (Ta), or strontium (Sr) is doped. Tantalum also proved to prevent oxygen vacancy in the structure. Alternatively stacking layers with high level of Ta doped and Bi oxide layers solved our problem,” Nagata says. (Fig. 2)

Nagata succeeded to develop lead-free capacitor thin-film material that functions at high temperature of 400℃ on the SiC substrate.

Non-Polar Gallium Nitride

On the other hand, the development of epitaxial wafer that reduces the cost of power semiconductors is also a big research theme for Nagata. Due to very low energy loss during power conversion between AC and DC, there are great expectations for SiC and GaN (gallium nitride) which are the next-generation power semiconductors to be the aces of energy saving to replace the current silicon (Si).

The SiC power semiconductors have been already used in the inverter systems for trains and are evaluated to be used in EVs and HEVs. On the other hand, GaN remains a great matter of research and development. The challenge is its inability to grow uniform single crystals at low cost. It is also polarized, which changes electrical characteristics. Polarization allows current to flow when it is preferred not to, which contributes to unnecessary power generation.

Then Nagata worked together with post-doctoral researchers on the development of the thin-film substrate material to create single-crystal GaN epitaxial wafer at low cost.

“If we use Si substrate instead of sapphire substrate to lower the cost, vertically growing the GaN crystals will polarize the material. To form non-polar material, we need to grow the crystal we used to grow vertically in parallel to the Si substrate,” says Nagata.

Then Nagata and researchers stacked sulfide (S) thin-film material on the Si substrate as a buffer layer and grew GaN on the buffer layer. As a result, they successfully grew uniform non-polar single-crystal GaN.

“Actually, it is Toyohiro Chikyow, a leader of NIMS team, who found it out about 10 years ago. This time, our group actually fabricated it to confirm its performance,” explains Nagata.

GaN is well known as a material for blue LED. Dr. Shuji Nakamura, a winner of Nobel Prize in physics in 2014, also mentioned that the crystals needed to be non-polar to enhance the luminescent efficiency of the LED. For this reason, Nagata believes that the technique to fabricate non-polar GaN will gain in importance in the future.

“The collaborative project among industries, universities, and national institutes succeeded to deliver all the performance demanded. However, there are many obstacles to put it into practical use. Vehicles have people's lives in hands and thus supreme reliability and safety are demanded. I would like to continue to contribute to the realization of safe, comfortable, and environmentally-friendly motorized society through material development,” Nagata renews his determination.

(by Kumi Yamada)

Fig. 1. Combinatorial film synthesis.
Step 1 and 2 are repeated until desired film thickness is obtained.

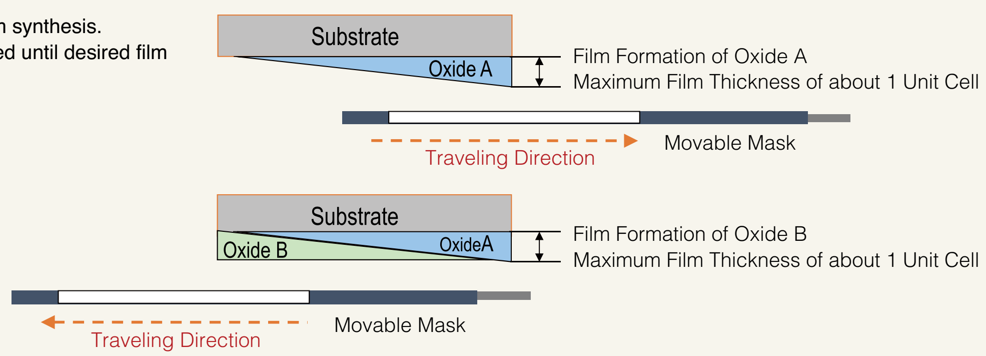
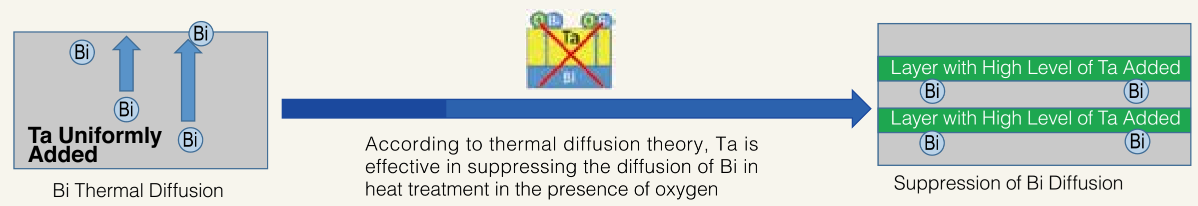


Fig. 2. Suppression of Bi Diffusion by Inserting A Thin-Film Layer with High Level of Ta Added

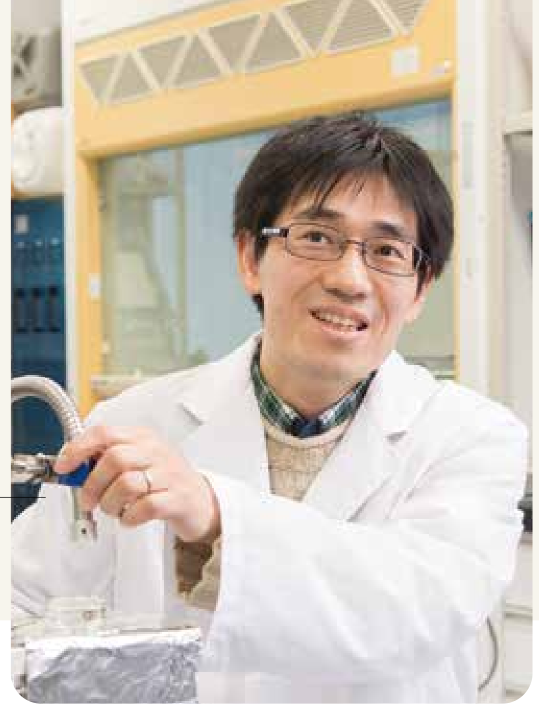


Attention-grabbing material and technology to install three-dimensional LSI

Low-cost Through-silicon via electrodes that can be produced in 10 minutes

Jin Kawakita

MANA Scientist, Semiconductor Device Materials Group,
Nano-Electronic Materials Unit,
Nano-Materials Field, MANA, NIMS



Improving LSI functions in anticipation of future market demand for image sensors

The use of an advanced operation support system (ADAS: Advanced Driver Assistant System) is set to become mandatory in the near future. As such, the image sensor market is expected to grow rapidly towards 2020. As for automotive image sensors, they are required to be high-performance, compact and low in power consumption. In fact, realizing three-dimensional (3D) LSI will be one of the way to achieve this goal. MANA Scientist Jin Kawakita is taking on the challenge of developing 3D-LSI with a Through-silicon via electrode technology.

Paradigm shift in three-dimensional arrangements

Electronic devices contain a large-scale integrated circuit (LSI). An LSI is a set of chips with various functions such as sensor, memory and CPU. By developing smaller chips, miniaturization of LSIs has been achieved. However, this approach has come to the point where no further downsizing is physically feasible. One of the promising techniques for further miniaturization is to vertically stack (laminate) chips in a three-dimensional arrangement (Figure 1).

Especially for image sensors, 3D-LSI is effective, because increasing the integration density per projected area by rearranging components such as the photo detector and logic circuit from the conventional two-dimensional integration to laminated (three-dimensional) integration, will lead to high-functionality. Also, we can increase the data transfer rate and reduce power consumption by shortening the length of the electrical wiring necessary to supply electricity to various components (in a vertical direction) as much as possible.

"The issue with 3D-LSI is to figure out how to run electricity between the stacked chips. There is a conventional method called wire bonding that can be applied to each layer of chips. But it requires sophisticated manufacturing technology. Besides that, it hardly helps shorten the wiring length," says Jin Kawakita at NIMS. So, he is applying an alternative method, attempting to supply electricity by vertically setting electrodes through the laminated chip layers. According to a preliminary calculation, the use of a through-silicon via (TSV) electrode would allow shortening the length of the wiring between chips, thereby reducing electric resistance and power consumption by 90%. Moreover, shortening of the wiring length would also lead to an increased data transfer rate.

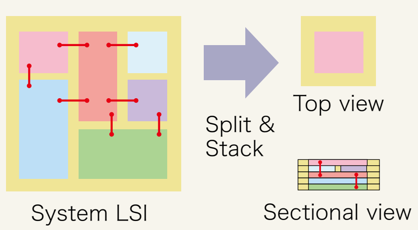


Fig. 1. 3D-LSI with high-integration capability. This design will reduce the chip-occupying area by dividing a system LSI into smaller pieces and stacking them.

Create TSVs in 10 minutes

A key challenge was figuring out how to insert an electrode through a hole with a diameter of tens to hundreds of micrometers. In order to create a TSV, it is necessary to pierce a vertical hole through chip-mounted silicon layers and fill the hole with a conductive material. The primary focus of 3D-LSI research at a global scale has been to find a method to create TSVs quickly. TSVs have already been created successfully by filling the hole with a conductive material using plating technology or the chemical-vapor-deposition method. However, both processes are time-consuming and costly. On the other hand, Kawakita says, "We are able to create TSVs in 10 minutes using the materials and technology we have developed. And, we can do so without using expensive, large equipment." He claimed superiority of the synthesis method his group developed.

In NIMS's method, we use a solution containing dispersed nanoparticles consisting of a conductive polymer and a metal (Figure 2). This solution has a small contact angle to silicon, and possesses a property of readily filling small holes and gaps by means of capillary action (Figure 3). Due to this property, the holes pierced for TSV in a silicon substrate can be filled with a colloidal solution by just immersing the substrate in the solution (Figure 4). Then by allowing the solvent to evaporate, the holes remain filled with the conductive material. This method has overcome the challenge of completely filling the holes.

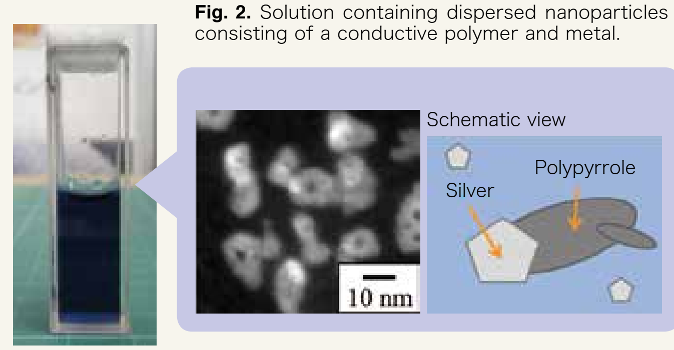


Fig. 2. Solution containing dispersed nanoparticles consisting of a conductive polymer and metal.

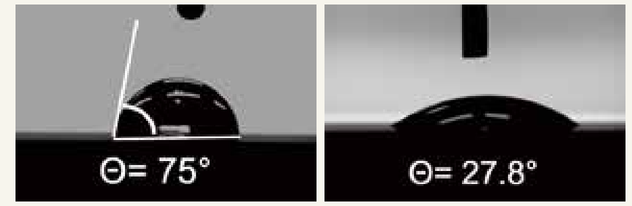


Fig. 3. Difference between contact angle of water and NIMS-developed dispersion solution to silicon.

Contact angle of water to silicon | Contact angle of NIMS-developed dispersion solution to silicon

Efforts toward practical application

Kawakita has developed inexpensive TSVs that can be created in 10 minutes. It seemed that he could put them into practical use soon, but in reality, he faced more issues to address.

Originally, Kawakita did not intend to develop this conductive polymer material to create TSVs. In fact, he was using this polymer material to develop a thin lead wire, since such wire cannot be created using metal materials. In order to improve the conductivity of the lead wire, he coated it with fine metal particles, which resulted in the development of the TSV technology.

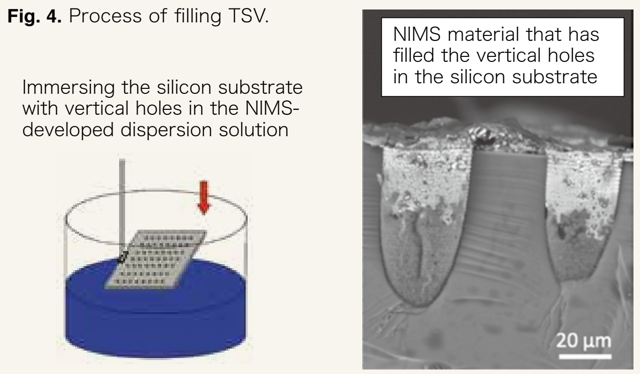


Fig. 4. Process of filling TSV.

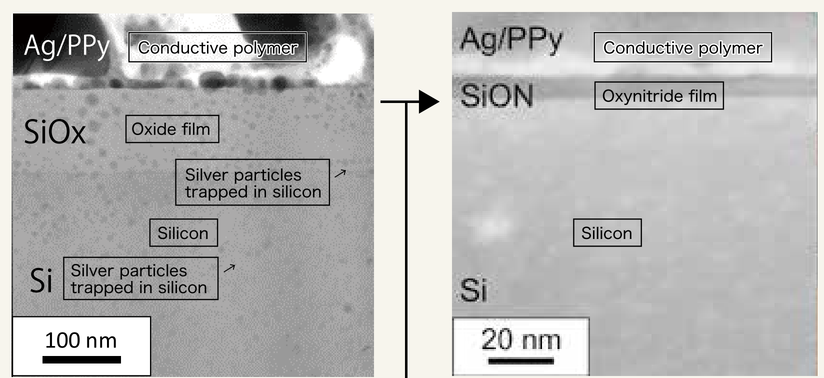


Fig. 5. Oxynitride film that prevents silver particles from entering voids in silicon. Without the film, silver particles that coat polymers enter voids in silicon (left), while with the film in place, silver particles are blocked from entering voids (right).

Since the material was originally developed for a different use purpose, an unexpected issue arose. Silver particles that coat the conductive polymer enter (or diffuse into) voids on the surface of the silicon substrate (Figure 5). It was pointed out that this issue might cause malfunction of the LSI. To deal with this issue, it was necessary to form a diffusion barrier layer over the silicon surface to prevent silver particles from entering the voids. It has been known that silicon nitride film is capable of suppressing diffusion of silver particles, but its interfacial adhesiveness is weak. In contrast, silicon oxide film hardly suppresses diffusion of silver particles, but its interfacial adhesiveness is strong. Applying this knowledge, silicon oxynitride (SiON) film was tested and found to be an effective diffusion barrier.

These technologies allow the creation of highly stable TSVs. "In order to popularize and spread the use of automotive image sensors in the future, we are aiming to commercialize them within five years. Some people might think that it is difficult to adopt a new manufacturing technology when an established manufacturing technology is already in use. However, when the copper plating wiring technology was first introduced, it was also established as a common technology after several years," says Kawakita. His goal of achieving commercialization within five years looks realistic now. The use of this material might lead to the successful commercialization of 3D-LSIs. Various interested parties are paying attention to the potential applicability of this advanced material.

(by Akiko Ikeda)

Green Display - The Fourth New Material

Reducing Power Consumption by Downsizing Thin-Film Transistors

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Toshihide Nabatame
Manager, MANA Foundry, NIMS

Toward the Next-Generation Display

See-and-touch displays that connect humans and machines have become remarkably popular. The touch screen display technology is also expected to be applied to automobile instrument panels in the near future. It is certain that popularization, resolution enhancement, and enlargement of touch screen displays will advance not only in automobiles but also in other fields. However, such achievements will accompany drastic increases in power consumption. To deal with this issue, Kazuhito Tsukagoshi and Toshihide Nabatame at MANA developed thin-film transistors using a new material.

Measures to Prevent 10-Billion-Watt Increase in Power Consumption

With widespread use of advanced HMIs (Human Machine Interface), we find touch screen displays everywhere, from smartphones, tablet terminals and vending machines to huge display panels at stations, airports and department stores.

An automobile instrument panel that displays a speedometer and mileage is expected to be replaced by an HMI display in near future. In addition, a new display technology was developed by which a driver is able to see an image of the ground right below the hood on the display. The role of display technology applied to automobiles is expected to be of great importance in the future.

Evolving automobile instrument panel display. Honda "Micro commuter concept." (Photo courtesy of Honda Motor Co., Ltd.)

The technologies for high definition and enlargement of touch screen displays are advancing rapidly. During the Tokyo Olympic Games to be held in 2020, huge 8K displays that consist of four times more pixels than the current 4K will be installed at many public viewing sites in the city so that people can enjoy vivid images of the games without actually going to the stadiums.

"However, we have to overcome a huge hurdle to achieve these goals," says Kazuhito Tsukagoshi, MANA principal investigator. "It is estimated that there are currently about 100 million TV units in Japan. If they are replaced with large 4K TVs, the power consumption will increase by more than 100 watts per unit. With the urgent need to reduce power consumption to prevent global warming, it is vital to radically reduce the power consumption of such displays."

Key to Power Saving - Downsizing TFT

Many of the displays are composed of LCD elements. Each pixel is equipped with a thin-film transistor (TFT) and plays the role of a switch. Various images are formed by turning on/off each pixel. An LED backlight is used to illuminate the screen, and makes up most of the power consumption of the display.

In efforts to achieve high-definition displays, the area of a pixel has been becoming smaller. Normally, it is also necessary to downsize the TFTs and wires as the area of the pixel is reduced. Otherwise, TFTs or wires block the backlight from passing through the pixels, dimming the screen. However, due to the low electron mobility of the existing materials, downsizing of TFTs has not been achieved. As a result, the current display has half of its area blocked by TFTs and thus light cannot pass through that area. To solve this problem, the brightness of the backlight was increased to maintain screen brightness. Consequently, the power consumption increased. (Figure 1)

"There are two ways of solving this problem. One way is to improve the luminescent efficiency of LEDs, and the other is to develop new materials that allows downsizing of TFTs and increasing the amount of light that passes through the pixels. If we can reduce the TFT area to a tenth or less, we can easily cut the power consumption by half," says Tsukagoshi.

Tsukagoshi and Nabatame have been carrying out research and development of new materials since 2010 with the goal of downsizing TFTs.

Existing TFTs Cannot Be Used in 8K TVs

At present, there are roughly three types of TFT materials. The first type is "amorphous silicon" used in relatively large displays such as LCD TVs. The second type is "polysilicon" used in medium- and small-size devices such as smartphones. And the third type is "IGZO,"an oxide semiconductor that was developed 10 years ago as a new material. IGZO is an amorphous semiconductor consisting of indium (In), gallium (Ga), zinc (Zn) and oxygen (O). It is currently used in some smartphones and tablet terminals.

However, these materials have both merits and demerits. Amorphous silicon can be produced at a relatively low temperature of about 250°C, and thus can be used to make large screens. However, the electron mobility in TFTs, which is essential for realizing high-definition and high image quality, is low. To increase the mobility, it is necessary to increase the area of the TFT, which leads to increased power consumption. Due to low mobility, it would be difficult to use amorphous silicon in next-generation displays such as 8K.

On the other hand, polysilicon has high mobility and can be used for 8K. However, its production temperature is high at 500 to 600°C, and its production cost is also high. Thus, its use is not practical for large screens.

IGZO has very high mobility which is dozens of times higher than that of amorphous silicon. However, its production temperature is high, so it would be difficult to create a uniform thin film over a large area using this material. Thus, this material, too, is not appropriate to be used for large screens.

In short, the existing materials cannot be used for next-generation displays, such as 8K that is capable of achieving high definition on a large screen while consuming a low level of power, because these materials contribute to increased power consumption and increased production cost, or they are not suitable for large screen displays.

"Then, we thought of developing an oxide semiconductor that can be produced at a low temperature while having mobility as high as that of IGZO," says Tsukagoshi.

Fig. 1. Image of pixels on a flat display. Color is generated after the backlight passes through the transparent pixel electrode ITO (Indium Tin Oxide) and color filters. While reduction of pixel size enables high definition displays, concurrent size reduction of thin-film transistors (TFTs) and wires are also necessary to prevent more light from being blocked.

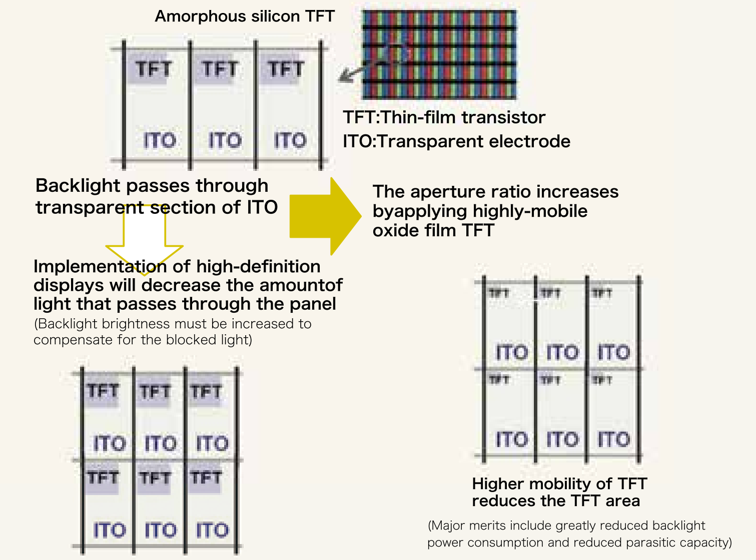


Fig. 2. Oxygen dissociation energy of elements. This is the amount of energy required to remove an oxygen atom from an element.

LOW (kJ/mol) → HIGH

Hg	269	Sr	426	Os	575	Zr	766
Na	270	D	429	P	589	Ce	790
Rb	276	H	429	Er	606	Pa	792
Cu	287	Se	429	Dy	615	La	798
Cs	293	Sb	434	Re	627	Si	799
Bi	337	Be	437	N	631	Hf	801
Li	340	Cr	461	V	637	B	809
In	346	Eu	473	Pu	656	Ta	839
Mn	362	As	484	Ge	658	Th	877
Ni	366	O	498	Ti	666	C	1076

Looking into Oxygen Dissociation Energy

Tsukagoshi's group first looked into the instability of the IGZO material.

"IGZO is an oxide consisting of the same number of In, Ga and Zn atoms. All of these elements have low 'oxygen dissociation energy,' which is the amount of energy required to dissociate binding oxygen. This means that oxygen can be unbound very easily. We realized that this is the reason why this material was unstable," says Tsukagoshi.

Tsukagoshi's group first focused on oxide made just with In, which exhibits low oxygen dissociation energy and is unstable but has high mobility. The group thought of replacing some of the In atoms with another element with high oxygen dissociation energy to improve the stability of the material. After excluding scarce elements and radioactive elements that are not suitable for practical use from all the elements examined, three elements remained valid: silicon (Si), tungsten (W) and titanium (Ti) (Figure 2). Then, Tsukagoshi's group selected Si from the three elements and decided to fabricate an amorphous thin film of indium oxide with small amount of silicon oxide added. This can be achieved at relatively low temperatures while acquiring mobility as high as that of IGZO. That was the expectation of Tsukagoshi's group.

"Based on calculation and experiments, we found that the replacement of a small number of In atoms with Si atoms is sufficient. We confirmed that such replacement drastically improved the stability of the material. Conversely, the addition of a large amount of silicon oxide will lower its mobility, since this compound is used as insulation film for semiconductors. In short, we succeeded in finding the right amount that maintains material stability while maintaining good mobility," Nabatame explains.

Moreover, Tsukagoshi and Nabatame found this in less than two years although it would normally take many years. This is "amorphous InSiO (amorphous thin film of indium oxide with silicon oxide added)," an original material developed at NIMS.

Proven High Reliability and Productivity

TFTs are created with a film-forming technique called "sputtering."

"In order to actually make a TFT, we needed to calculate the percentage of the elements to be mixed, prepare the target (sputtering material), form the film at a semiconductor manufacturing line owned by a collaborating company, and evaluate the performance of the resulting TFT. It takes several months just to complete one cycle of these steps. Usually, we need to repeat this cycle many times over several years before identifying the desired performance. So, we may have been very lucky in identifying it in just two tries. However, since we meticulously verified various issues beforehand, we might say that the result was within our expectations," Tsukagoshi looks back.

A new TFT created in this way possessed mobility that was more than 10 times higher than that of conventional amorphous silicon, and was physically and electronically very stable despite the fact that it was created at very lower temperatures of 250 to 300°C.

"If this TFT is put into practical use, we can downsize its area to a tenth of the area we use for amorphous silicon while maintaining great mobility. The downsizing should drastically reduce the power consumption," says Nabatame.

Success through Bold Thinking

Nevertheless, the reaction of the industry to this result was surprising.

"Researchers specialized in conventional TFTs seemed to feel that our approach is too new. For that reason, they found our results interesting, but did not take them very seriously," explains Tsukagoshi.

IGZO is a bulk material and a "compound film" containing the same percentage of In, Ga and Zn. We are taking advantage of the semiconductor-like property of this material. On the other hand, the thin film Tsukagoshi and Nabatame developed is a dope-controlled semiconductor, which is made of indium oxide with a small amount of doped silicon oxide. In other words, this approach is the same as the approach taken to create conventional silicon semiconductors. This consistency is probably related to Tsukagoshi and Nabatame's earlier experience in R&D of semiconductors in industries for many years.

"In addition, silicon oxide is usually an insulation film material for semiconductors. Any scientists with good common sense would never think of doping that," says Nabatame.

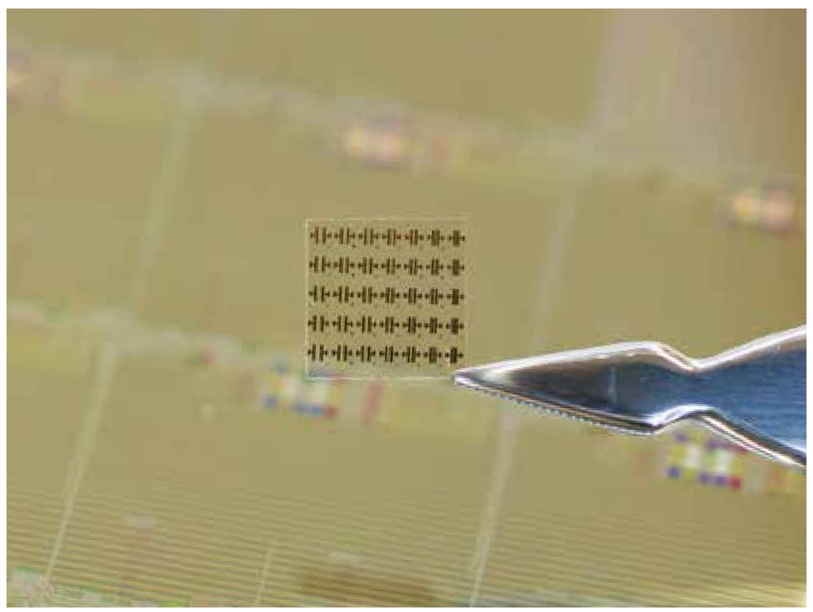
On the other hand, Tsukagoshi believes that their success can be attributed to their open-minded and unbiased thinking and their principle-based approach.

Also, the support of collaborating companies was critical for this success. Many companies such as the target material manufacturer, equipment manufacturer and display manufacturer offered to carry out joint R&D with them.

However, this new material still has many unknown characteristics. For this reason, Tsukagoshi's group is currently making efforts to understand the basic characteristics of this material using analyzers such as SPring-8 (large synchrotron radiation facility in Hyogo, Japan). Identification of new characteristics will lead to further improvement in mobility and optimization of manufacturing methods based on the principle. That would be a huge step toward practical use.

"We need to provide numerous data assuring high reliability before the collaborating companies can decide on whether to commercialize and mass produce this material. While it will take some more time to achieve practical use of this material, we have already cleared the first stage. We would definitely like to have this material put into practical use and contribute to the development of the next-generation, energy-saving display technology." Tsukagoshi and Nabatame's studies are expected to bring innovation to the future display industries.

(by Kumi Yamada)



NIMS's original oxide film transistor produced experimentally on glass.

Sciense is even more amazing than you think (maybe...) 5

Amazing Evolution of Computers

Written by Akio Etori

Title lettering and illustration by Shinsuke

The world's first computer was created in 1946. It was a numerical integrator called ENIAC built at the University of Pennsylvania to quickly compute artillery trajectories. The machine was enormous, containing about 18,000 vacuum tubes. Since it could compute much faster than any existing calculators at that time, it was gradually applied to different types of calculations other than for military purposes. Seventy years have passed since then. Computers are now used everywhere in our society, drastically changing our life. It is truly amazing how rapidly the computer has evolved.

When the first computer was created, it had four major problems: large and heavy, expensive, power-consuming and easily breakable. Furthermore, special expertise was required to operate it.

However, because computers are capable of high-speed calculation processing and are able to accurately process and store vast amounts of information, their use spread rapidly in such areas as office work, calculation for designing and construction purposes, and machine control. New technologies were introduced and computers evolved even more rapidly. The invention of transistors acted as a key catalyst for the evolution of computers. As transistors replaced vacuum tubes, the general public view that computers are huge and breakable machines completely dissolved.

Have you heard of the acronym MTBF? It is a criterion used to judge the quality of earlier computers and stands for "mean time between failures." Early computers turned on and off many vacuum tubes while computing, and this causes the vacuum tubes to blow from time to time. Computers were regarded as excellent if their vacuum tubes were durable without blowing (a large MTBF value). When transistors were introduced and blown tubes were no longer an issue, the term MTBF was forgotten.

Then, transistor computers were improved rapidly in terms of reduced size, price and power consumption as well as reliability. Lowered price of computers under 10,000 dollars made news around the world. Today, computers are generally cheaper than some other machine parts with which computers are integrated. By the way, I asked an automobile company how many computers (electronic control units) are installed in a car. They replied, "About 100 units."

As illustrated by this example, we are living in close association with computers. In 2001, President Clinton stated that all the documents in the National Diet Library will someday be stored on a sugar-cube-sized memory device. Computer technology has advanced greatly and now it is said that computers might be able to work just like the human brain or even exceed it.

The development of nanotechnology has led to the creation of many innovative devices. Recently, I hear that further downsizing of ICs and LSIs is about to hit a wall. However, this could be achieved through the development of quantum circuits or molecular/atom circuits.

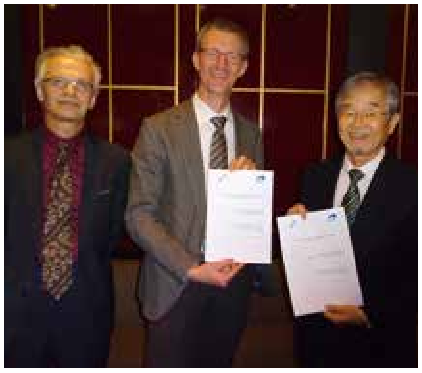
I wonder where the computer evolution will take us to in the future.

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 signed an ICGP Agreement with University of Strasbourg, France.

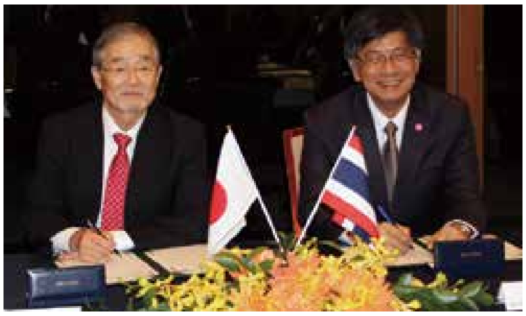
(Jan. 26, 2015) NIMS signed an International Cooperative Graduate Program (ICGP) Agreement with University of Strasbourg (UNISTRA), France. UNISTRA was founded in 1631 and had been divided in three since 1970 and again was integrated in as UNISTRA in 2009. NIMS delegation visited UNISTRA in March 2013 for the first time, and result of continuing courteous discussions and workshops for two years, the signing ceremony of the agreement was held on January 26, 2015 during UNISTRA-NIMS Workshop at NIMS. The signing of the agreement is believed not only to reinforce the existing research collaborations but also to enhance personal and academic exchanges with institutions in all France, and, moreover, those in Europe countries through UNISTRA in addition to University of Rennes 1 which is the first ICGP in France.



Signing Ceremony at Tsukuba:(from the left) Prof. Carlo Massobrio (Deputy Director, Institut de Physique et Chimie des Materiaux de Strasbourg, IPCMS), Prof. Stefan Haacke (Director, IPCMS) and Prof. Sukekatsu Ushioda (NIMS President)

2 NIMS Concludes a MOU with the National Science and Technology Development Agency of Thailand

(Jan. 30th, 2015) NIMS signed a Memorandum of Understanding (MOU) with the National Science and Technology Development Agency (NSTDA) of Thailand at the International House of Japan in Tokyo. NSTDA is an autonomous state agency, a member of Ministry of Science and Technology, responsible for driving the scientific and technological capabilities of Thailand. Its roles include research and research funding, technology transfer, human resources development and S&T infrastructure, collaborating closely with academic institutes, other government agencies and industries, domestically and internationally. NSTDA and NIMS concluded the first MOU, effective for five years, in 2009. Since then, NIMS has been actively collaborating with National Nanotechnology Center (NANOTEC) and National Metal and Materials Technology Center (MTEC) of NSTDA. Two e-ASIA trilateral research projects, with NANOTEC and MTEC, respectively, have been successfully under way with the Institute of Materials Science (IMS) of Vietnam. This MOU will not only reinforce the existing collaboration with the two research centers but also envisage new and broader cooperation with the extensive NSTDA operation.



Prof. Ushioda (left) and NSTDA President Dr. Thaweesak Koanantakool (right) signing the MOU.
(*: Photo courtesy of NANOTEC)

Hello from NIMS

Hello. My name is Xi Wang, came from China. I received my Ph.D. degree in physical chemistry from the Institute of Chemistry, Chinese Academy of Sciences (ICCAS) in 2010. Afterwards I joined the National Institute for Materials Science (NIMS) as a JSPS postdoctoral fellow of Prof. Yoshio Bando's group and then became a researcher of the International Center for Young Scientists (ICYS) within NIMS. My research interests include the controlled synthesis and exploration of fundamental physical properties of inorganic functional nanomaterials, as well as their promising applications in energy science, electronics and optoelectronics.

I have already spent four and half years in Tsukuba City. I deeply love Japan, and this city. All over the country, there are kind persons, no pollution, many beautiful scenery … It is no exaggeration to say that it is the cleanest and best-mannered place. Many moments touched me (and my family, see the following photo), enjoying hot spring in winter, climbing Mt. Fuji and Mt. Tsukuba, seeing sakura blossoms in the Ueno park, visiting Todai-ji temple, touching the lovely deer in Nara, skiing in Nagano ski resort, enjoying the sights in Hakone… In addition, I greatly appreciate and enjoy the kind of environment in NIMS and our group, in which our thoughts and ideas can turn to be real. Furthermore, my most precious possessions, two babies, were born/grown in Japan. Above all, I will never forget the experience in Japan!

Xi Wang (China)
ICYS researcher (October 2010 - present)
International Center for Young Scientists (ICYS)
International Center for Materials Nanoarchitectonics (MANA)

NIMS NOW International 2015. Vol.13 No.2
National Institute for Materials Science
http://www.nims.go.jp/eng/publicity/nimsnow/

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