Feature 1 Invention of 2014 Nobel Prize-Winning Blue LEDs, Diffusion and Perspective of LED Lights

In 2014, Isamu Akasaki, Professor Emeritus at the Graduate School of Science and Technology of Meijo University, Hiroshi Amano, Professor at the Graduate School of Engineering of Nagoya University and Shuji Nakamura, Professor at the University of California, Santa Barbara in the U.S. were awarded the Nobel Prize in Physics. The principle, government support and future perspective of blue light-emitting diodes (LEDs[1]) are discussed in this feature.

1 2014 Nobel Prize in Physics

On October 7, 2014, the Royal Swedish Academy of Sciences announced the winners of the 2014 Nobel Prize in Physics, Profs. Akasaki, Amano and Nakamura, "for the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources." The number of Japanese Nobel Prize laureates in natural science is second only to the United States this century, globally reflecting the high R&D capability of Japan.

The three Nobel laureates invented the blue LED after long and hard work to overcome a number of difficulties. Akasaki started growing crystal using gallium nitride (GaN) in 1973 and while other global researchers gave up testing this material due to innumerable difficulties in producing the desired crystals, he persisted, convinced that strong and stable crystals withstanding severe conditions could be produced if a single crystal could be created in gallium nitride. Amano locked himself away in the laboratory 364 days a year, except New Year's Day and conducted more than 1,500 experiments over one and a half year. Nakamura self-imposed the severe rule that "Commercialization must be proceeded in a unique and inimitable way" and patiently continued R&D until the answer emerged; substantially modifying a commercial crystal-producing machine for this purpose.

Akasaki, Amano and Nakamura studied gallium nitride and invented the blue LEDs that most researchers convinced were unattainable within the 20th century, paving the way for their commercialization and application. Namely, an innovation took place.

2014 Nobel Prize ceremony

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The Royal Swedish Academy of Sciences praised their achievements, saying, "They succeeded where everyone else had failed. Akasaki worked together with Amano at the University of Nagoya, while Nakamura was employed at Nichia Chemicals, a company in Tokushima. Their inventions were revolutionary. Incandescent light bulbs lit the 20th century; the 21st century will be lit by LED lamps," and evaluated the significance of their contribution as follows: "The LED lamp holds great

1 LED stands for light-emitting diode.

promise for increasing the quality of life for over 1.5 billion people around the world who lack access to electricity grids; due to low power requirements, it can be powered by cheap local solar power. The invention of the efficient blue LED is just twenty years old, but it has already continued to create white light in an entirely new manner to the benefit of us all."

The research outcomes of the three shed "light" to illuminate the future of people worldwide.

2 History of Lighting and the Blue LED

The LED was studied from the 1950s by several research institutions and the "Father of LED," Nick Holonyak Jr., former engineer of General Electric (GE) and present Professor Emeritus of the University of Illinois and others developed a world-first red LED bright enough for practical use in 1962. A green LED was subsequently developed by the late 1960s, but developing a commercial level blue LED proved difficult and it was even said that "research would not bear fruit within the 20th century."

Blue light is one of the primary colors that can produce any other color and both academia and industry sectors have long strived to develop a blue LED. Akasaki, Amano and Nakamura succeeded in inventing the blue LED, to go down in the history of lighting as great figures.

The history of lighting in mankind is introduced below.

Various remains showed flames were used as lighting by human beings during the Stone Age. Since then, the efficient use of flames as lighting had been sought until the 19th century and methods utilizing chemical and oxidation reactions, such as torches, candles and gas lamps, were gradually developed.

An incandescent light bulb, known as the second lighting and emitting light when the inner filament was heated to about 2,000 degrees, was invented by Joseph Swan in the U.K. in 1878 and improved by Thomas Edison in the U.S. to a practical level. Mankind had finally acquired light emitted by electrical energy.

In Japan, Hakunetsusha (currently TOSHIBA Corp.) founded by Ichisuke Fujioka and Shoichi Miyoshi, first started the full-scale production of incandescent light bulbs in 1890. In the autumn of 1884, 27-year-old researcher Fujioka was assigned as national missionary to the United States and visited the laboratory of Thomas Edison. When Fujioka declared "I would devote myself to start a business to introduce electricity in Japan," Thomas Edison advised "It is great to make Japan an electric nation, but I will warn you one thing. All the electricity in the world would be worthless unless a country was free from relying on imposed electrical appliances, such as bulbs. You must start by manufacturing these basic appliances, to make Japan self-sufficient." At the time, cutting-edge technologies such as glass tube technology and technology eliminating air from tubes were required to manufacture light bulbs. The success of Hakunetsusha in developing these technologies and manufacturing incandescent light bulbs domestically propelled Japan a giant step forward toward becoming an independent, modern nation.

Manufactured by Hakunetsusha in 1890
Source: Toshiba Lighting and Technology Corp.

In the 20th century, the filament in the light bulb was replaced from carbon to the brighter and more robust tungsten. The incandescent light bulb glows when heat is radiated from the filament mounted in the center of bulb and heated to high temperatures by an electric current. In short, the bulb emits light with accompanying heat like flames in principle and the energy conversion efficiency is low.

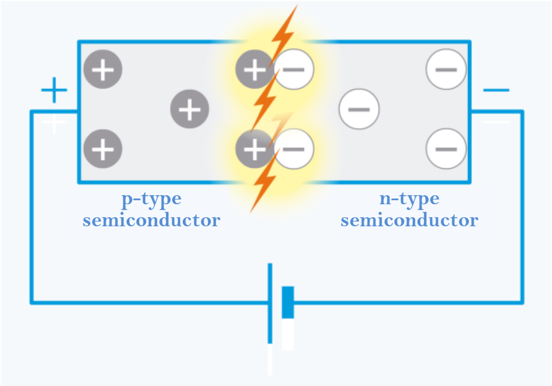
Subsequently, the third form of lighting, the fluorescent light, was invented by Edmund Germer, et al. in Germany in 1926. In the 1930s, GE of the U.S. succeeded in commercializing the fluorescent lamp, which emits light by converting ultraviolet rays acquired by the electric discharge of mercury gas into white light by fluorescent material. Fluorescent lamp has the feature of efficient energy conversion, which outperforms that of incandescent bulbs.

The fluorescent lamp was sold in Japan in the 1940s. The first president of Tokyo Shibaura Electric Co, Ltd. (currently TOSHIBA Corp.) visited GE to inspect the fluorescent light and subsequently sent three engineers to GE in 1939 in order to commercialize the fluorescent light business in Japan. Next year, in 1940, the company succeeded in manufacturing a small quantity of fluorescent lights and on August 27th the same year, these sample products were used in the Horyuji Mural Painting Reproduction Project to commemorate the 2,600th year of the founding of Japan. This is a memorial day for the debut of fluorescent lights in Japan. Following continuous improvements, domestic fluorescent lights finally reached international standards of brightness in 1951, while the average service life reached 7,500 hours in 1954, on a par with foreign counterparts.

The first domestic fluorescent light
Source: Toshiba Science Museum

LED is the fourth form of lighting to "illuminate the 21st century." Unlike conventional lighting, LED emits light by changing the energy status of electrons in semiconductor crystals. Because electrical energy is converted directly into light energy, highly efficient light emission is achieved without accompanying heat.

Specifically, p- and n-type[1] semiconductors are combined and when voltage is applied in a forward direction[2], electrons in n-type semiconductors and positive holes in p-type semiconductors move to the boundary. When electrons and positive holes meet, they recombine and generate surplus electrical energy, which is then converted into light energy to produce light. The colors are determined by the level of generated energy. The photon energy of red is the smallest of the three primary colors, at about 1.9 electron volts[3]. The photon energy of blue is the largest of the three, about 2.6 to 2.8 electronvolts.



Mechanism of light-emitting diode
Source: Toshiba Lighting and Technology Corp.

Red and green LEDs were developed in the 1960s, but the blue LED, with a practical high brightness level, was difficult to develop, mainly due to its high energy. When a high-luminosity blue LED was finally

1 "p-type" semiconductors contain a surplus of positive holes, which are virtual particles with a positive charge. "n-type" semiconductors contain a surplus of negative electrons, which move freely in the semiconductor.
2 Apply positive voltage to an anode (+) and negative voltage to a cathode (-).
3 Electron volt (eV) is a unit of energy. 1 eV is the kinetic energy acquired by an electron when accelerated at a potential difference of 1V.

invented, LED light bulbs were immediately commercialized and put on sale in 1993. Compared to conventional light sources, LEDs have a number of advantages, including long service lives, low power consumption, a compact and lightweight structure and no hazardous mercury content. "The Basic Energy Plan" decided by the Cabinet on April 11, 2014, also states around a 100% flow by 2020 and 100% of stock[1] by 2030 to disseminate LEDs and other highly efficient lighting appliances to promote saving energy in business and household sections. LED lighting will dominate the lighting market in future.

3 Relating Industrial Trends and Application Areas

(1) Trends in the LED light industry

Low power consumption LED lights have gained the largest share of the lighting market in Japan since the supply-demand situation of electricity became tight following the Great East Japan Earthquake. In 2011, the year in which the earthquake struck, the domestic LED light market soared to 222 billion yen, roughly 2.5 times the figure for the previous year and will be worth 479.6 billion yen in 2013[2]. LED lighting fixtures have replaced conventional lighting fixtures, particularly in the field of light-source embedded base lights, high-ceiling lighting and outdoor lighting and the share of LED lighting fixtures as a proportion of the overall lighting fixture market exceeded 50 percent in 2013[3]. The global LED light market was roughly worth 1.3 trillion yen in 2013 and is expected to grow mainly in developed nations, to 5.5 trillion yen in 2020[4]. Demand for LED lights remains strong, but considering their extended service lives, domestic markets are forecast to shrink in the medium- to long-term. Taking account of the plateau of growth, expanding into overseas markets expected to grow in future and developing new businesses are required.

(2) LED application

LED lights have a wide applicable scope. Because the semiconductors themselves emit light in LED, there are no concerns about broken filaments as with incandescent light bulbs, lasting several tens of thousands of hours. The service lives of LED are dozens of times longer than incandescent light bulbs and several times longer than fluorescent lights. The luminance efficiency of LED lights also exceeds that of incandescent and fluorescent lights and has improved each year as recent technology has progressed. With a long life and low power consumption, LED lights are often used as street lights and security lamps, which need to be illuminated for an extended period. Refurbishment of lighting in Napoleon Square, Pyramid and Pyramidion at Louvre Museum with LED lights is one of the famous applications in recent years. This refurbishment is estimated to save 73% of annual power consumption[5].

Light emitted from white LEDs is virtually free of infrared and ultraviolet rays, which makes it useful for protecting cultural assets and usable when lighting art and craft works which deteriorate under ultraviolet rays.

1 "flow" means the number of products shipped to domestic markets, and "stock" stands for the quantity of implementation in a fiscal year.
2 "Special Application: Current Situations, Technologies and Prediction of Light Source/Lighting Fixture Market Report 2014," Fuji Keizai Group
3 "Special Application: Current Situations, Technologies and Prediction of Light Source/Lighting Fixture Market Report 2014," Fuji Keizai Group
4 "Special Application: Current Situations, Technologies and Prediction of Light Source/Lighting Fixture Market Report 2014," Fuji Keizai Group. The LED tube lamp market was worth 500 billion yen in 2013 and is expected to increase to 1.3 trillion yen in 2020.
5 Comparison of 4,500 lighting apparatuses (392,000 Wh) at Napoleon Square replaced with 3,200 LED lights (105,000 Wh, power consumption).

Louvre Museum Lighting Refurbishment Project

Source: TOSHBA Corp.

Ultra-fine brightness control of LED lights is possible by combining the three primary colors, red, green and blue LEDs with a microprocessor, which enhances the lighting performance by increasing the number of reproducible colors and promptly changing colors, such as in decorative and visually appealing illuminations, e.g. beautiful winter illuminations in various areas.

LEDs are also used in the medical fields, where compact, slim and light LEDs allow highly flexible equipment design and formation. One example of a product making the most of these features is the capsule endoscope, inserted orally into the patient's body to take internal images. The smaller the endoscope is, the less stressful to the patient. LED lighting devices can be designed in a compact form and with a smaller battery for energizing low-power LEDs, making them ideal lighting for capsule endoscopes.

About 250,000 blue LED light bulbs used for illumination

Source: Caretta Shiodome

("Canyon d'Azur - Canyon of Light -" 2014)

The compact design feature of LEDs also makes them useful for backlighting liquid crystal displays and slim LED backlights with good color reproducibility are used for various electrical appliances, including mobile phones and televisions.

LEDs are also expected to be applicable to agriculture. By making the most of their easy light control, nutritious plants can be grown under optimal light irradiation suited for each vegetable. In July 2014, the world's largest plant factory was completed in Miyagi prefecture. LEDs are used for all the lighting and about 10,000 heads of lettuce can be harvested a day. Power consumption is saved by 40% and the crop yield increased by 50% compared to the use of fluorescent lights.

All LED artificial light-based plant factory
Source: Mirai Co.

Column Feature-1

LED Traffic Signals

When blue LEDs with practical brightness suitable for traffic signals were developed, world-first LED traffic signals for vehicles were installed in Aichi and Tokushima prefectures in 1994.

LED traffic signals are prominent, using LED elements as the light source to emit light in the relevant colors without a reflecting mirror. For that reason, they are not prone to pseudo-lighting phenomenon caused by reflection from the afternoon sun, as is often the case with incandescent light signals. LED traffic signals are also energy-saving, consuming only around 1/6 of the power of incandescent light signals. Their service life is about six to eight years, while that of incandescent light signals is about six months to one year, which means they excel when it comes to reducing costs and preventing traffic obstructions by frequently replacing signal bulbs.

LED traffic signals account for 45.3% of all traffic signals for vehicles and 37.7% for pedestrians, or 42.0% overall in Japan as of the end of March, 2014. LED traffic signals are also used overseas, including in Singapore and Stockholm. LED traffic signals will be further promoted in future.

4 Government Approaches

The R&D leading to the Nobel Prize in Physics owed greatly to private companies such as continuous financial support by a manager's decision. The contribution of public funding in the process of R&D is also fairly large. An overview of public funding for R&D and the present public funding for gallium nitride is given below.

(1) Government policy for supporting the development of blue LEDs

Akasaki moved from Nagoya University to the laboratory of Matsushita Electric Industrial Co., Ltd. (currently Panasonic) in 1964 and formally started studying "blue" emitting semiconductor elements in 1973. The government supported his research with "Critical Technology R&D Subsidy Scheme" by the Ministry of International Trade and Industry (currently METI) for three years from FY 1975. After Akasaki returned to Nagoya University in 1981, the basic research by Akasaki and Amano was supported by subsidiary programs such as the basic research funds (unit cost per professor) and KAKENHI for Scientific Research (KAKENHI) by the Ministry of Education (currently MEXT), which resulted in the first important achievement, high-quality gallium nitride crystallization. Akasaki and Amano pointed out that the crystallization of gallium nitride was the result of a lot of basic research, all of which, including the failed trials, elicited useful feedback for subsequent research and indicate the direction.

The Contract Development Program (present ASTEP Commercialization Challenge Type Contract Development) by the New Technology Development Foundation (currently JST) played a central role in transferring blue LED technology to industry. The Contract Development Program subcontracts the commercialization of research outcomes at universities, which involves high risk in development, to companies with funds from the New Technology Development Foundation.

The contract development project "GaN Blue Light-emitting Diode Manufacturing Technique", supported by the New Technology Development Foundation, lasted three and a half years from FY 1997 to FY 1990. During this project, the "connoisseur" of the New Technology Development Foundation played a significant role. Although zinc selenide was the main material studied at the time, the New Technology Development Foundation had the insight to recognize that the research by Akasaki using gallium nitride had the potential for commercialization and proposed support via the Commissioned Development Program. A total of 550 million yen was invested in this project (after the success was recognized, the development expenses were returned to the Foundation). This meant that mass production of high-quality gallium nitride was possible and paved the way to realize the blue light-emitting diode. It is important to effectively exploit "connoisseurs" to find potentially commercialized technologies from abundant research outcomes in universities and commission them to companies. The total patent fees paid by companies supported by this project to JST reached about 5.6 billion yen as of FY 2013, part of which was distributed to Nagoya University and other stakeholders.

(2) Energy-saving innovation with advanced technologies

Three Nobel Prize laureates used gallium nitride as the key material for their research. Gallium nitride is also applicable to other fields, for example, power semiconductors which have recently become increasingly prominent. Power semiconductors are used to control electrical power efficiently, by switching current from direct to alternate and vice versa, or raising and lowering voltage. They are equipped in part of systems to connect electricity generated by photovoltaic cells to the electric grid, various home electrical appliances such as air-conditioners and refrigerators and controllers of motors in electric vehicles.

Although silicon (Si) has long been used as the material for power semiconductors, gallium nitride is expected to have application as a new material. A proposal for devices featuring wide-gap semiconductors[1] was made in the Frontier Electronics[2] proposed by Akasaki in 1990 and "Research of wide bandgap group III nitride semiconductors for realization of novel devices " selected as a "High-Tech Research Center" Project as part of the Program for Promoting the Advancement of Academic Research at Private Universities by the Ministry of Education in FY 1996. Gallium nitride single crystal substrate growth technology and epitaxial growth technology, etc. were developed and new growth technologies were proposed in METI-sponsored "Development of basic technologies for nitride semiconductors for next-generation lighting / Development of new materials and new structural technologies for nanoelectronic semiconductors - Development of nitride system compound semiconductor substrates and

1 A semiconductor with a large band gap, meaning the area in which no electrons can reside. Semiconductors with a large band gap are characteristically suitable for electronic devices withstanding high voltage and output and with low power loss.

2 The Frontier Electronics proposed by Akasaki in 1990 is named after the collective development of new electronics with devices that cannot be achieved by conventional materials such as silicon and gallium arsenide (GaAs), for optics, communication, power, environment resistance and functions.

epitaxial growth technologies[1] -" led by Amano as the project leader (until July 2009) from FY 2007 to 2012. Recently, R&D in this field has progressed significantly, mainly spearheaded by Amano.

A significant increase in gallium nitride efficiency is thus theoretically possible and according to MOE (Ministry of the Environment), the energy loss of gallium nitride is 1/6 or less that of silicon, which is currently used as the main material for devices. Bonding of gallium nitride is as stable as silicon carbide (SiC), which is called another new material and gallium nitride has immense potential for use in producing devices operating at high voltage and high temperatures as silicon carbide. It also includes an effective high-frequency property, which is applicable to the power supply of communication equipment.

METI initially conducted R&D, primarily for the early commercialization of silicon carbide power in its "Next-generation power electronics technology development project" from FY2009, but in light of the importance of application of gallium nitride to power semiconductors, it changed its policy to include the development of gallium nitride-based power semiconductors from FY 2014. The "Development of innovative photovoltaic cells - R&D of post silicon, ultra-high efficiency photovoltaic cells," conducted from FY 2008 to 2014 by orchestrating the scientific insight of industry and academia, aimed to develop power semiconductors using new materials for producing innovative and ultra-high efficiency photovoltaic cells using new materials and structures[2]. In this project, Amano strove to apply gallium nitride to photovoltaic cells using crystal growth technology which is also promising for the study of gallium nitride-based power semiconductors.

MOE has engaged in developing and verifying technologies for high efficiency of power and optic devices, used in various electrical appliances such as lighting and air-conditioning; mainly in the private and service sectors, using the highest quality gallium nitride substrates and maximizing energy-saving in the "Technology Innovation Project Realizing the Ideal Future Society and Lifestyle (development of high-efficiency devices, etc.)" started from FY 2014 by the development team led by Amano.

The Cabinet Office founded the "Cross-ministerial Strategic Innovation Promotion Program (SIP)" in FY 2014 to promote R&D across the frame of ministries and fields with commercialization and business deployment in mind and promoting the R&D of the next-generation power electronics in collaboration with METI as one of the themes in this program. The goal is to achieve unprecedented energy-saving by 2020 through ultra-high efficiency energy utilization using power electronics technologies attained by the basic study of silicon carbide and gallium nitride applicable to power conversion and automobiles and innovative study of future power electronics.

MEXT designates energy-saving innovations with cutting-edge technologies as one of the pillars of its policies for special promotion in future and defines next-generation power semiconductors as an important element for achieving this goal. It also promotes "Nitride semiconductors and new fields of electronics"[3] selected in FY 2012 as the Supported Program for the Strategic Research Foundation at Private Universities , in which the research group of Meijo University led by Akasaki studies the formation of basic technology for nitride semiconductors. The project has spawned various application seeds, including

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1 One of the thin-film crystallization technologies used to form (grow) single crystal thin film on semiconductor substrates.

2 New materials include those used for compound semiconductors such as indium and gallium which are expected to have higher power generation efficiency than silicon, which is currently the main material. New structures include new concepts, such as multiple layers of p-n junctions to expand the available solar wavelength and improve power generation efficiency, rather than the p-n junction, which is currently the common structure used for semiconductors.

3 The support period extends from FY 2012 to 2016.

ultraviolet emission devices (Laser LED), ultraviolet light receiving elements, nitride semiconductors, vertical cavity surface emitting laser[1] and white LED without fluorescence body. Progress is expected in nitride semiconductor light-emitting devices. MEXT also installed a set of experimental devices in Nagoya University in FY 2014 to construct an environment including all processes from crystal formation to device production. The acceleration of R&D and social implementation in future, supported by the government as a whole, to achieve "All-Japan" industry-academia-government collaboration is currently under discussion.

1 Laser emitting light perpendicular to the semiconductor substrate, used as a light source for ultra-fast data communication and laser printers.