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Latest Trends in LED Lighting

MAKOTO BESSHO and KEIICHI SHIMIZU
Toshiba Lighting and Technology Co., Ltd., Japan

SUMMARY

LED is the fourth and latest generation of light sources, following the first-generation incandescent lamps, the second-generation fluorescent lamps, and the third-generation HID lamps. Their excellent characteristics, such as high efficiency, long life, compactness, light weight, zero mercury content, very slight IR and UV emissions, and the like, are advantages in comparison with conventional light sources. With the progress of LED lighting technologies, their application is spreading in sign and display devices, spot lighting, base lighting, and security lighting, and new applications that cannot be realized with conventional light sources are expected. This article reports the latest trends in LED lighting. © 2011 Wiley Periodicals, Inc. Electron Comm Jpn, 95(1): 1–7, 2012; Published online in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/ecj.10394

Key words: LED; lighting; light source; lamp; fixture; efficiency.

1. Introduction

LEDs have been used as indicator lights in household electric appliances and other applications for more than 30 years, and have become a part of everyday life. However, in the last few years, these devices, offering high efficiency and long life, have entered into the field of general lighting, and are gaining wide public acceptance as a light source that is indispensable for the prevention of global warming.

In the historical development of light sources, LEDs constitute the fourth generation, following incandescent lamps, fluorescent lamps, and HID lamps. Compared to existing lighting devices, LEDs have a number of advantages, such as energy saving (high efficiency), long life, small size, light weight, a wide variety of light colors, excellent on/off response, crack resistance, low emissions other than visible light, tolerance of low temperatures, no content of environmentally hazardous mercury (Hg), etc. One can expect that by using these outstanding properties, new lighting applications that were impossible in the past will be implemented in various fields.

Here we give an outline of the latest trends in LED lighting.

2. LED Lighting Background

As estimated by the National Institute for Environmental Studies, greenhouse gas emissions produced by household energy consumption, including emissions of power plants associated with household electricity consumption, in addition to direct combustion of heating oil, automotive gasoline, and other fuels, amounted to about 137.4 million tons (CO_2 equivalent) in 2007. Forests and other vegetation can absorb only 81.4 million tons of CO_2, which is barely 5.9% of total greenhouse gas emissions. About 30% of total CO_2 emissions are associated with electric power generation, of which about 15% is consumed for lighting.

In more intuitive terms, this emission amount corresponds to about 5 kg of CO_2 emitted per capita per day. For comparison, the amount of trash collected by municipalities is about 1 kg per capita per day. Thus, every day we discard much more CO_2 than trash [3]. Furthermore, Japan has no system for collecting the emitted CO_2. The developed countries of the West are in a similar situation, which necessitates urgent energy-saving measures in every field.

In addition, according to a report by the Mid-Term Target Committee of the Council on Global Warming Issues (published by that *Institute*), unless efficient measures are taken, the average air temperature will increase by 3.1 to 3.4 °C by the end of the 21st century, compared to the preindustrial era, and annual losses will constitute 1 to 3% of the world's GDP. Assuming that the greenhouse gas concentration in the atmosphere must be stabilized at 445 to 490 ppm in order to restrict the temperature rise to 2.0 to 2.4 °C, the developed countries must reduce greenhouse gas emissions by 25 to 40% in 2020, and by 50 to 85% in 2050, compared to 1990. Multiple scenarios have been proposed for the achievement of this target, for example, the replacement of 15 compact fluorescent lamps by LED lamps in every household in 2013 [2].

Thus, the introduction of LED devices in the field of general lighting can be considered a necessary measure to solve global problems.

3. LED Lighting

3.1 LED types

(1) LED design

LEDs are electronic components, like transistors or ICs, and they are usually mounted on the printed circuit boards of lighting devices. LEDs can be classified by their shape and packaging as follows (Fig. 1).

(a) Lead-wire type (miniature type or lens type)
(b) SMD (Surface Mount Device) type
(c) Power type (power LED)

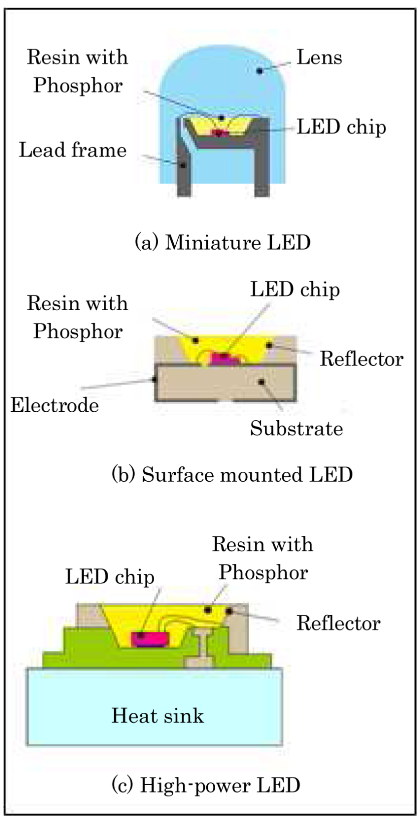

Fig. 1. Structure of typical LED modules. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In the lead-wire type, the LED lead wires are passed through holes in a printed board and soldered. This is one of the early packaging schemes. Since LED packages are provided with lens functions in many cases, such LEDs are often called the lens type.

In the SMD type, components are attached to a printed board without using holes, by direct soldering to a conductive pattern. When LEDs are used for general lighting, greater light intensity is required than for indicator devices. However, LEDs release more heat. The SMD design offers better conduction of heat to the heat sinks provided on printed boards or peripheral devices.

Power LEDs have a high power per element, and their packages are designed with consideration of heat conduction and dissipation.

(2) LED emission color

White light is needed for general lighting. White light can be obtained by mixing multiple colors. The main three approaches to obtaining white light are shown in Fig. 2.

(a) blue LED + green LED + red LED
(b) near-UV or UV LED + RGB phosphor
(c) blue LED + yellow phosphor

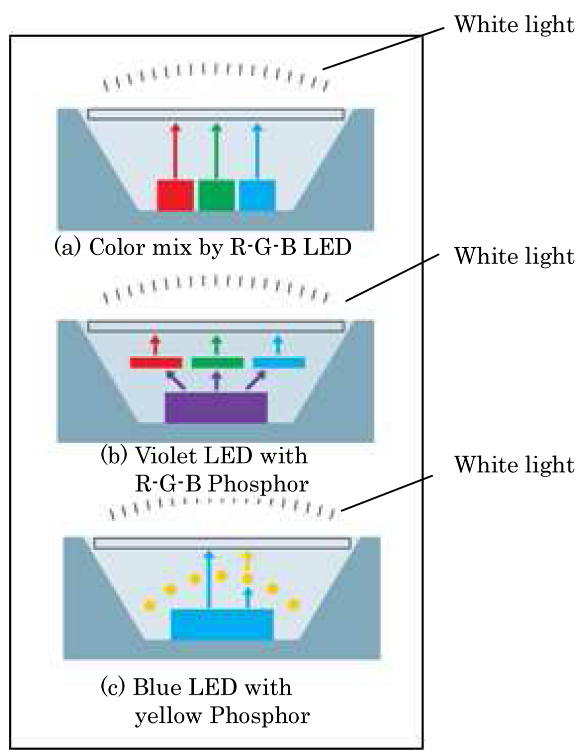

Fig. 2. Methods of producing white light. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

In scheme (a), an LED chip emitting the three primary colors, blue, green, and red, is employed, and white light is obtained by mixing these three colors. However, use of this design for illumination may produce unnatural colors because the devices radiate no energy in some wavelength bands. This method is usually used in backlighting for displays.

Scheme (b) uses the same principle as three-band fluorescent lamps: namely, an LED light source with shorter-than-blue wavelength excites an RGB phosphor. In this case, the shade of the white light varies with the LED emission wavelength depending on the temperature and current, and with the phosphor application conditions. However, phosphor emission is not very sensitive to LED wavelength variation, and the color can be controlled accurately.

Scheme (c) combines a blue LED and a yellow phosphor excited by blue light (complementary color). This method, which is more efficient than methods (a) and (b), is currently used in most cases. Color rendition is evaluated by the general color rendering index (*Ra*). This scheme has an *Ra* of about 70. Recently, the color rendering properties of this scheme have been improved by compensation for red and blue-green components.

(3) LED characteristics (efficiency and lifetime)

Since LEDs are semiconductors, they are almost free of the wire-breakage failures inherent in conventional light sources. However, the light intensity decreases with length of service because of material degradation. In general-purpose light sources, the lifetime is defined as the time to failure, or to a decrease in the light intensity below 70% of its initial value. The same concept is adopted in the standardization of LEDs intended for general lighting. The relationship between variation of the light intensity (lumen maintenance) and the lighting time for incandescent lamps, fluorescent lamps, and LEDs is illustrated in Fig. 3.

The actual LED lifetime depends greatly on the design, the materials employed, the heat release conditions, and other factors. Generally, the peripheral components degrade as the temperature rises, and the lifetime decreases exponentially. For example, the lifetime of the long-known miniature white LEDs is estimated as about 10,000 hours at the rated current. However, the light flux declines over time due to a fall in the light transmittance of the epoxy resin used for packaging drops, owing to the synergistic effect of light and heat. In contrast, when an LED is sealed in a ceramic package made of durable silicone resin, lifetimes over 40,000 hours are attained. In any case, a temperature rise accelerates degradation, and hence heat release control is an important issue in the design of LED modules and lighting devices. In order to attain a lifetime of 40,000 hours at the current level of technology, the working temperature of LED semiconductor chips must be kept below about 100 °C. New materials and technologies are also being developed in order to provide long life at higher temperatures.

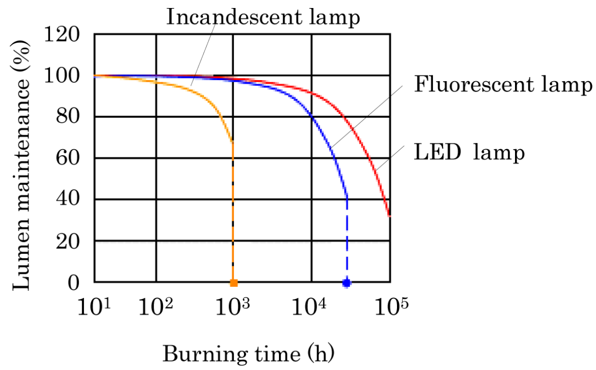

Fig. 3. Lumen maintenance of various lamps. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

(4) LED performance measures

The efficiency of a light source is the most important measure for evaluating the energy saving provided by lighting devices. The efficiency is defined as the luminous flux (light intensity) in lumens (lm) per watt (W) of electrical input. The theoretical limit of light source efficiency in the absence of loss is 683 lm/W at a wavelength of 555 nm (green light, to which the human eye is most sensitive). Usual lighting sources are required to emit not monochromatic light, but white light, which is composed of multiple spectral components, and as a result, the theoretical efficiency limit drops to 300 lm/W. The efficiency of actual LEDs is illustrated in Fig. 4 in accordance with a forecast

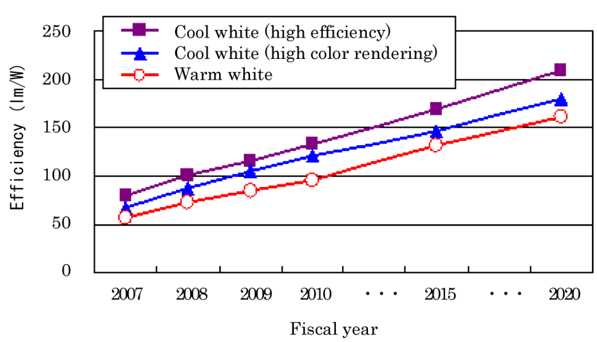

Fig. 4. Load map of efficiency increase (results of questionnaire [4]). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

published by the Japan LED Association (JLEDS) in 2008. As of 2010, the efficiency already exceeds 100 lm/W, and it is expected to reach 150 lm/W by 2015. R&D is progressing steadily, and miniature elements with an efficiency of 150 lm/W are already available. Furthermore, power LEDs with a luminous flux above 100 lm per element and an efficiency of about 100 lm/W are available on the market. Thus, the forecast is becoming a reality. High-frequency fluorescent lamps, used as high-efficiency light sources for indoor lighting, have an efficiency of 100 lm/W: thus, LED lighting will obviously outperform fluorescent lamps.

Lamps with a reddish shade such as incandescent lamps or lamps with improved color rendering have an efficiency that is 20 to 40% lower than high-efficiency lamps, and hence lighting devices should be selected appropriately for specific applications. The overall efficiency of lighting devices using LEDs is calculated with regard to losses in electric circuits, the optical characteristics of the lighting fixtures, the decrease in luminous flux due to temperature rise, and other factors. The overall efficiency estimated in this way is lower than the LED efficiency itself. When considering the performance of LED lighting, it is important to compare the overall efficiency of lighting devices, without being distracted by pure LED efficiency.

3.2 Quality and safety design of LED lighting devices

(1) Safety criteria and standardization

Aiming at wide acceptance of LED lighting, one must not only improve the device characteristics, but also create an environment for the safe use of LEDs according to consumers' needs. Conventional lighting devices are subject to the Electrical Appliance and Material Safety Law (PSE law), and products not providing a certain safety level cannot be produced or sold. Incidentally, most LED lighting devices are not currently considered as electrical appliances, and the PSE safety standards do not apply to them. However, the concept of the PSE law is to regulate electrical appliances powered by commercial utility power and widely used by the general public, and hence LED lighting devices will certainly be designated as electrical appliances; but until then, the adoption of LED lighting devices should be based on sufficient safety inspection.

Compared to incandescent lamps, fluorescent lamps, and other existing light sources, LED lighting offers greater freedom in luminous flux design, color temperature, dimmer control, etc., and hence a wide range of products can be expected. When considering LED lighting as a replacement for existing lamps, a system to provide consumers with LED devices that they need becomes increasingly important. Consequently, the establishment of safety and functional standards as well as testing methods is necessary. At present, the Japan Electric Lamp Manufacturers Association (JELMA), in cooperation with the Institute of Illumination Engineers of Japan (IEIJ), the Japanese National Committee of CIE (JCIE), the Japan Luminaries Association (JLA), and other institutions, and also with the International Electrotechnical Commission (IEC), is working on a JIS (Japanese Industrial Standard) draft that agrees with international specifications. For example, the development of photometric specifications for lighting devices requires the cooperation of experts in color evaluation and other fields. Therefore, the international framework includes, in addition to the aforementioned, such institutions as CIE (Commission Internationale de l'Eclairage), NIST (U.S. National Institute of Standards and Technology), and IEA (International Energy Agency).

International standards are enacted by IEC in most cases. Some time is required for convergence between international standards and local standards such as ANSI (American National Standards Institute), EN (European Norm), or Japanese JIS. For this purpose, major makers establish consortia such as Zhaga for the promotion and implementation of standards in cooperation with IEC.

(2) Reliability

The lifetime of LEDs is determined primarily by degradation of package materials because of the synergistic effects of light and heat. As mentioned above, such degradation accelerates with rising temperature. Therefore, when mounting LED lighting fixtures, particular attention must be paid to providing heat insulation in accordance with the specifications and operation manuals so as to assure heat dissipation.

The lifetime of LED lighting devices depends not only on LED components but also on power supply units. Thus, LED lighting devices must be equipped with highly reliable power modules, which requires sufficient knowledge and experience for component selection and circuit design.

(3) LEDs and heat

LEDs are usually considered as "cold" light sources, but this is not necessarily the case. The light emitted by LEDs contains very little IR and UV radiation, which means that irradiated objects do not heat up; however, the part of the electrical input not converted into light causes a rise in the LED temperature. Figure 5 shows an example of the estimated energy balance, indicating what part of the electrical input is converted into light in the case of blue LEDs with an efficiency of 100 lm/W combined with yellow phosphors.

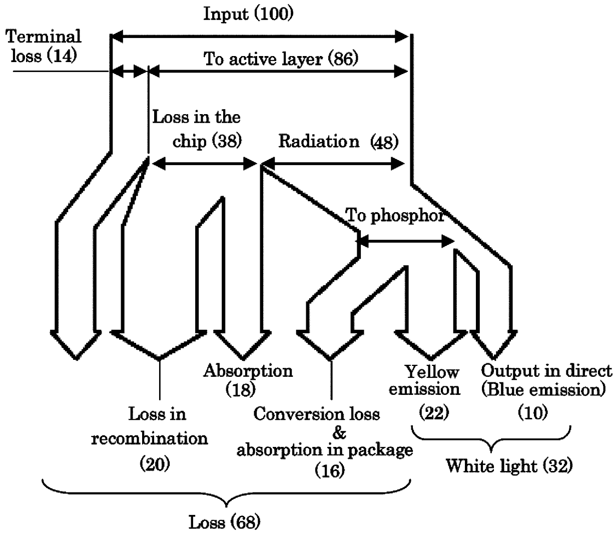

Fig. 5. Energy balance of typical white LED.

(4) Harmonics and power factor

Harmonic currents may occur with some loads connected to AC supply. Particular attention must be paid to circuits containing diodes and certain other elements. Conventional LED lighting devices consume only a few watts, and the harmonics produced by such devices are ignored. However, with the future spread of LED lighting, more luminaries will be connected to one power circuit, and unit power consumption will grow, so that harmonics must be taken into consideration.

In 2000-lm- and 8600-lm-class lighting devices such as down lights, security lights, and base lights (introduced below), PFC (Power Factor Correction) circuits are employed, and harmonics are reduced to well below the limit set by JIS C 6100-3-2 for lighting devices of Class C (over 25 W). In addition, the power factor reaches nearly 100%.

3.3 Features of LED lighting devices

As mentioned above, LEDs offer a number of features unavailable in existing light sources. This offers great freedom in lighting design, and makes possible the development of novel lighting devices.

(1) High efficiency and long life

LED lighting offers significant energy savings at the same level of brightness as conventional luminaries. Lower power consumption means low operating costs, and LED lighting is more economical than existing light sources even though the initial costs are relatively high. In addition, lower power consumption results in lower emissions of carbon dioxide (CO_2), so that LEDs are regarded as "new eco-friendly lighting."

LED life is about 40,000 hours (about 10 years in normal usage), compared with 1000 hours for incandescent lamps and 6000 hours for fluorescent lamps. This is particularly advantageous when lamp replacement is burdensome, for example, when luminaries are installed in high locations or embedded in the ground.

(2) Compactness

In existing lighting devices, the flux distribution of the light emitted by the light source is adjusted by using reflectors and other components. Incandescent lamps and fluorescent lamps have a large light-emitting area, and hence a large reflection area is required for regulation of the luminous flux. In contrast, LEDs have a small light-emitting area combined with light directionality, which allows compact mechanisms of flux distribution adjustment. Furthermore, no receptacles are needed for power connections, so that lighting fixtures can be made slim.

Such small and slim devices can be mounted where existing lighting fixtures cannot be mounted, for example, in narrow spaces or near beams and other construction elements. In addition, LED lighting can be designed so that its presence is not evident. Unprecedented harmony of light and the interior of living spaces or shops can be realized by integration of lighting with construction elements, making the most of LED features and diversity of mounting patterns.

(3) Lack of harm to objects

Illumination of objects degradable by light was a major problem in the past. For example, when paintings are illuminated from a short distance, small quantities of UV radiation promote discoloration. LED light includes hardly any UV components, and thus is much less harmful than existing light sources at the same illuminance, which is advantageous in the case of paintings and other cultural heritage objects. In addition, heat is a main factor in degradation of foodstuffs, but LED light includes little heat (infrared radiation), and foodstuff degradation is substantially reduced compared to conventional light sources at the same illuminance, even in illumination from a short distance.

Thus, LED lighting can be used safely at art museums, shops, fresh produce departments, etc.

(4) Low insect attraction

Insects are prone to fly toward light. However, they do not react to light of all wavelengths: they are attracted only by invisible light in the range from blue to ultraviolet. Since LEDs emit little ultraviolet, LED lighting attracts insects less than conventional light sources do. As a result, LED lamps are not easily contaminated by insect bodies, thus facilitating the maintenance of neatness and hygiene.

3.4 Latest LED lighting devices

(1) Down lights

Down lights using incandescent lamps and producing a luminous flux of 400 to 500 lm may well be replaced by LED down lights. The device shown in Fig. 6 consumes just 26 W, but is as bright (2080 lm) as a down light with a 42-W compact fluorescent lamp. This device has a height of only 80 mm and can be easily mounted on almost every beam or duct behind the ceiling.

Among high-power products, down lights equivalent in brightness to 150-W HID lamps have been implemented at 115 W using a combination of densely packed LED modules and advanced heat dissipation technology. Such luminaries produce illuminances above 1000 lx even in the case of a 6-m-high ceiling, and thus are suitable for the entrances of large shops and offices. A dimming controller provides continuous regulation in the range of 5 to 100%. The device has the same dimensions as conventional lights designed for a mounting hole diameter of 150 mm.

(2) Road lighting

LEDs have begun to be used for road lighting. The product shown in Fig. 8 produces a luminance of 1.0 cd per square meter when mounted at a height of 10 m with a spacing of 40 m. While consuming only 122 W, it has the same level of performance (in the case of power control by initial illuminance correction) as the 400-W mercury lamps or high-pressure sodium lamps used currently for illumination of highways.

(3) Base lights

Since special high-efficiency high-frequency fluorescent lamps are used in most cases as base lights in offices and schools, it was considered difficult to achieve a significant energy-saving effect by using LED lighting in this field. However, the product shown in Fig. 9 combines a

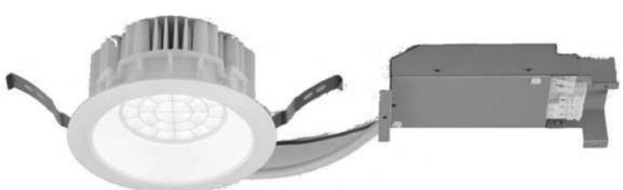

Fig. 6. 2000-lm-class down light.

Fig. 7. 8600-lm-class down light.

Fig. 8. Street light (1.0 cd·m^{-2} class).

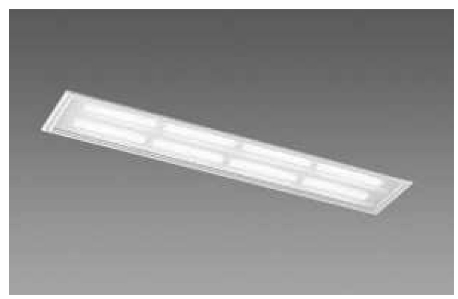

Fig. 9. 7600-lm-class base light.

Fig. 10. Retrofit lamp (8.7 W).

high-efficiency LED module with other high-efficiency components, including a power unit and reflector, and as a result, this luminary outperforms the conventional 32-W devices using high-frequency fluorescent lamps, and produces a luminous flux of 7600 lm with an overall efficiency of 110 lm/W. In past LED lighting, the high brightness of multiple LED elements made the light feel “grainy”; however, diffused light with suppressed glare is now achievable by optimization of the LED module arrangement, multiple reflection using high-reflectivity materials, and other advanced techniques.

High-efficiency fluorescent lamps have been employed for base lights in most cases, and the adoption of LED lighting was considered more difficult than in other fields. However, further increases of efficiency are expected with the development of new LED lighting fixtures.

(4) Retrofit LED lamps

The product shown in Fig. 9 consumes 8.7 W and produces an overall luminous flux of 810 lm at an efficiency of 93 lm/W for white light, and 600 lm at 69 lm/W for the incandescent lamp color. In the latter case, *Ra* is about 80, which provides a sense of comfort in a living room or hotel room. Retrofit LED lamps are a promising means of energy saving because lower power consumption and longer life can be achieved by simply replacing existing incandescent lamps.

4. Future Prospects

In 2009, LED lighting products by different makers were placed on the general lighting market. One can expect that from 2010 on, LED energy-saving characteristics will be continuously improved and that the further spread of LED lighting will be promoted by stricter efficiency requirements, restrictions on the use of mercury in fluorescent lamps and HID lamps, falling costs of LED devices, and other factors. Wise utilization of LED features will improve lighting quality, reduce environmental burdens, and produce economic benefits, thus promising a major social contribution.

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AUTHORS (from left to right)

Makoto Bessho (nonmember) completed the degree program at the Graduate School of Science and Engineering, Waseda University, in 1985. He is now involved in the development of LED modules. He holds a D.Eng. degree.

Keiichi Shimizu (nonmember) completed the degree program at Tokyo University of Science in 1980. He is now involved in the development of LED lighting devices. He holds a D.Eng. degree.