Technical Trend

Present Status of White LED Lighting Technologies in Japan

Tsunemasa TAGUCHI

Department of Electrical and Electronic Engineering, Faculty of Engineering,
Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi, 755-8611, Japan

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ABSTRACT

"The light for the 21st century" Japanese national (Akari) project, which is based on the high-efficient white light-emitting diode (LED) lighting technologies using near ultraviolet (UV) LED and phosphor system, has been started at 1998. The near UV white LED system linked with semiconductor technologies on GaN LED and ZnS phosphors for general lighting applications has for the first time been proposed in the project. The outline and purpose of this project are briefly introduced. In particular, we have demonstrated high-efficient nUV LED having external quantum efficiencies more than 43 % around an emission wavelength of 400 nm. Basic illumination properties of the high luminous efficacy (>40 lm/W) and the high general color rendering index (R_a>90) white LED sources are described. The near UV white LED technologies in conjunction with phosphor blends can offer superior color uniformity, high R_a and the excellent light quality for many lighting applications.

KEYWORDS: white LED, LED lighting, near UV LED, luminous efficacy, color rendering, external quantum efficiency

1. Introduction

At COP3 held in Kyoto during December 1997 (so-called, Kyoto Protocol), Japanese government agreed to reduce the amount of CO_2 emissions caused by energy use to the level of 1990 by the year 2010[1]. Following this, we must consider the best method in social engineering system to reduce the amount of greenhouse effect gases including CO_2, which have been implemented in the industrial, household and transportation areas.

The purpose of "The light for the 21st Century" (Akari) project based on the high efficient compound semiconductors between electricity and light, is to contribute to the above target by reducing the amount of energy spent on lighting, which accounts for approximately 20-40 % of all electrical power use. The high efficiency of white LEDs means that the active potential exists for enormous energy savings. The original proposal of near ultraviolet (nUV) white LED lighting technologies using phosphor materials for general lighting applications has been done by the author[2][3] before July, 1997. If it is promised that the energy savings by white LED lighting could be realized, optimistic estimations speculate that no new power plants would need to be built during the next 20 years[4].

This project has been jointly carried out by the New Energy and Industrial Technology Development Organization (NEDO) and the Japan Research and Development Center for Metals (JRCM) through a subsidy provided to NEDO by the Ministry of Economy Trade and Industry (METI). We are carrying out the research and development with the cooperation of the seven universities, thirteen enterprises and one association(Japan Electric Lamp Manufacture Association: JELMA)[1].

Basically, it is expected that white LEDs can offer advantageous properties such as high brightness, reliability, lower power consumption and long lifetime in stead of conventional light bulbs and fluorescent lamps. In particular, this white LED technology does not include Hg element which requires for generating UV radiation. During the last few years, the technology for white LEDs which is connected with the $In_xGa_{1-x}N$ blue LED coated with a YAG:Ce^{3+} phosphor, has improved the white LED efficiencies up to approximately 60 lm/W[5]. However, the brightness and color purity of blue LED-based white LEDs are strongly dependent on the conditions of forward-bias and phosphor coating[6]. The Akari method of making a color conversion white LED is that a true white can be achieved using three colors from red, green and blue phosphors excited by nUV LEDs, similar to three colors fluorescent lamp. At present, external quantum efficiencies are now as high as 43 % for the nUV LED which is operated at about 400 nm[7][8].

Since the Akari project has been established[2], the

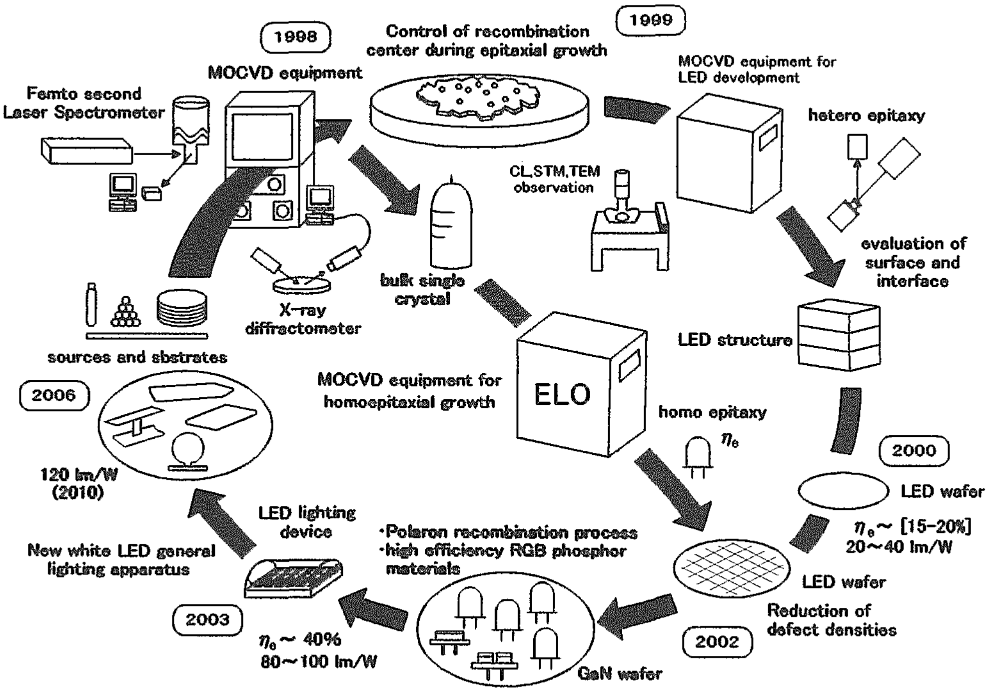

Fig. 1 Roadmap of near UV white LED technological development in "The Light for the 21st Century" National Project in Japan.

development of high-brightness blue and nUV light-emitting diodes (LEDs) based on III-nitrides has been carried out for making white LED light sources in semiconductor (solid state) lighting in all over the world. The revolutionary new approach is connected with the development of new phosphor-converted white LEDs and could be improved by scientists and engineers involved in the compound semiconductor, phosphor and lighting communities.

In this article, the outline and purpose of this national project are introduced, and the recent results and future prospect on development of near-UV white LED lighting are described.

2. Basic Research Programmes and Strategies on White LED Lighting

It has been well-known that visible LEDs offer a number of advantages compared to existing light sources because of the increased lifetimes, reduced power, small size, higher brightness and better spectral purity. LED performance has improved at a rate of approximately 10 times per decade. During the last decade, the technology of white LEDs has also been improved remarkably. In order to develop efficient lighting sources using high-brightness white LEDs, four research programmes have been carried out.

1) Fundamental studies on emission mechanism in ZnS and GaN-based wide bandgap compound semiconductors
2) Improvement of epitaxial growth methods for near UV LEDs

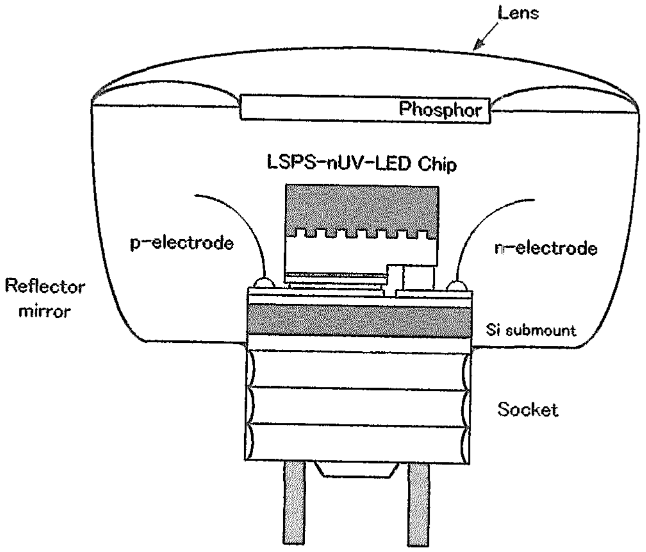

Fig. 2 Novel white LED with high-*R*a (>90) developed in the Akari National project.

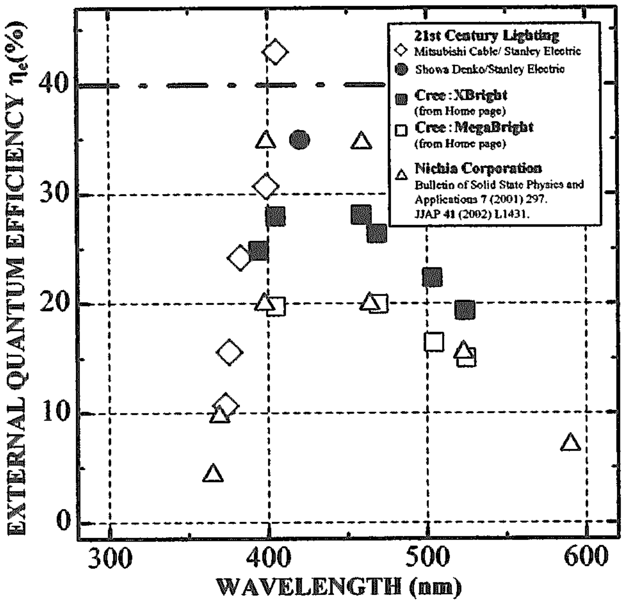

Fig. 3 Best reported η_e of each LED for three research groups as a function of wavelength.

3) Large substrates for homoepitaxial growth
4) Development of muli-color phosphors which generates white light excited by nUV LEDs and realization of illumination source using white LEDs

A national programme on white lighting research and development is attempting a luminous efficacy to 60-80 lm/W at the year 2003 and to 120 lm/W at the year 2010. Fig. 1 shows the roadmap of the national project for developing the high efficient nUV LED, where there appear the basic research issues for improvement of the external quantum efficiency and luminous efficacy. Recently, we have fabricated InGaN-based n UV LEDs on a patterned sapphire substrate using lateral epitaxy method (LEPS)[7]. The LED structure is composed of four periodic multiple quantum wells (MQWs) of InGaN/GaN, where barrier layers consist of n- and p-type $Al_{0.2}Ga_{0.8}N$. External quantum efficiencies (η_e) as high as 43 % and output powers as high as 26 mW can be obtained using a method of flip-chip bonding onto a Si submount as shown by LEPS-n-UV-LED chip in Fig. 2[8].

Currently, it has been indicated that the highest η_e for GaN-based LEDs seems to be in near UV (400 nm) spectral range. Fig. 3 shows the best reported η_e for LEDs operated at 20 mA as a function of emission wavelength in three research groups ("The Light for the 21st Century" Japan project (◇, ●), Cree Inc. (■, □) and Nichia Chemical Ind., (△)[9]. The Japan project has already achieved the external quantum efficiency of 43 % in a near UV LED operated at a wavelength of 405 nm.

If appropriate multi-color phosphor and encapsulation material can be matched to the nUV region (380-410 nm), then white LEDs with both high color rendering and high luminous efficacy can be obtained[10]. The basic mechanism of white light generation is the same as the commercial tri-color fluorescent lamp using a Hg discharge line (254 nm), which is related to the conversion of UV radiation to visible light. It is obvious that the conversion efficiency of a lighting device would increase as the primary UV wavelength is moved closer to the average visible light wavelength. Consequently, it is essential to develop a high-efficiency excitation source of 380-410 nm near UV radiation[11].

3. The Methods for Obtaining White Lights

Table 1 shows two methods which can produce white light using LEDs[12][13]. These technologies are likely to include : 1) $In_xGa_{1-x}N$-based blue and n UV LED system employing and fluorescent phosphors 2) RGB LED combinations. In the latter case, we need at least three LEDs which primary generate red, green and blue colors from each LED. Since the different semiconductors are used, one of each primary color must be adjusted by individual supply circuit in order to control the intensity of each color. On the other hand, white LEDs by exciting phosphors have been fabricated using blue and nUV

Table 1 Two methods for obtaining commercially available white LEDs.

Method	LED source	Luminescence materials	Emission mechanism
1 LED chip	Blue LED	$In_xGa_{1-x}N$/YAG:Ce/G, R phosphors	Binary complementary color white from blue EL emission and yellow PL emission or green and red PL emissions
	near UV (Akari Type)	$In_xGa_{1-x}N$/R,G,B phosphors O, Y, G, B phosphors	White PL emission from phosphors excited by nUV LED
3 LED chips	Blue LED, Green LED, Red LED	InGaN, AlInGaP	White EL emission from individual R. G and B LEDs

EL: injection electroluminescence, PL: photoluminescence
R: red, G: green, B: blue, O: orange, Y: yellow

LEDs with sufficiently optical excitation energy. Using the blue LED, the YAG:Ce^{3+} phosphor is excited by 465 nm and then emits yellow florescence around 555 nm. The mixture of the blue light from the blue LED chip and the yellow from the phosphor results in a white emission similar to the binary complementary LED system. Mueller et al.[14] have also reported RGB white LED using green and red phosphors excited by blue LED.

3.1 Blue LED Excited YAG Phosphor

Fig. 4 shows the temperature dependence of the forward biased electroluminescence (EL) spectra of a cannon-ball type white LED between 20 and 160℃[15]. An emission peak at 465 nm at temperature (RT) originates from a blue LED. An yellow emission at 555 nm with a bandwidth of about 150 nm is generated by an excitation of a Ce^{3+} center whose excitation wavelength exists near 460 nm. It is thought that energy from the 465 nm excitation band can be trapped at the Ce^{3+} ion and emits as cerium yellow emission at 555 nm. With increasing temperature, the 465 nm peak moves towards longer wavelength, which is similar to the temperature dependence of band gap energy of InGaN semiconductor. On the other hand, the 555 nm peak position did not change with temperature. Due to the change in the emission peak wavelength of the blue LED with temperature, the effective excitation efficiency for YAG phosphor is decreased. As a result, the emission intensity of the 555 nm band becomes weak at 160 ℃. It is therefore suggested that the emission properties of the InGaN white LED depends upon the temperature, and that an emission efficiency of the yellow band at 555 nm becomes weak above 50 ℃.

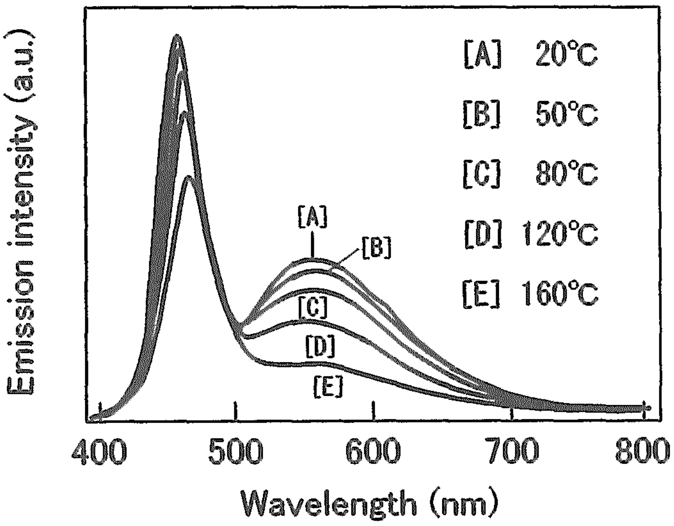

Fig. 4 Temperature dependence of EL spectra [A~D] of a white LED device between 20 and 160℃.

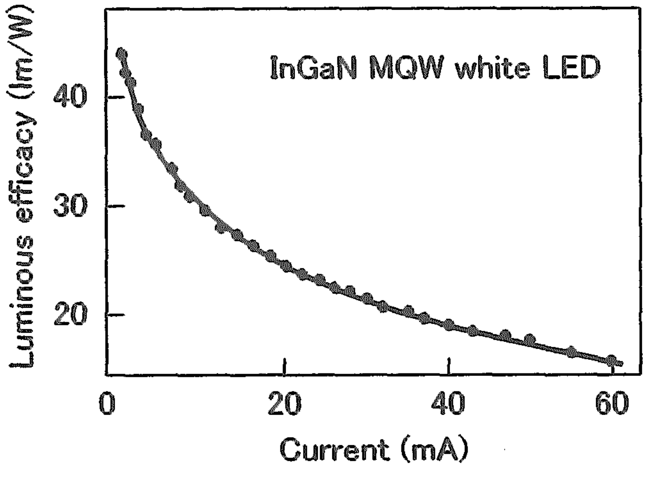

Fig. 5 Luminous efficacy of a white LED chip as a function of forward-bias current.

Fig. 5 shows the characteristics of luminous efficacy of a 10 cd class white LED chip as a function of forward-bias current. The onset for the white emission starts from forward-bias current of about 9 × 10^{-2} mA. At 1 mA, the luminous efficacy is estimated to be about 45 lm/W. However, the luminous efficacy is estimated to be about 27 and 23 lm/W at a constant forward-bias current of 10 and 20 mA, respectively.

Using this type of white LEDs, the first prototype solar cell type energy conservation street lamp has been demonstrated in Fig. 6. The prototype street lamp uses white LEDs of excellent ultrahigh-brightness of high electroluminescence conversion efficiency as its light source. By using solar cells and batteries in combination, the lamp can operate in the nighttime without having to use any power unit. A total of 700 units of these LEDs are installed inside a case having the size of 28×13 cm^2 for use as the light source. The prototype street lamp is equipped with two light sources. This street lamp has a voltage of 24 V and power consumption of 56 W. Its brightness is normally 80 lx, but whenever a person approaches within two meters near the lamp, the sensor senses this situation and increases the brightness to 660 lx. The lamp is 46 times brighter than a white incandescent bulb having the same power consumption rate, and the color rendering index representing the color is 85, close to that of the white fluorescent lamp[12].

There are however several problems which appear in the white LED composed of blue LED and YAG yellow phosphors, such as Halo effect of blue-yellow color separation, strong temperature and current dependence of chromaticity, and poor color rendering, due to the lack of green and red components[13]. In order to overcome these problems, an there is alternative method in which a color conversion white LED can be fabricated using both

Fig. 6 White LED lighting as a street lamp in the nighttime. A maximum illuminance over 660 lx.

RGB (red, green and blue) or OYGB (orange, yellow, green and blue) phosphors and near UV LEDs.

3.2 nUV LED Excited RGB Phosphors

The nUV or UV white LED approach is analogous to three-color fluorescent lamp technology, which is based on PL process in phosphor materials due to visible light conversion of UV radiation[16]. This technology can provide a higher quality of white light than the blue and YAG method.

Fig. 7 shows a typical PL spectrum of RGB phosphor materials excited at 20 mA of nUV LED with a wavelength of 382 nm. There are at least three main peaks locating at 447, 528 and 626 nm, respectively. The 447 nm blue emission, 528 nm green emission and 626 nm red emission bands are originated from fluorescent emission of $(Sr, Ca, Ba, Mg)_{10}(PO_4)_6CL:Eu^{2+}$, $ZnS:Cu,Al$, and $L_2O_2S:Eu^{3+}$ phosphors, respectively. The blue phosphor indicates two absorption peaks at about 330 and 380 nm and occurs the $4f^7 \rightarrow 4f^6 5d^1$ optical transition in Eu^{2+} ions. The green phosphor indicates absorption peak at about 400 nm and occurs a donor-acceptor pair transition. The red phosphor indicates an absorption peak at 350 nm and occurs both the f-f transition in Eu^{3+} ions and a charge transfer process.

We have obtained chromaticity points (x, y), color temperature (T_c) and general color rendering index (R_a) to be (0.290, 0.336), 7644 K and 93, respectively, at a forward current of 20 mA. The R_a>90 is close to that of three-band emission fluorescent lamp. The luminous efficacy of radiation (K) is estimated to be about 30 lm/W for the present white LED. Both components of green and red emission are very important to improve the T_c and R_a value. The illuminance distribution from the present white LED indicates the full radiation as described by cosθ as shown in Fig. 8. The life is estimated to be more than 6000 hrs at a forward-bias of 20 mA.

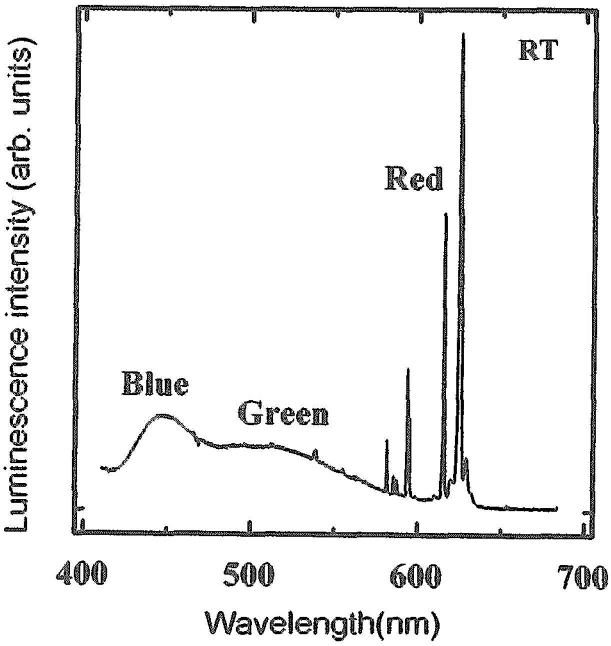

Fig. 7 A typical Luminescence spectrum of RGB phosphors excited by a nUV LED.

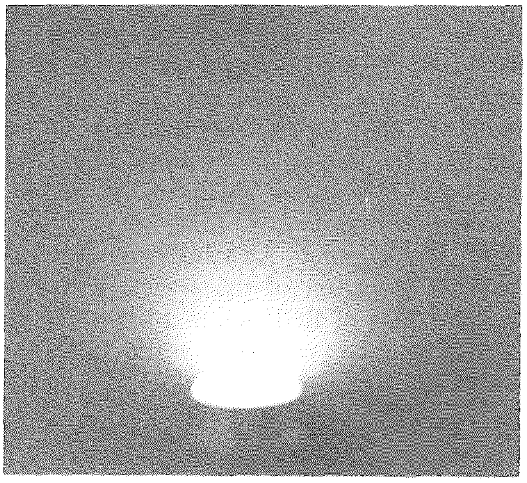

Fig. 8 Illuminance distribution described by cosθ profile in a white LED having high-Ra (93).

3.3 nUV LED Excited OYGB Phosphor

Fig. 9 shows a typical emission spectrum of an OYGB white LED consisting of OYGB phosphor

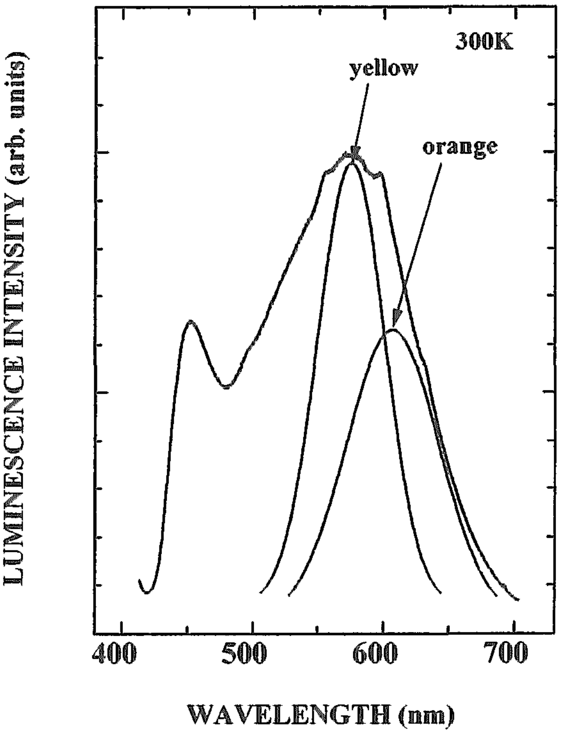

Fig. 9 Typical luminescence spectrum of the OYGB white LED at a forward-bias current of 20 mA.

materials and nUV LED operated at 20 mA13). There are three peaks locating at 450, 520 and 580 nm obtained from florescent emission of Sr material and ZnS-based long-wavelength phosphor materials, respectively. When the near UV LED was operated at a current of 20 mA at RT, chromaticity (x, y), color temperature (T_c), general color rendering index (R_a) and luminous efficiency of radiation (K) of the white luminescence are estimated to be $(x, y)=(0.39, 0.39)$, $T_c=3{,}700K$, $R_a \geqq 93$ and $K=40$ lm/W, respectively. The luminescence spectrum of the OYGB white LED is broader than that of RGB white LED. The general color rendering index of OYGB white LED is higher than that of RGB.

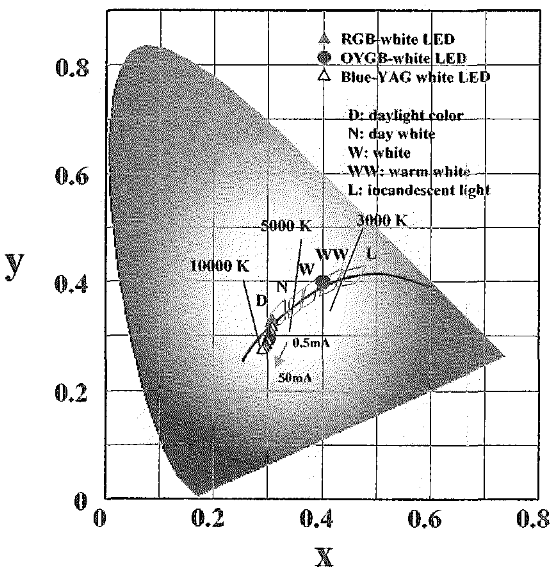

Fig. 10 Forward-current dependence of chromaticity points of three white LEDs.

4. A Comparison of Luminous Characteristics among Three Kinds of White LEDs

As shown in Figs. 7 and 9, white lights can be obtained from photoluminescence spectrum of RGB or OYGB phosphor materials under the nUV excitation condition.

The luminous performance of the white LED excited by nUV light is than given by the following equation,

$$\eta_{white} = \frac{\int \frac{\lambda_0}{\lambda} F_{ph}(\lambda)\kappa \cdot (\lambda) d\lambda}{IV \int F_{ph}(\lambda) d\lambda} P \eta_{UV_{ph}} \eta_{ph} \quad \cdots\cdots\cdots\cdots \quad (1)$$

where I and V are the forward-bias current and voltage, respectively, λ_0 is the emission peak position of nUV LED, P is the output power of nUV LED, η_{ph} is phosphor internal quantum efficiency of nUV to visible light, $\eta_{UV_{ph}}$ is the conversion efficiency

Table 2 Comparison of three white LED sources on luminous efficacy, color temperature and general color rendering index.

Type	BY	RGB	OYGB
luminous efficacy	> 20 (lm/W)	> 30 (lm/W)	40~60 (lm/W)
color temperature (T_c)	6,500 K (day light)	4,000 K (day light)	3,700 K (white)
general color rendering index (R_a)	> 80	> 90	93

BY: Blue-YAG

of the phosphor, $F_{ph}(\lambda)$ is the emission spectrum of each phosphor and $\kappa(\lambda)d\lambda$ is the human eye response factor.

Assuming that $\eta_{UV_{ph}}$ is 85 % and η_{ph} is 80 %, the luminous efficacy of radiation can be obtained to be approximately 100 lm/W at an output power of about 60 mW at 380-410 nm. The present red phosphors generally do not strongly absorb radiation in 380-410 nm range. In order to obtain more than 100 lm/W, it is necessary to develop new red phosphor whose absorption rate exceeds 90 %.

Fig. 10 describes the experimental plots in (x, y) chromaticity coordinates of chromaticity at bias currents more than 20 mA in three kinds of white LEDs (Blue-YAG: △, RGB: ▲ and OYGB: ●). As seen in this figure, the changes in x-and y-coordinate are extremely small in the OYGB white LED compared to that of Blue-YAG white LED, so that the RGB and OYGB white LEDs indicate the excellent luminous characteristics for high current operation.

Table 2 summarizes the comparison of the typical luminous characteristics such as luminous efficacy (K), color temperature (T_c) and general color rendering index (R_a) obtained in three white LEDs which are composed of blue LED-YAG phosphor, nUV LED-RGB phosphors and nUV LED-OYGB phosphors. The nUV LED white LED technology can offer superior color uniformity and the excellent light quality. Nearly all of the white (incandescent light, warm white, white, day white described in Fig. 10) from low T_c to high T_c can be obtained using multi-color phosphor blends.

5. Future Prospects and Collaborations among Semiconductor Engineers, Lighting Engineers and Lighting Designers

Following the technologies roadmap shown in Fig. 1, we have succeeded in achieving the highest external quantum efficacy (η_{ex}) over 40 % at the end of the year 2002, and the Akari National project will finish the 1st phase for the purpose of research and development programmes as shown in Fig. 11. The new target for the external quantum efficacy is set to be 60 % by the year of 2006 as the 2nd phase programme, and to be about 80 % by the year of 2010 as the final phase programme[18].

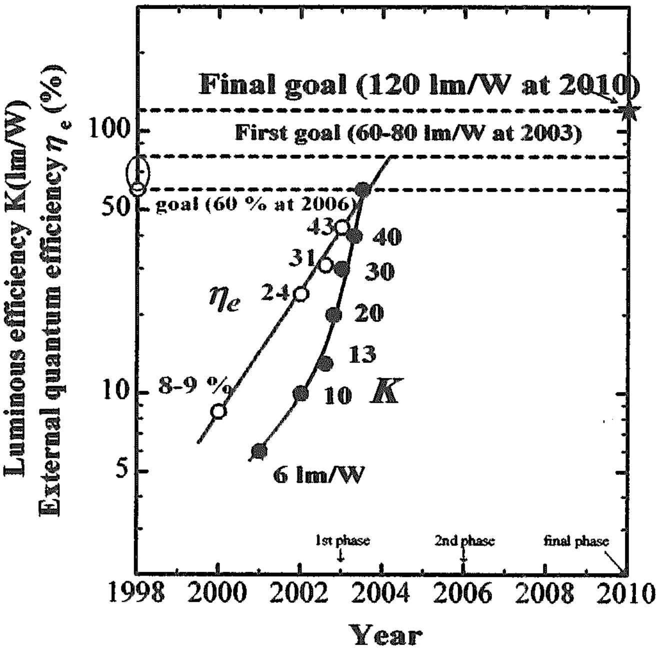

Fig. 11 Roadmap of external quantum efficiency (η_e) and luminous efficacy(K), and its final goal by the year of 2010.

On the other hand, concerning the luminous efficacy of radiation (K) for white lights, we can see a significant increase in lm/W in Fig.11. We have already obtained the highest luminous efficacy of 30 lm/W in the practical RGB white LED having high-R_a, whose life is over 6000 hrs. It seems that this type of white LED can replace the conventional BY

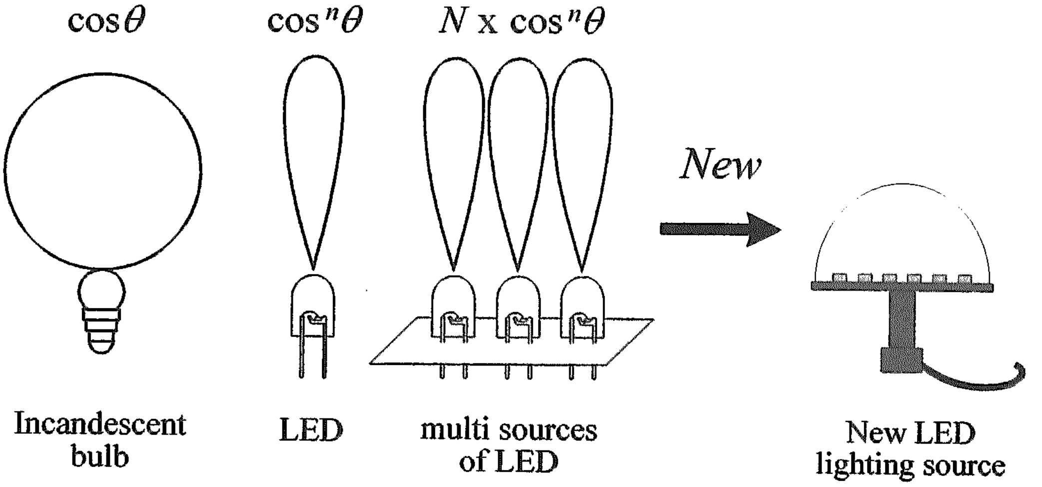

Fig. 12 Illuminance distribution of incandescent bulb, a single radial LED, multi sources of LED and a new LED lighting source.

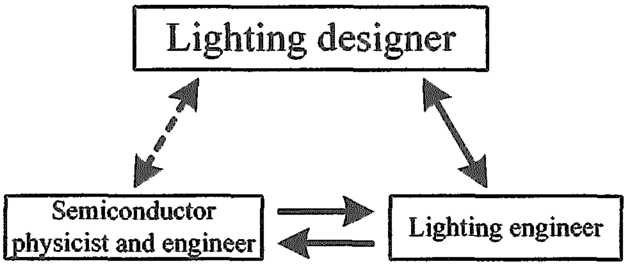

Fig. 13 Collaboration among semiconductor physicist and engineer, lighting engineer and lighting designer. A connection between lighting engineer and designer seems to be strong, but a relationship between semiconductor engineer and lighting designer does not exist.

white LED. At March, 2003, we have obtained the value of K to be about 60 lm/W for greenish-white phosphors. In order to achieve the luminous efficacy over 80 lm/W, we will need the appearance of new phosphor materials and novel structures which are suitable for the excitation wavelength at 380-410 nm. Our target in the Akari project will be 80 lm/W by the year of 2006, and over 120 lm/W by the year of 2010, from the practical point of views of general lighting applications.

As shown in Fig. 8, the white LED should require the similar illuminance distribution as the incandescent bulb. Fig. 12 shows the example of the illuminance distribution between incandescent bulb, and a radial LED and multiple LEDs. The radial LED indicates a sharp intensity distribution described by $\cos^n\theta$, and the multiple LED source also indicates a sharp intensity distribution described by $N\cos^n\theta$, where N is the number of LEDs[17]. However, for general lighting applications, it is hoped that a novel type of white LED source and instrument will appear, which is most likely to be different from the cluster and module types.

For future development of lighting applications up to the year of 2010, we will need the definition of infrastructure and the international performance standard of LED lighting technologies and system. In order to accelerate the LED lighting concept, market and culture, we also need the good collaboration among semiconductor engineers, lighting engineers and lighting designers as suggested in Fig. 13. In Japan, we have already organized the special committees on "White LED lighting enviroment" in the Japan illumination Socity at June, 2002 including many members from semiconductor and lighting companies, and lighting designers. Further more, it is expected that a new lighting concept between semiconductor physicist and lighting engineer is considered for the manufacture of LED light sources.

6. Conclusions

The near-UV white LED features a number of distinct advantages, one of which is able to convert the light to white by passing it through a phosphor, similar to the tri-color RGB fluorescent tubes. White LEDs are easy on the environment because of no need of its rejection due to long lifetimes.

In general, the nUV white LEDs are a superior approach to making white lights using LED system in comparison with the ordinary blue-white LEDs with a yellow phosphor coating due to its better color rendering, manufacturability, and various color temperatures. The project aims to develop a new illumination white source that is lighting efficient, and has excellent luminous characteristics using the new type of multi-color phosphor-based white LEDs, which will be able to replace incandescent bulbs and fluorescent tubes. The biggest potential application for nUV white LEDs will be in general illumination and lighting, and medical applications.

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