# Fabrication of LED lighting goggle for surgical operation and approach toward high color rendering performance

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## ABSTRACT

The first internal shunt operation in the left forearm has successfully been performed using the surgical lighting goggle composed of InGaN-yttrium aluminum garnet (YAG)-based white light emitting diode(LED) arrays. This system supplies a total luminous flux of about 200 lumen for several hours by driving with rechargeable Li-ion batteries. Further increase in luminous flux can be achieved by both the progress of emission efficiency of white LEDs and the development of dense packaging technique of LED chips. Moreover, the color rendering properties of white LEDs are inferior to the standard illuminant especially in violet, green and red spectral range. In this paper, several device structures are proposed for achieving power lighting and for higher color rendering properties. The key technology for power lighting is how to radiate the heat out of LED chips, and that for higher color rendering is how to add desired illumination-spectral-components to LEDs according to the application fields.

**Keywords:** white LED, mobile lighting system, power lighting technology, synthesis of lighting spectra

## 1. INTRODUCTION

The lighting commonly used for the surgical operation has been the ceiling one composed of Xe-lamps or metal halide lamps. The problem for such system is that the surgeons' heads prevent the illuminations from reaching the operation field resulting in the inadequate amount of beams for operation. Our idea was to put the handy lighting panels onto plastic goggle by which such a problem mentioned above would be solved. After the discussion between a surgeon (Shimada) and researchers of solid state science (Kawakami and Fujita), a surgical lighting goggle composed of InGaN-yttrium aluminum garnet (YAG)-based white light emitting diode(LED) arrays has been produced experimentally. The first surgical operation using this solid state lighting system has successfully been performed for an internal shunt operation in the left forearm of a female patient on September 11, 2000 at Kyoto Prefectural Yosanoumi Hospital (Iwataki-Cho, Kyoto, Japan). [1-3]

Since this system supplies a total luminous flux of about 200 lumen [4] for several hours by driving with rechargeable Li-ion batteries, new applications as mobile lighting are expected not only in the field of medical services such as surgical operation, out patient clinic or dentists but also for patrolling, night skiing, scuba diving or reading books with lying and so on.[5] Currently, external quantum efficiency ( $\eta_{\mathrm{ext}}$) of InGaN-LEDs commercially available is about 10 %. However, the $\eta_{\mathrm{ext}}$ value more than 20 % is now achieved at the level of laboratory. For further increase of luminous flux in LED-based lighting system, it is essential to improve an efficiency. Another important point is to develop a dense packaging design of LED chips that can be improved by the heat dissipation technique.[6]

The spectrum of white LED is composed of two emission bands, where the blue band peaking at 460 nm is the emission from InGaN quantum-well-active layers, and the broad yellow band at 560 nm is the one from YAG:Ce $[(Y_{1-x}Gd_x)_3(Al_{1-y}Ga_y)_5)O_{12}$:Ce] phosphor.[7] Comparing with the standard illuminant, the spectral distribution in violet color is missing, and the components in green and red are inferior in intensity. Among them, the distribution in red spectral region is very important for the medical application.

In this paper, several device structures are proposed for achieving power lighting and for higher color rendering properties.

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## 2. EXPERIMENTAL PROCEDURE

Figure 1 shows a white LED lighting system, where 56 LEDs were mounted on both sides of the plastic goggle. Therefore, the total number of white LED lamps are 112. InGaN-YAG-based LEDs (NSPW310AS, NICHIA) with a luminous efficiency of about 15 lumen/W under normal operation condition (3.5 V, 20 mA) , and a directivity of 60 degree have been adopted for this purpose. For the purpose of a mobile application, rechargeable Li-ion batteries (NP-F960, SONY) were used for power supply. It is necessary to supply a constant current to LEDs even if output voltage from the batteries decreases according with a discharging process. Therefore, a DC-DC converter (SVM-15SC12, ETA) was connected between batteries and a lighting goggle.

Illuminance properties of a lighting goggle were measured by an illuminance meter (510-01, YOKOGAWA). A thermoviwer (JTG-7000, JEOL) was used in order to assess the heat distribution in the LED-arrays.

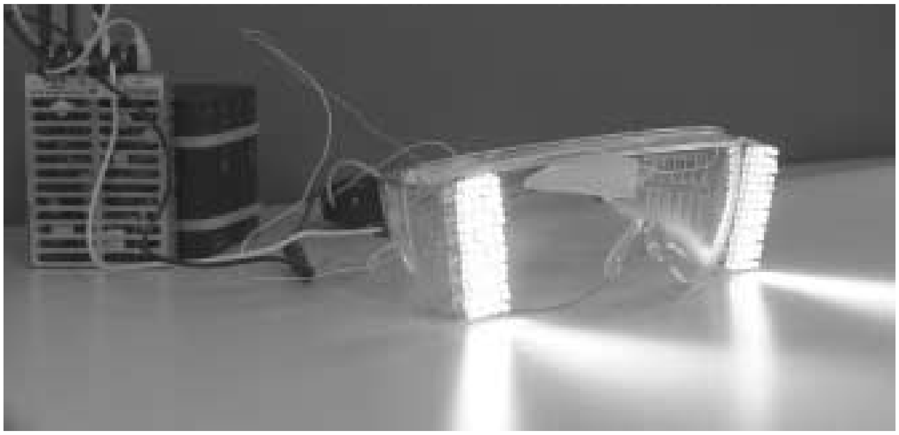


Figure 1 : A surgical lighting goggle composed of white LED arrays. The weight of the goggle is as small as 65 g. LEDs are driven by Li-ion batteries and a DC-DC converter.

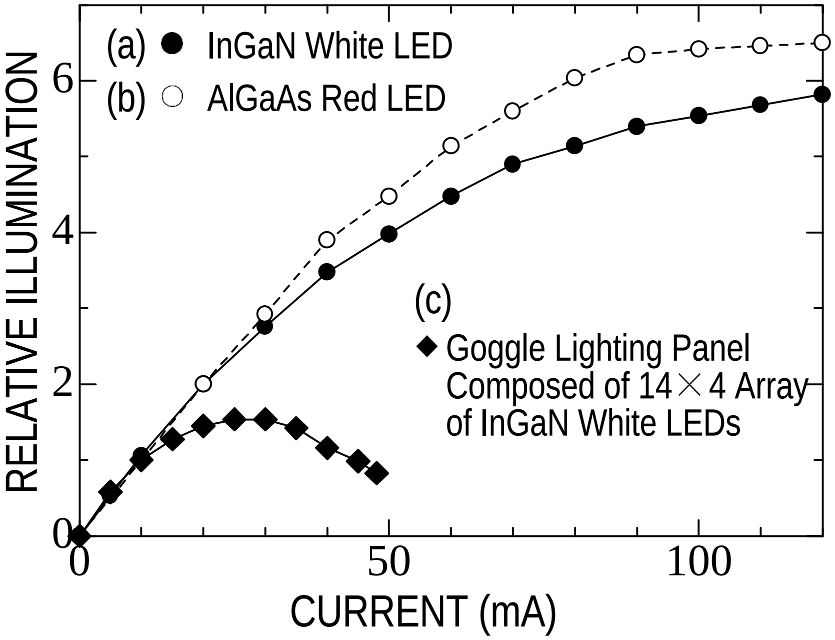
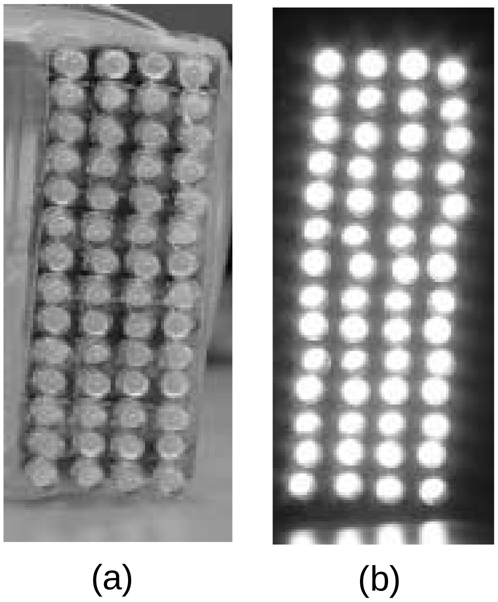


Figure 2 : Relative illumination intensity as a function of current per one chip for (a) a discrete InGaN white LED, (a) a discrete AlGaAs red LED and (c) goggle lighting panel composed of 14×4 array of InGaN white LEDs where no heat radiator was installed. In each device, illumination under 10 mA/chip was normalized to unity.

## 3. RESULTS AND DISCUSSION

### 3.1 Illuminance properties of white LEDs

A minimum illuminance required for surgical operation is 20000 lux (lumen/$m^2$) in a law of Japan. Although this value is much larger than an illuminance used in everyday life, an illumination area required for the operation field is rather small, for example, 0.15 m square (0.00225 $m^2$ in area) would be enough in many applications. In such a case, a total luminous flux of 450 lumen is required from the lighting system. Figure 2 (a) shows a relative illumination of a InGaN white LED as a function driving current. For a reference, the characteristics of a AlGaAs red LED is also plotted. At low current region, illumination intensity is almost proportional to the driving current. However it becomes sublinear relationship above about 20 mA and tends to saturate above about 100 mA. Nevertheless, nitride-based semiconductors are so robust that a stable operation more than 100 mA is possible for one chip. At an initial design, a total iluminance of about 350 lumen was expected from the lighting goggle under a driving condition of 150 mA/one chip. This suggested that the 20000 lux condition would be almost achieved with one lighting goggle. Nevertheless, a goggle lighting panel composed of 14×4 array of InGaN white LEDs exhibits a maximum illuminance at 25mA/one chip, and then decreased for further increasing current as shown in Fig. 2 (c). Actually, for the surgical operation, it was necessary for achieving the illuminance standard to illuminate the same operation field from lighting goggles of three people (two surgeons and one nurse) as shown in Fig. 3.



(a) (b)

Figure 3

Figure 4

Figure 3 : The first surgical operation using white LEDs goggles. An illuminance standard of 20000 lux was achieved by the lighting from two surgeons and one nurse.

Figure 4 : Photographs of LEDs array (a) without and (b) with current operation.

### 3.2 Heat distribution in LEDs array

In order to assess the reason for such a discrepancy, the heat generation from the LEDs array was investigated by employing a thermoviewer observation. Photographs of LEDs array without and with current operation are shown in Fig. 4 (a) and 4 (b), respectively. Figure 5 shows the temperature mapping of LEDs arrays illustrated with gray scale driven under 20 mA/chip for (a), and under 45 mA/chip for (b). The thermoviewer observation of a discrete white LED chip operated under 20 mA at 20℃ atmosphere showed that the core of LED chip is increased to 35 ℃. On the other hand, it was found that the temperature of the panel was increased to the range from 62.5 to 87.5 ℃ even with normal operation condition (20 mA/chip). The temperature further increased to the range between 100 and 160 ℃ under 45 mA/chip condition. Figure 6 shows a relative illumination of an InGaN white LED and of a AlGaAs red LED as a function of temperature. An illumination intensity gradually decreases with increasing temperature because the pathway to nonradiative recombination

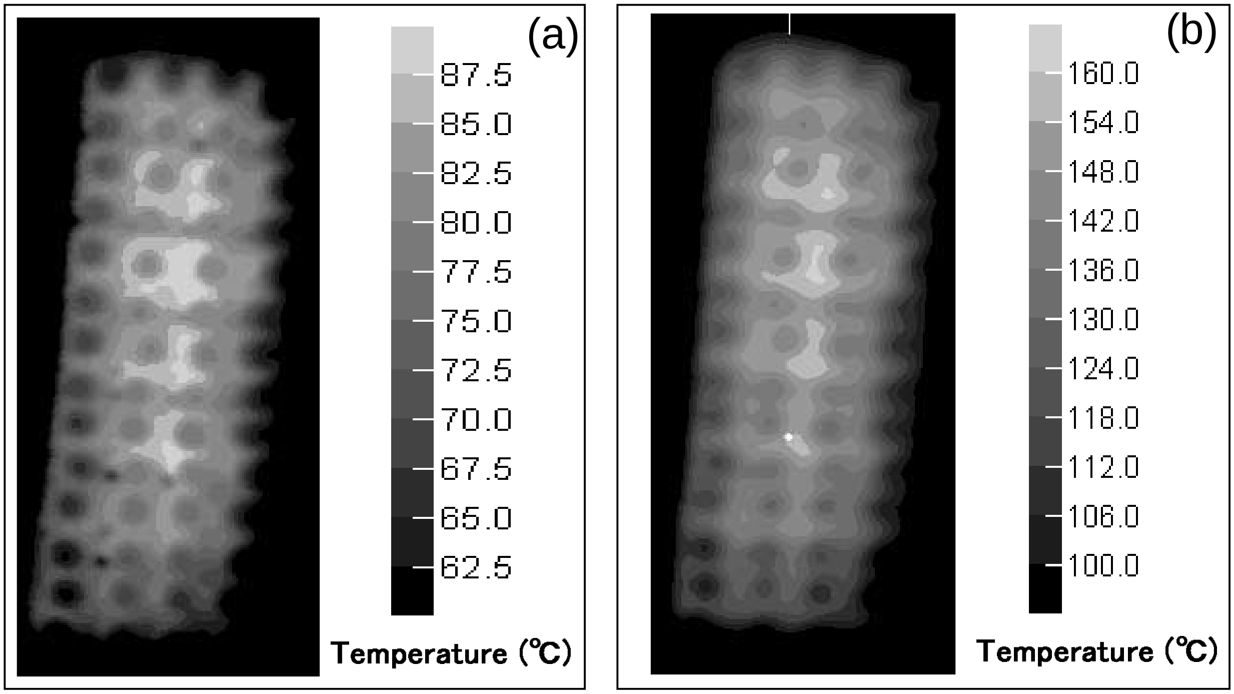


Figure 5 : Heat distribution in LEDs array panel observed by a thermoviewer under operation conditions of (a) 20 mA/chip and (b) 45 mA/chip.

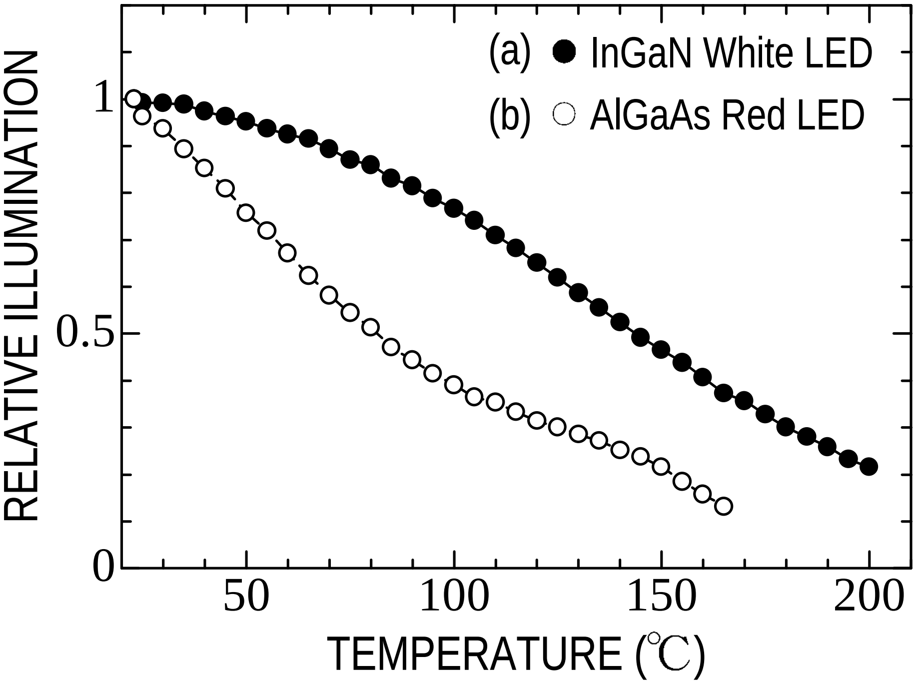


Figure 6 : Relative illumination intensity of a discrete chip of (a) InGaN white LED and (b) AlGaAs red LED plotted as a function of ambient temperature.

with respect to radiative one becomes predominant in such a condition. Therefore, it was confirmed that the illumination saturation of LEDs array under lower current condition is due to heat accumulation in the panel. It should be noted that the temperature in the epoxy panel is higher than that in the core region of LED chips. This indicates that higher thermal conductivity and proper heat sink structures are the key technology of LED package for achieving power illumination.

### 3.3 Diamond-based package technology

Recently, we are going to develop a dense LED packaging technology by using diamond as thermal conductive material. Diamond substrates are currently mass-produced by either bulk growth or chemical vapor deposition.[8] The thermal conductivity of diamond is the largest of all materials. It is optically transparent and electrically insulating in intrinsic conditions. Moreover, p-type conductivity of diamond can be controlled by doping. These features suggest that diamond is the most promising material for LED package. Figure 7 shows the schematic of diamond-based package technique. Even with the junction-top configuration, the heat generation from active layers can be effectively dissipated by depositing diamond or diamond like carbon (DLC) on top of LED chips. Another idea is to use a package based on insulating-diamond / conductive-metal multi-layered structure. By scooping the surface of a package with a shape as shown in Fig. 8, LED chips can be mounted directing each beam to a same focus point.

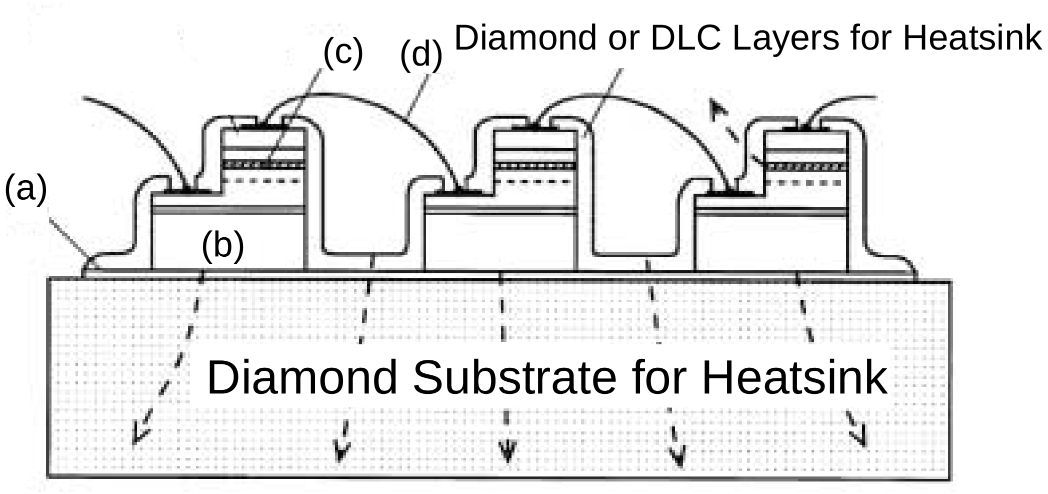


Figure 7 : A diamond packaging technique for power lighting application. (a) AuSn bonding metal, (b) sapphire substrate, (c) InGaN active layer and (d) Au wiring.

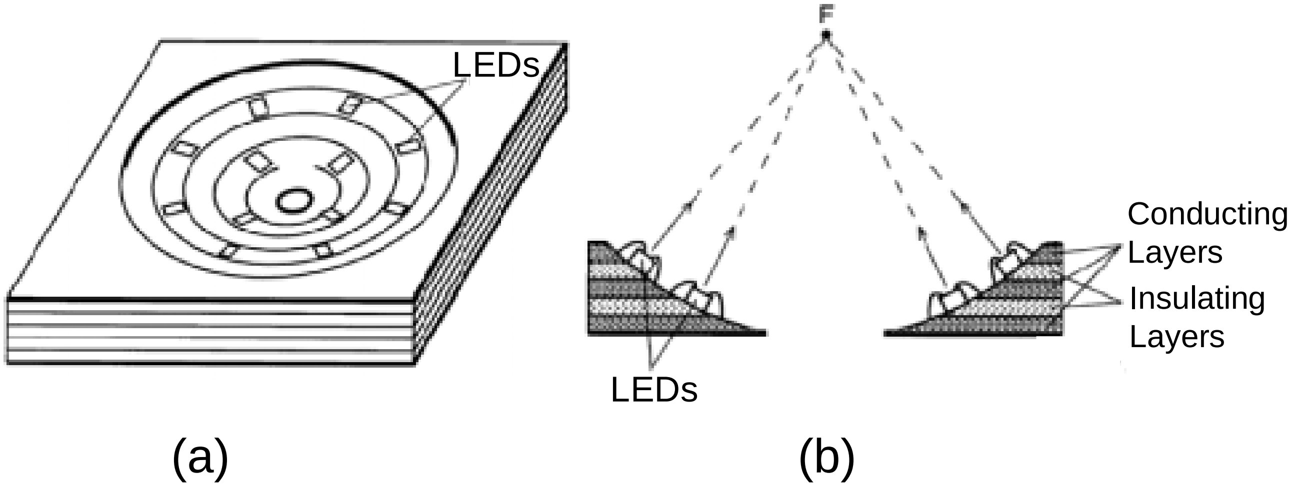


Figure 8 : Metal-diamond hybrid package. Proposed structure is suitable for controlling luminous intensity distribution.

### 3.4 Color rendering properties of InGaN-YAG-white LED

Figure 9 (a) shows spectral distribution of radiation flux taken at an InGaN-YAG-white LED. Chromaticity coordinates are x=0.310, y=0.320, corresponding to the correlated color temperature of 6500 K (daylight color). Spectrum of standard illuminant $D_{65}$ (color temp.: 6504 K, x=0.3127, y=0.3290) is also plotted in Fig. 9 (b). General color rendering index ($R_a$) of the white LED is estimated to be 87 that is substantially high. However, special color rendering index of $R_9$ (red), $R_{11}$ (green) and $R_{12}$ (purplish blue) are as small as 51, 73 and 62, respectively. Such low indexes correspond to the spectrally deficient region in the white LED. In a medical application, color rendering in red spectral region is especially important. For instance, hemoglobin in artery is rich in oxygen, and shows bright red in contrast to dark red in vein. However, a surgeon pointed out that it was rather difficult to distinguish between artery and vein using the LED goggle.

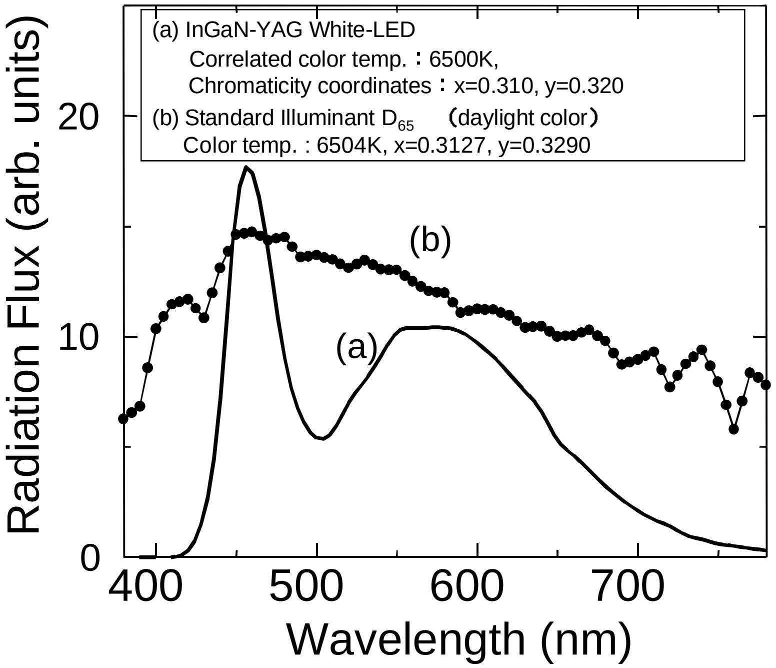


Figure 9 : Radiation flux spectrum taken at (a) an InGaN-YAG-white LED, and (b) standard illuminant $D_{65}$.

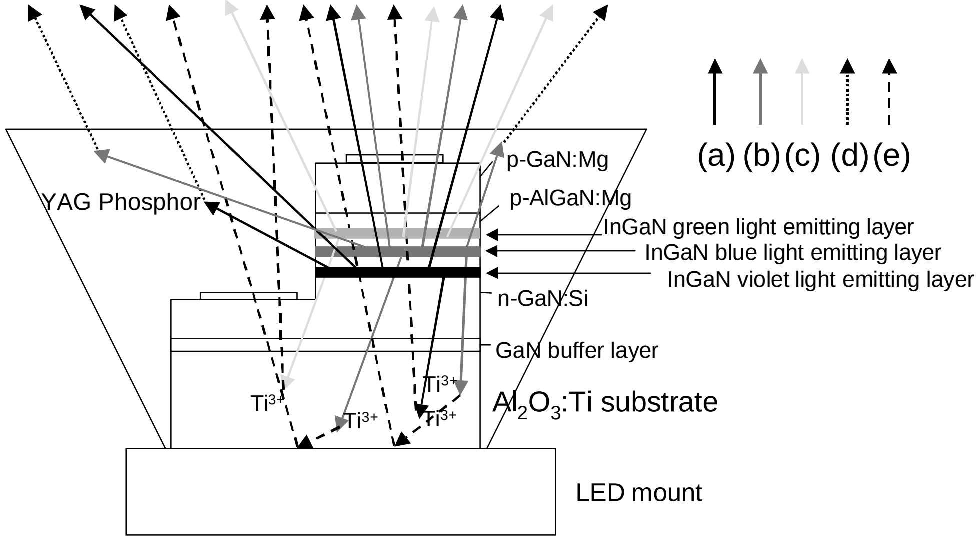


Figure 10 : Proposed structure ($Al_2O_3$:Ti substrate) for achieving higher color rendering properties.

### 3.5 Proposed device structure for higher color rendering performance

In order to improve spectral distribution in red color component with one LED-chip configuration, two structures are proposed in this paper. One structure is the use of $Al_2O_3$:Ti as a substrate of nitride semiconductors. This material, $Ti^{3+}$ ion is substituted for an $Al^{3+}$ ion in $Al_2O_3$, is widely used as laser crystals. $Al_2O_3$:Ti crystals[9] exhibit a broad absorption band (400 nm to 600 nm), located in the blue-green region with a peak of 490 nm, and a broad emission band (600 nm to 1000 nm) , in the red-near infrared (IR) region with a peak of 780 nm. Therefore, it is possible to photo-excite $Ti^{3+}$ ion by the blue-green emission from InGaN active layers, and to covert to longer wavelength emission band. One promising device structure is schematically illustrated in Fig. 10. The structure consists of $Al_2O_3$:Ti substrate, LED structure having three different InGaN active layers emitting violet (420 nm) , blue (460 nm) and green (520 nm) spectral components and YAG-phosphor. Figure 11 shows an expected emission spectrum from the device structure proposed in Fig. 10. Although one drawback is that this structure is unfavorable for achieving higher luminous efficiency because of the component in IR spectra, high color rendering characteristics can be attained even with LED-based lighting.

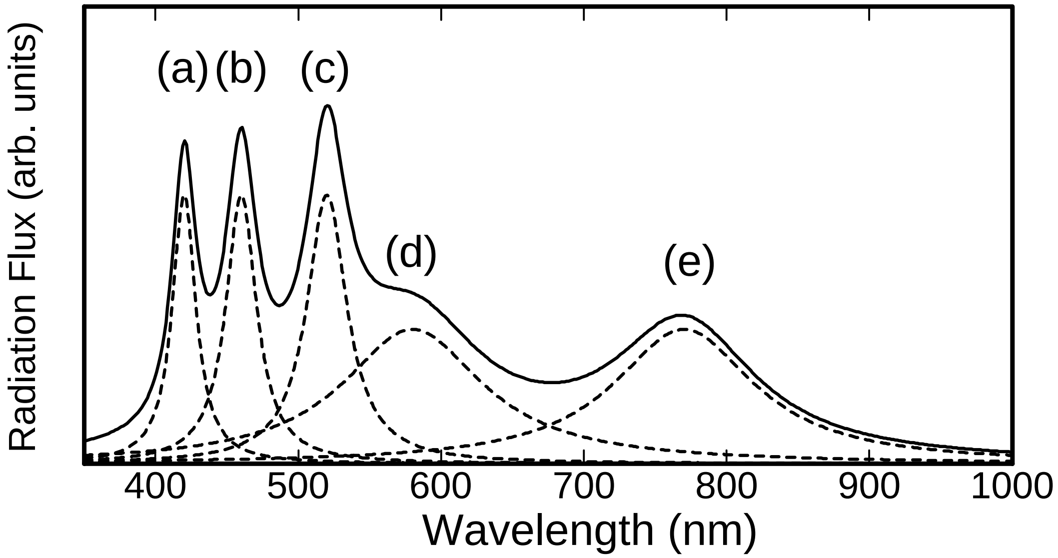


Figure 11 : An expected radiation flux spectrum from the structure depicted in Fig. 10. (a), (b) and (c) are violet, blue and green emissions from InGaN QW active layers with different alloy composition. (d) is the fluorescence from YAG phosphor, and (e) is that from $Al_2O_3$:Ti substrate.

### 3.6 Proposed device structure for high color tunability

Another structure is a use of $Al_2O_3$:Cr (ruby) as a substrate. This material, $Cr^{3+}$ ion is substituted for an $Al^{3+}$ ion in $Al_2O_3$, is also well known as the first visible solid laser crystal.[10] Fluorescence in this crystal can be obtained by irradiating it with green light to excite the ${}^4A_2 \rightarrow {}^4F_2$ transition, violet light to excite the ${}^4A_2 \rightarrow {}^4F_1$ transition. The emission spectrum consists of a sharp doublet (${}^2E \rightarrow {}^4A_2$) in the red whose components are at 694.3 nm and 692.9 nm with respective half widths of 0.4 and 0.3 nm. Absorption spectrum in green band is in the range of 500 nm to 620 nm peaking at 560 nm, while that in violet band is from 350 to 450 nm peaking at 410 nm. One feasible device structure using a $Al_2O_3$:Cr substrate is schematically shown in Fig. 12. Green light from InGaN active layer is partly absorbed by $Cr^{3+}$ ion converting to the red fluorescence, and remaining part transmits a $Al_2O_3$:Cr substrate. Blue light from another InGaN active layer almost penetrates the substrate. Figure 13 shows an expected spectral distribution from the structure. Emission colors can be tuned by controlling the intensity ratio among R (red), G (green) and B (blue) components. This can be achieved by the adjustment of the number of quantum-well-active layers emitting blue or green colors, and by that of Cr composition and/or thickness of a $Al_2O_3$:Cr substrate.

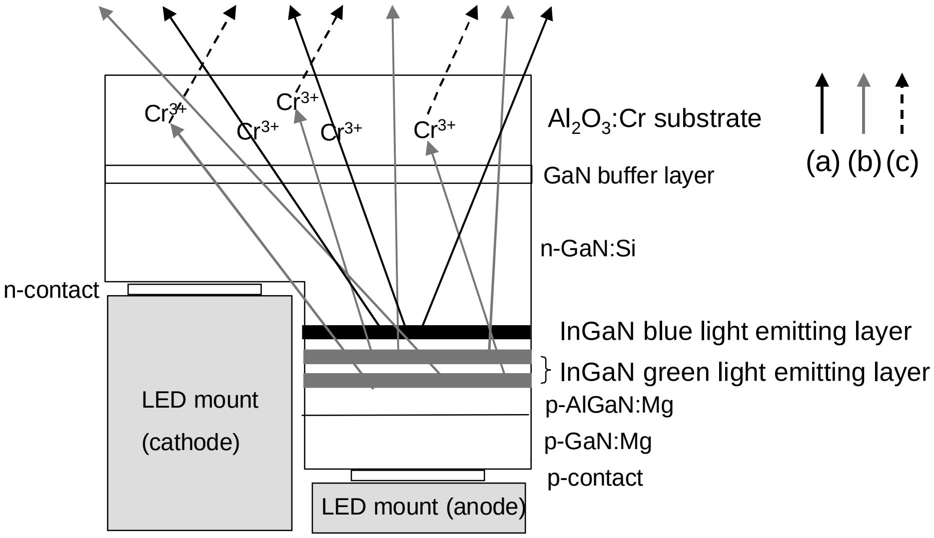


Figure 12 : Proposed structure ($Al_2O_3$:Cr substrate) for achieving high color tunability.

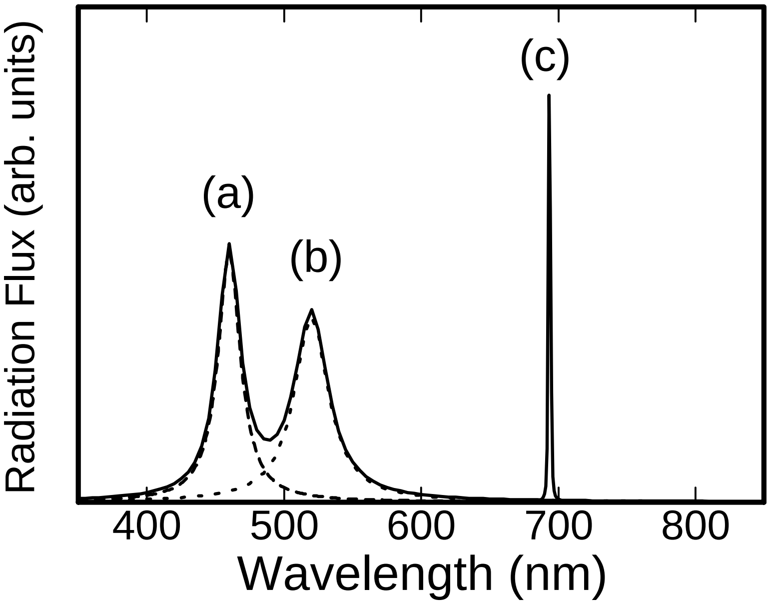


Figure 13 : An expected radiation flux spectrum from the structure depicted in Fig. 11. (a) and (b) are blue and green emissions from InGaN QW active layers with different alloy composition. (c) is the red fluorescence from $Al_2O_3$:Cr substrate.

## 4. CONCLUSIONS

In conclusion, a lighting goggle composed of InGaN-YAG-based white-LED-arrays has been fabricated for the surgical operation. Heat distribution in LED arrays has been assessed by the observation of a thermoviwer. Several device structures are proposed for achieving power lighting and for higher color rendering properties. The key technology for power lighting is how to radiate the heat out of LED chips, and that for higher color rendering is how to add desired illumination-spectral-component to LEDs according to the application fields. The breakthrough in such aspects will open the way to new applications of solid state lighting based on LEDs.

## ACKNOWLEDGEMENT

The authors acknowledge Dr Tomosumi Kamimura for the assistance of a thermoviewer observation and Professor Yusuke Mori for introducing us to the diamond packaging technology. They also thank Nichia Corporation for generous gift of white LEDs. A part of this work was performed using the facility at the Venture Business Laboratory in Kyoto University (KU-VBL).

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