

# Self-adaptive phosphor coating technology for white LED packaging

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**Abstract** Phosphor-converted light-emitting diodes (pc-LEDs), which employ blue LEDs with yellow phosphors to generate white light illumination, is a widely used solid-state lighting source. In order to conduct a phosphor layer coating with high quality on LED chip, a self-adaptive coating technology is introduced in this paper. A slurry coating technique combined with self-exposure method is applied and developed to demonstrate the benefits of self-adaptive coating layer. For self-exposure, the slurry coating is exposed to the blue emission of LED itself other than to ultraviolet (UV) light outside to make photoresist crosslinking. Results of measurement indicate that white LEDs with self-adaptive coating have shown self-adaptability to the angular distribution of intensity of blue light and performed higher spatial color uniformity than those with conventional coating and other conformal coating.

**Keywords** white light-emitting diodes (LEDs), phosphor coating, self-adaptive, slurry method, self-exposure

## 1 Introduction

White light-emitting diodes (white LEDs) have been taken as the next generation lighting source owing to their distinguished advantages compared with the conventional ones such as incandescent lamp and compact fluorescent lamp (CFL), such as high luminance, high efficiency (energy saving), long lifetime, environmental friendliness and adaptability for variety of application so on. It has been attracting increasing attention and enthusiastic activities of enterprises and governments all over the world because of

its enormous significance in economy and sustainable development of society [1].

At present, phosphor-converted LEDs (pc-LEDs), which typically combined blue LED chips with yellow phosphors (e.g.,  $\text{Ce}^{3+}$ :YAG), are widely adopted and extensively investigated for its simplicity and feasibility in massive production. Some commercial pc-LED products have been available in the market as competitive light sources over conventional ones, because the luminous efficiency of blue LED chips has been considerably improved as result of intensive investment in research and manufacturing field worldwide in recent years. Cree has proclaimed that there is the efficacy 231 lm/W in his laboratory recently, and some commercial products (white LEDs beads) with the efficacy over 150 lm/W are now emerging in the market<sup>1)</sup>. One of key techniques in pc-LEDs processes is the phosphor coating method for converter layer, because the thickness, shape and uniformity of the phosphor layer are crucial factors that determine light uniformity in terms of luminance and chromaticity, and even influence the efficacy of the whole pc-LED device.

Conventional phosphor coating processes for pc-LEDs can be described as follows: the mixture of phosphor and silicone (or epoxy) with proper ratio is prepared thoroughly and degassed; the mixture is distributed onto the surface of LED chip by a dipping process; the coating layer is then solidified in oven at a certain temperature for a period of time; finally, a dome-like phosphor converter layer is formed onto the chip as schematically shown in Fig. 1(a). The primary problem with the conventional coating is inhomogeneous distribution of phosphor due to deficiency of precise control in thickness and shape of coating layer. Additionally, diversity inevitably happens among those conventional coating products because of the variation in concentration of phosphor from batch to batch and the fluctuation of dipping quantity in every operation

Received December 21, 2011; accepted February 9, 2012

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1) <http://scn.cree.com/about/milestones.asp>

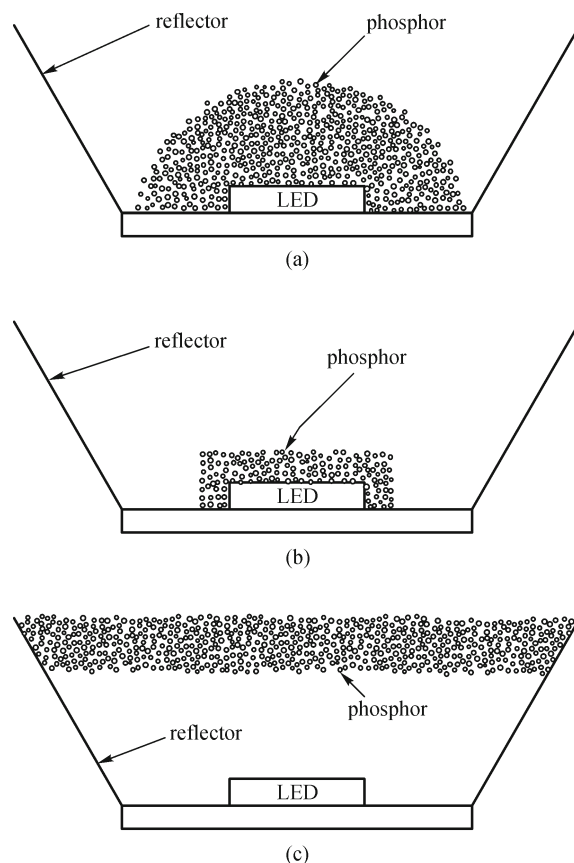
no matter with hand or automatically.

Furthermore, the direct contact of the phosphor layer with chip surface will bring about other problems such as deficiency of light extraction and heat dissipation, i.e., light (initial blue light and converted yellow light) is scattered back into the chip by phosphor particles and undergone undesired re-absorption resulting in a loss in total output of LEDs at a considerable proportion. It also brings about the increase of the temperature of the p-n junction, and subsequently the decrease of the internal quantum efficiency (IQE) and also of the converting efficiency of phosphor (known as temperature quenching). The high temperature also accelerates the degradation of the organic polymer binder used as phosphor dispersion medium such as silicone or epoxy.

In order to overcome those inherent defects of conventional coating method, a number of coating techniques and configurations of phosphor layer have been proposed to realize the uniformity of performance and maneuverability of parameters of pc-LEDs. The conformal coating and remote phosphor coating are prevailing among those schemes. As shown in Fig. 1(b), the conformal coating technology is the methodology first proposed by Lumileds in the pursuit of the precise control of shape, thickness and particle content of phosphor layer [2]. While the remote phosphor with the physical separation of LED chip and phosphor layer was first proposed in 1995, in order to realize improved life and higher luminous efficacy [3], as depicted in Fig. 1(c).

By now, as reported, the world pioneers of pc-LEDs manufactures, such as Cree, Lumileds and Osram, have developed their own conformal coating methods and put their products with conformal coating into markets. A variety of phosphor deposition methods for CRT and FED application, such as settling, electrophoretic deposition (EPD), spreading (or spinning), spraying, printing etc, have been introduced into, investigated and developed to implement the conformal coating of phosphor layer surrounding the LED chip for white pc-LEDs application [4,5]. Overmolding technology is also suggested for conformal coating application because of its convenience and simplicity, even though it is obvious deficient of precision [6]. The Wafer Level Chip Scale Packaging based on conformal coating methodology has recently widely discussed and been taken as the tendency of the packaging technology for pc-LEDs application [7].

With the benefits of decreased back scattering and improved heat dissipation, remote phosphor coating technology has been taken as one of the most efficient methods for packaging of illumination-grade high power white LEDs. In 2005, Narendran et al. reported a remote phosphor coating method known as scattered photon extraction (SPE) with an experimentally 60% improvement in light output and luminance efficacy by extracting back-scattering light [3]. Now, some pc-LED products embodying remote phosphor concept are available in the



**Fig. 1** Schematic diagrams of different coating configuration. (a) Conventional coating; (b) conformal coating; (c) remote coating

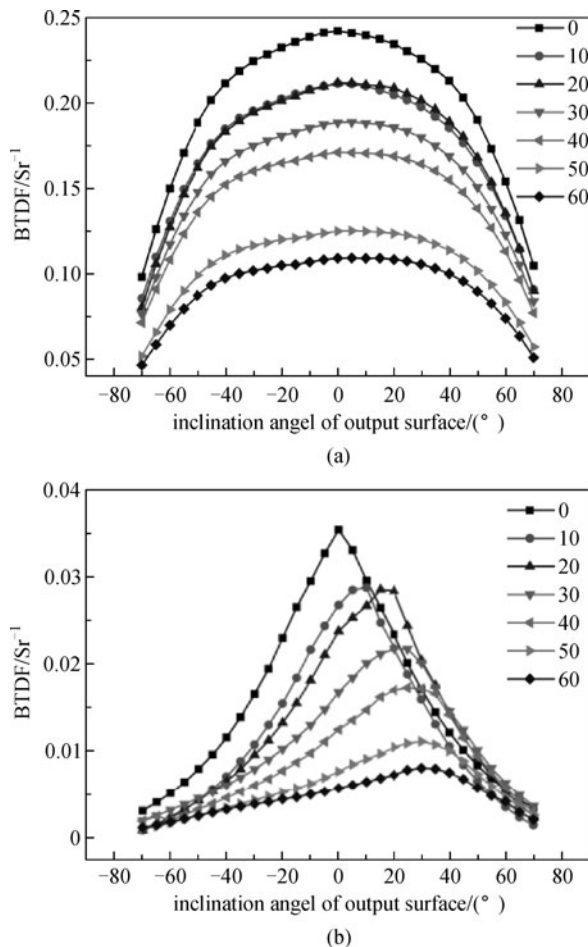
market such as bulb LEDs by Philips (Luminleds) and a kind of phosphor coating plate used as a remote phosphor component for white LEDs with trademark of Chromalite by Intematix.

The most commercial phosphor-converted white LEDs followed common essential package design where short-wavelength (blue) chip is surrounded by a phosphor layer. As the phosphor layer here both acts as an incident blue light diffuser and a wavelength down-converter, the configuration of phosphor layer need to be precisely controlled to achieve the harmony between blue and yellow light across the illuminated area, which means the uniformity distribution of chromaticity of light over the whole radiant angle.

Therefore, a conformal coating concept has been brought forward as a methodology of precise control of shape, thickness and particle content of phosphor layer to match blue and yellow light for a more uniform output of white light.

Although a variety of techniques and processes have been used in research works and commercial products to realize the conformal coating scheme, the configuration of the existing so-called conformal coating layer is exactly the conformal shape of the geometry of the LED chip.

Owing to the two kinds of optical mechanisms under the blue light illumination, the diffused blue light and the emitted (converted) yellow light are different in the term of transmittance of the emitting angles as shown in Figs. 2(a) and 2(b) [8]. The measured bi-directional transmittance distribution functions (BTDFs) results of the YAG-phosphor reported by Tien et al. [8] revealed that the angular distribution of the excited yellow light is close to lambertian and has a wider full width at half maximum (FWHM) than that of the diffused blue light. Therefore, the ideal YAG-phosphor layer for white emission with high quality should be characterized as a mapping of the intensity distribution of the diffused blue light. It is strongly suggested that the geometry of phosphor layer should be the conformal shape of the angular distribution of blue emission from LED chip. It comes from the concept of self-adaptive phosphor coating. In this paper, a novel method is proposed and experimentally demonstrated to realize a phosphor layer with self-adaptability to light emission of LED chip based on a slurry coating technique combined with self-exposure process.



**Fig. 2** Measured BTDFs of (a) emitted yellow-light radiance and (b) scattered blue-light radiance [9]

## 2 Experimental methods

The slurry method developed for conformal coating packaging at early stage in this lab is based on a phosphor suspension in a water-soluble photoresist, which is consisted of polyvinyl alcohol (PVA) and dichromate or diazo compound [9,10]. Typically, the slurry was prepared by suspending 180 mg phosphor particles into 1 mL solution of PVA based water-soluble photoresist, which is composed of 2.5% PVA and 0.025% ammonium dichromate (ADC, or diazo resins).

The emission surface of the LED chip is coated with the slurry and dried. The slurry is distributed onto the surface by one of several methods, such as flowing, dipping, or spinning. The coating is either exposed to ultraviolet (UV) light outside through a mask or to blue emission inside out from LED chip (known as self-exposure) to determine the areas where phosphor is desired. The coating is then developed with hot water and dried. A phosphor layer remains on the LED surface only where it is exposed and insolubilized. These procedures are shown schematically in Fig. 3.

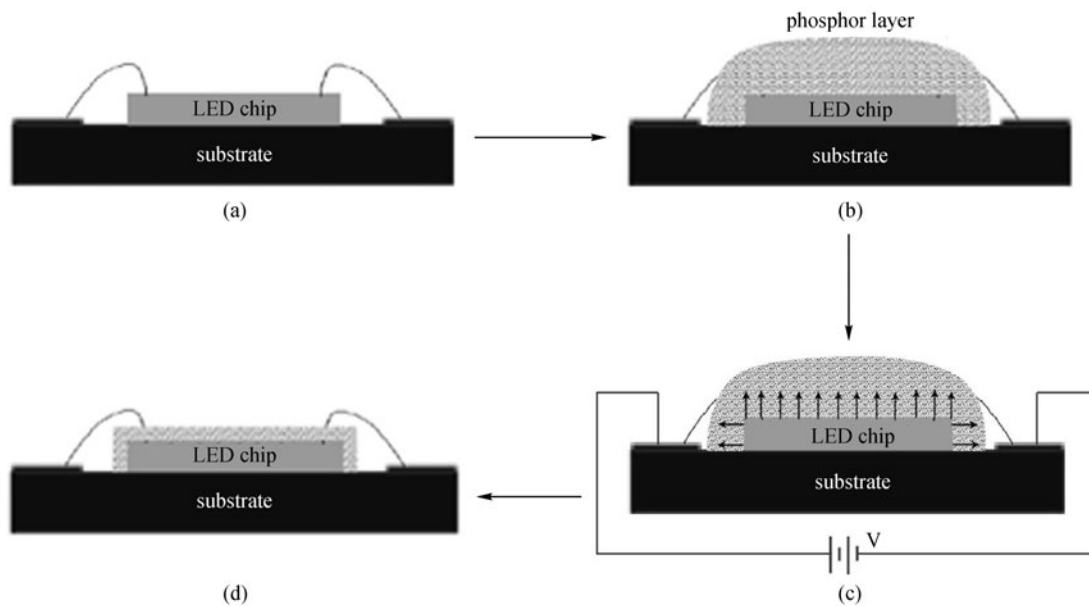
The quality of phosphor layer around LED chip depends upon the photochemical reaction of the photoresist, particle size distribution, surface condition of the phosphors, added dispersants, emission intensity and profile of blue LED chip, and exposure and development conditions of the photoresist.

Because of the photosensitivity of the PVA slurry to blue light, the printing (cross-linking of PVA) also occurs with the photoreaction by the absorption of 450–465 nm light of blue LED, while the traditional slurry printing technology does with 365 nm light from a mercury UV lamp. As an alternative way to conventional UV light exposure, the self-exposure process with blue emission of LED chip was employed to realize a more convenient and self-alignment method to make the photoresist cross-linking. The coating is exposed to emission of blue LED chip itself through so-called “back exposure”, i.e., the coating is exposed from the LED surface instead of from an outside UV light source through “forward exposure”. With this self-exposed process, the desired coating patterns, the thickness distribution of remained phosphor layer are determined simultaneous corresponding to the blue light intensity and profile of LED chip.

With much easy, the overall thickness of phosphor layer patterns was controlled just by altering the time of exposure (time in operation) or the light intensity with adjustment of the current through LED chip.

Of course, with silicone lens molding on the surface of the LED chip firstly, the self-adaptive coating also provides a feasible way to realize a kind of remote phosphor configuration also with self-adaptability to the LED emission.

The chromaticity coordinates of illumination of white LEDs were measured by CS-100A chroma meter.

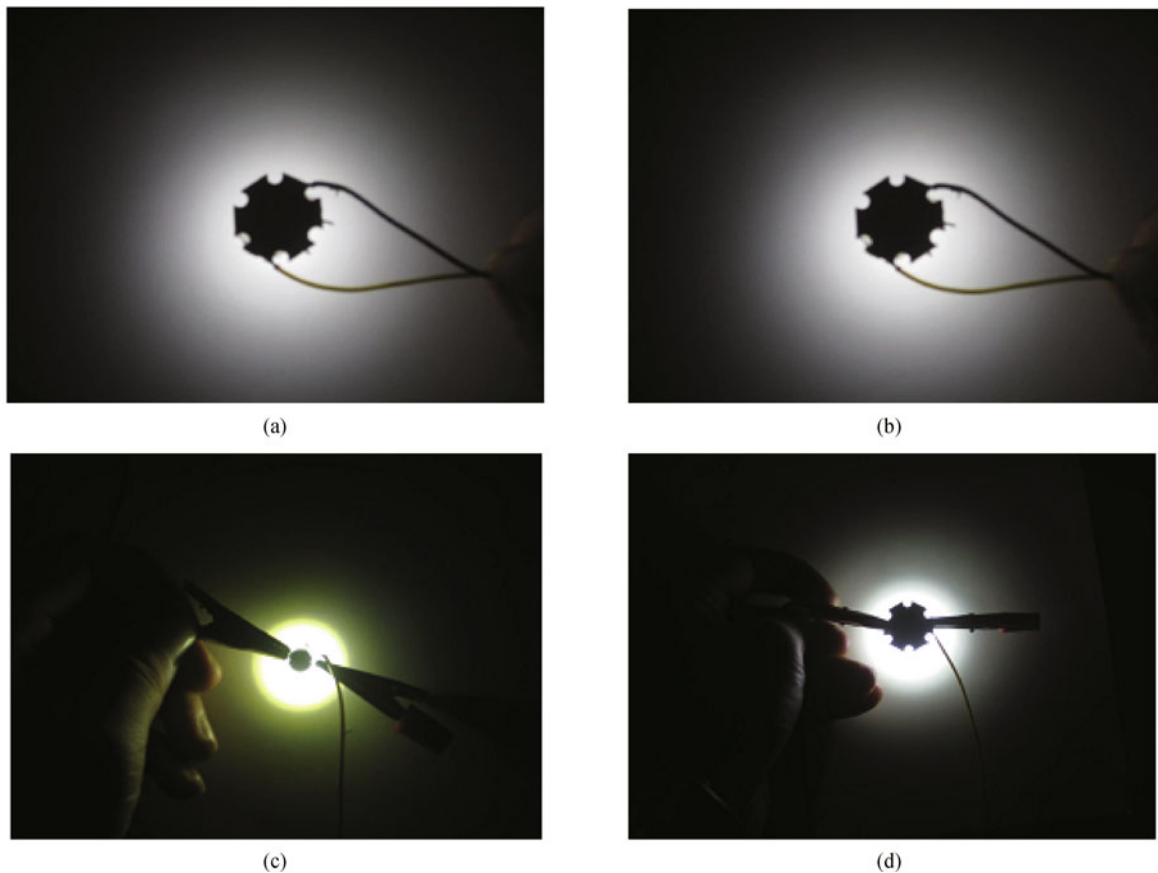


**Fig. 3** Schematic diagram of slurry coating process with self-exposure. (a) Blue LED; (b) phosphor coating; (c) exposure; (d) develop

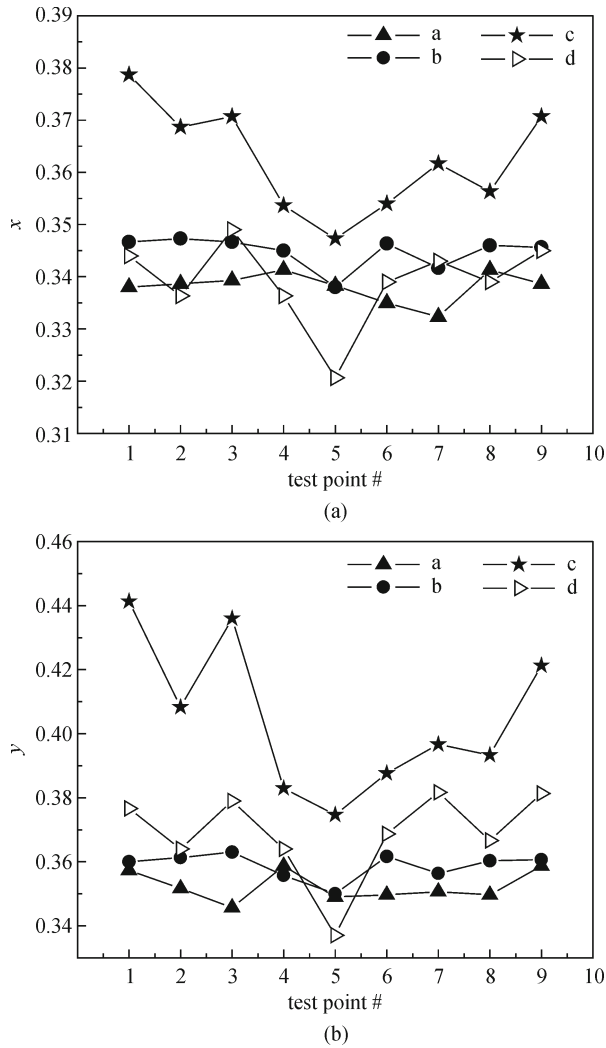
### 3 Results and discussion

Shown in Fig. 4 are the white light emission pictures of pc-

LED examples with different phosphor coating techniques: a self-exposure coating pc-LED (Fig. 4(a)), a self-exposure remote phosphor coating pc-LED (Fig. 4(b)), a conven-



**Fig. 4** White light pictures of white LEDs with different coating techniques. (a) With self-exposure conformal coating; (b) with self-exposure remote phosphor coating; (c) with conventional phosphor coating; (d) commercial conformal coating product



**Fig. 5** Chromaticity distributions of white LEDs with different coating layer. (a)  $x$ ; (b)  $y$ . a: With self-exposure conformal coating; b: with self-exposure remote phosphor coating; c: with conventional phosphor coating; d: commercial conformal coating product

tional pc-LED (Fig. 4(c)) and a commercial conformal coating product (Fig. 4(d)).

The illuminated area at 15 cm distance from each of the white pc-LED beads with different coating technology was divided into nine sections of 15 cm  $\times$  15 cm. The chromaticity coordinates of the center point of each section were measured to give a nine-point chromaticity distribution results shown in Fig. 5. The standard deviation of the chromaticity coordinates for both self-exposure coating examples is 0.003 in  $x$  and 0.004 in  $y$ . Comparatively, the data for commercial conformal coating example is 0.008 in  $x$  and 0.013 in  $y$ , and those for conventional coating product is 0.010 in  $x$  and 0.023 in  $y$ .

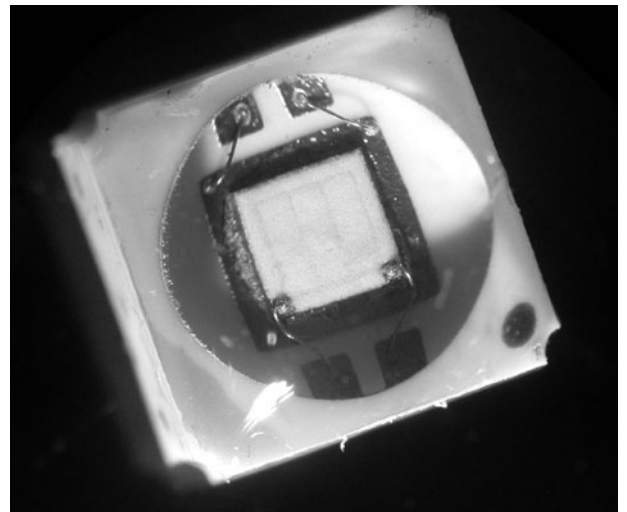
It is clearly shown with these measurements that the color uniformity of light output with self-adaptive coating and conformal coating is superior to that with conventional coating. And the self-adaptive coating is even more

advanced than current conformal coating which shows a discriminable color deviation (bluish) in center point 5# compared with other 8 points off the center section over the illuminated area.

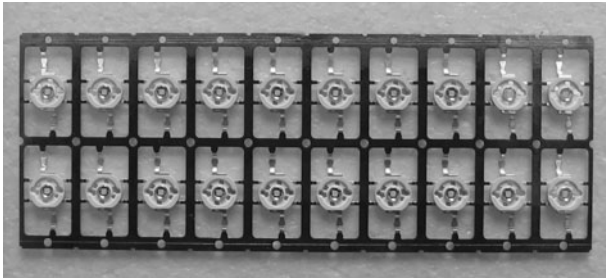
According to Fig. 2(b), there is an intensive diffused blue light transmittance in the normal direction, it is reasonable to deduce that the output of diffused blue light have a decreasing intensity distribution from center or edge. That is why a current conformal pc-LED product with phosphor layer of conformal shape (i.e., uniform thickness) would still suffer a color deviation due to the mismatch between more intensive blue light emission and relative thinner phosphor converter layer in the central part of illuminated area.

The slurry deposition is actually a method of photolithography in mechanism. The PVA-based photoresist adopted in this paper is a negative one. As mentioned above, the phosphor layer coated with self-exposure process is the remained part where it is exposed to blue light of LED chip. The thickness and shape of phosphor layer around LED chip with self-exposure process are therefore controlled by light intensity and profile of LED chip. The configuration of self-exposure coating layer is the mapping of the intensity distribution of LED chip itself, i.e., the thickness of self-exposure phosphor layer over the LED chip surface area changed automatically with the intensity of the blue light at the different emitting angles (known as self-adaptability). It gives a substantial improvement on angular color uniformity (ACU) of white pc-LEDs as a result of emission with a higher consistency of yellow blue light ratio at different emitting angles as demonstrated in Fig. 5.

The pictures of a single white LED bead and an array of white LEDs with phosphor layer embodied self-adaptive coating technology are shown in Figs. 6 and 7, respectively.



**Fig. 6** Picture of white pc-LED with self-adaptive phosphor coating



**Fig. 7** Picture of white pc-LED array with self-adaptive phosphor coating

In order to meet the high-temperature stability requirement in some special processes such as reflow welding for white LED application, the slurry coating phosphor layer in the terms of phosphor-dispersed photoresist needs further treatments such as baking in air or oxygen plasma bombardment (reaction ion etching) to remove the organic photoresist ingredients, then refilled with some more stable transparent organic binder such as silicone or epoxy, etc.

## 4 Conclusions

The current popular phosphor coating technology for white LED packaging, such as conformal coating and remote phosphor, has been discussed. A self-adaptive coating configuration has been brought forward in this paper. A slurry coating technique combined with self-exposure method is presented and applied to demonstrate the benefits of this self-adaptive coating configuration. For self-exposure process, the slurry coating is exposed to the blue light of LED itself other than the UV light outside. The white pc-LEDs with self-exposure coating technology shows the self-adaptability to the angular distribution of intensity of blue light and performs a higher spatial color uniformity than those with conventional coating or commercial conformal coating techniques. The results clearly suggest that light chromaticity distribution of self-adaptive coating white pc-LEDs has the lowest chroma-

ticity standard deviation of 0.003 in  $x$  and 0.004 in  $y$  across the illuminated area. Consequently, the self-adaptive coating technology is indeed the potential packaging scheme for developing the future high quality white pc-LEDs in illumination application.

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