Large-area, uniform white light LED source on a flexible substrate

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Abstract: This study demonstrates the flexible white LED structure with high lumen efficiency and uniform optical performance for neutral white and warm white CCT. Flip-chip LEDs were attached on a polyimide substrate with copper strips as electrical and thermal conduction paths. Yellow phosphors are mixed with polydimenthysiloxane (PDMS) to provide mechanical support and flexibility. The light efficiency of this device can reach 120 lm/W and 85% of light output uniformity of the emission area can be achieved. Moreover, the optical simulation is employed to evaluate various designs of this flexible film in order to obtain uniform output. Both the pitch between the individual devices and the thickness of the phosphor film are calculated for optimization purpose. This flexible white LED with high lumen efficiency and good reliability is suitable for the large area fixture in the general lighting applications.

OCIS codes: (230.3670) Light-emitting diodes; (230.2090) Electro-optical devices.

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1. Introduction

Recently, the light-emitting diode (LED) technology have become an important solid-state lighting source due to its advantages of high efficiency, small size and low power consumption. Since the beginning of the decade, they have been widely used in backlight, lighting, signal, and automotive applications [1–3]. The combination of blue chips with yellow phosphor together is the most common method to obtain white light sources in the industry [4,5]. To further extend their usage, the LED with flexible substrate is one of the important directions and has attracted many attentions in the fields of display, wearable device, lighting and biomedicine [6–9]. Moreover, for flexible lighting application, the light guide plate (LGP) is considered as an important component because the LGP is the backbone of module, and is usually made of polymethylmethacrylate (PMMA) [10,11]. However, this materials is not suitable to use in some flexible applications such as watch or wearable device

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when the LGP needs to be bent seriously. Therefore, to truly fulfill the requirement of flexible devices, the material of LGP component needs to be re-designed.

For the III–V-based LED, Kim et al. demonstrated the micro-structured GaAs LED printed on a polyethylene terephthalate (PET) substrate [12,13]. The flexible GaN LEDs were also manufactured by micro-structure transferring process and the module was housed on a liquid crystal polymer (LCP) substrate [14,15]. Although there are several methods to produce the flexible LEDs, the optical characteristics and the substrate analysis of flexible LED still need to be discussed. Specifically, to fabricate the flexible LED, there are two important parts to be investigated: the light source and flexible mechanism. First, for the light source, it will be easier to use blue GaN LEDs owing to cost consideration. However, these LEDs need to be cut from the regular sapphire substrate in order to show the suitable flexibility. Based on this idea, the flip-chip GaN LEDs can be a better candidate than the regular P-side up devices. The flexible substrate can be further patterned to facilitate the wire-bonding and thermal dissipation. Second, proper flexible mechanism needs to be adapted to have a uniform white source with good bending capabilities. Current main stream source of yellow photons in the white light LEDs is to mix the YAG phosphor with silicone or other polymers [16]. Thickness and concentration of this mixture can be critical for the quality of light [17], and thus needs to be carefully controlled. Similar consideration should be taken for the flexible LEDs. Instead of dropping the phosphor/ polymer mixture into the package, now it is housed by another pliable substrate, and the thickness and concentration uniformity are also critical for this type of devices. In addition, such point light source is hard to become a panel light source. Certain investigation on film thickness control is necessary to obtain enough light scattering in the phosphor layer.

In this study, a uniform flexible LED with high efficiency is demonstrated by the combination of the flip-chip LED and phosphor film for the cool and warm white light emission. Polydimethylsiloxane (PDMS) is employed to host the yellow phosphors because of its high degree of transparency, stability, and flexibility [18]. A wide range of bending can be achieved without deterioration of total light output. Furthermore, the optical simulation is employed to simulate the light uniformity of flexible LED.

2. Experiments and Simulation

To fabricate the devices, Fig. 1 shows the process flow of the flexible LED. The Polyimide(PI) substrate was covered with 1/2 oz. copper foil shielding tape. The adhesive thickness is 30 μm. The stripes of copper were defined by photolithography and wet-etch. Then 45x45 mil blue LEDs were flip-chip-bonded on the polyimides(PI) substrate. The total number LED chips are 81 pcs and each chip size is 45x45 (mil). The nominal power output of the blue chip is 517 mW at 350 mA and the emission wavelength is 455 nm at 350 mA. We use silicone-based anisotropic conductive adhesive to stick the flip chip LED with the substrate. The adhesive can maintain the electrical conductivity between chip metal contact and AuSn solder and save several steps of process (such as bumping and underfill) while performing all processes at low temperature. The bond head temperature is 230 °C and the bonding pressure is 2500 gram force(gf). For the phosphor film, the yellow phosphor ($Y_3Al_5O_{12}$:Ce^{3+}) with the particle size of 13 μm and the red phosphor ($CaAlSiN_3$:Eu^{2+}) with the particle size of 25?μm are used in this experiment. The concentration of the yellow phosphor in the PDMS film is about 10 wt% for the neutral white LED. For the warm white LED, the concentrations of the yellow and red phosphor in the PDMS film are about 12 wt% YAG and 3 wt% red phosphor, respectively. The phosphor glue was poured over the glass substrate using the spin-coating method. The thickness of the flexible film can be adjusted via different process parameters such as revolution per minute (RPM) and its optimal value will be calculated in the following section. When all the processes are finished, a blue LED array with 81 individual chips is bonded on a 5cm by 5cm PI substrate, as shown in Fig. 1. The emission wavelength of the LED is picked to be 455 nm under normal operation.

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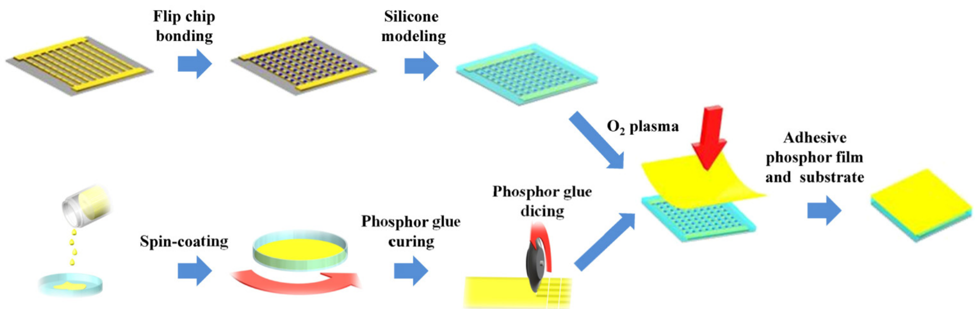

Fig. 1. Schematic illustration of process flow of flexible white LED structure

Figure 2(a) shows an optical microscope (OM) image and (b)(d-e) shows a scanning electron microscope (SEM) image of the cross section of the flexible white LED structure. The total thickness of flip chip and polyimides (PI) substrate is 228.3 μm. The thicknesses of flip chip, adhesion layer, PI substrate are 148 μm, 33.4?μm, 21.9 μm and 25 μm, respectively Figs. 2(d) and (e) show the close-up views of metal particles in the silicone-based anisotropic conductive adhesive. The metal particles can help to improve the light extraction and heat dissipation for flexible white LEDs. The element of silicone-based anisotropic conductive adhesive with silicone encapsulant was analyzed by Energy Dispersive Spectrometer (EDS), as also shown in Fig. 2(c) and (f). From the data, We can confirm the existence of Au and Sn elements in the silicone encapsulant.

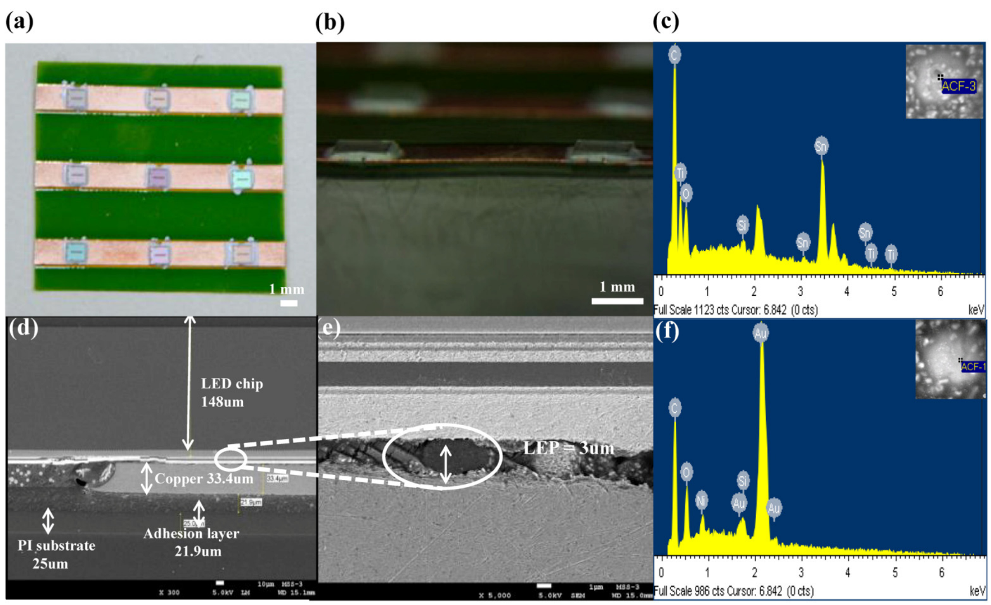

Fig. 2. (a) LED array under optical microscope; (b) SEM of the flexible white LED; (d) Cross section between LED and PI substrate; (e) the metal particle in silicone-based anisotropic conductive adhesive bonding material (c)(f) The energy dispersive spectrometer (EDS) of silicone-based anisotropic conductive adhesive showing the different compositions in the substance.

Figure 3(a) and (d) shows a scanning electron microscope (SEM) image of the cross section of the phosphor film structure for 5000K and 3000K of correlated colortemperatures (CCTs). The thicknesses of the phosphor film are approximately 187 μm in 5000K samples and 496 μm thick in 3000K samples. The results indicated that the thickness of the phosphor film at 3000K is thicker than that of the 5000K CCT film because the warm white light 3000K phosphor film include red phosphor ($CaAlSiN_3$). And this kind of red phosphor ($CaAlSiN_3$) particle size is 2 times than phosphor(YAG) particle. Furthermore, these two different PDMS layers were analyzed by EDS and the element of YAG and $CaAlSiN_3$ phosphors could be observed, as also shown in Fig. 3(b) and (e). Figure 3(c) and (f) shows the emission spectra of the phosphor films. The emission peak spectrum is at 560 nm and 630 nm. As the result, the flexible cool and warm white can be demonstrated in a large-area format.

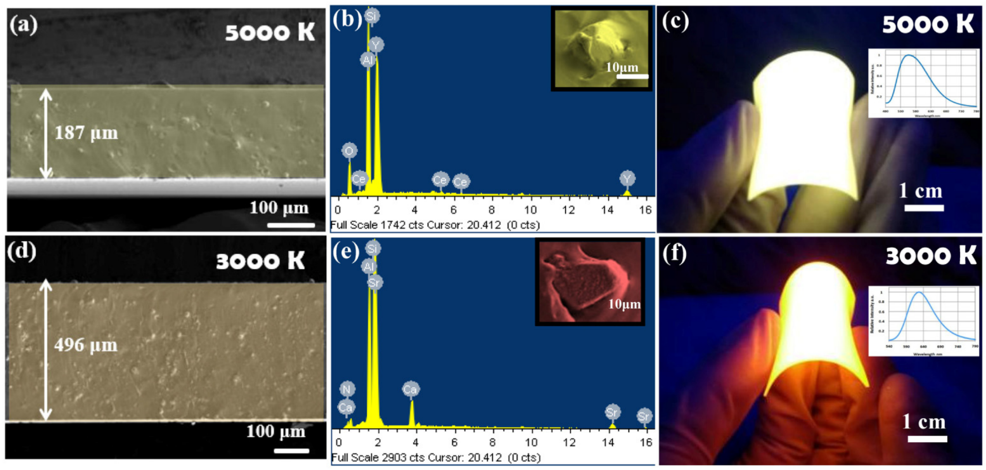

Fig. 3. (a)(d) Scanning electron microscope (SEM) images of the cross section of the phosphor film structure at 5000 K and 3000 K. (b)(e) The EDS spectra for phosphor layers of 5000 K and 3000 K samples, respectively. (c)(f) The pictures of the phosphor film for neutral and warm white at 5000 K and 3000 K color temperature.

3. Measurement and analysis

First, we demonstrate the flexible LED array without the phosphor layer. Figure 4(a-b) shows an array of flip chip blue LED with flexible substrate with and without current injection. The design of copper stripes and the layer can be very different according to the specific application. Because the individual LED is attached to the copper stripe; the final lighting pattern can be also changed by the layout of this copper stripes. Figure 4 (c) shows the EL spectra of blue LED with the injection current from 90 mA to 540 mA. The blue chip's power and the luminous efficiency were measured using a calibrated integrating sphere and are plotted in Fig. 4(d) as a function of injection currents ranging from 100 mA to 540 mA. Their forward voltages are between 23V to 24.8V. Regarding luminous flux, its luminous flux exceeded that of GaN-based LED device over the entire current range. Once the blue LED chips were attached successfully on the flexible substrate, it is ready to add the phosphor layer to generate white light.

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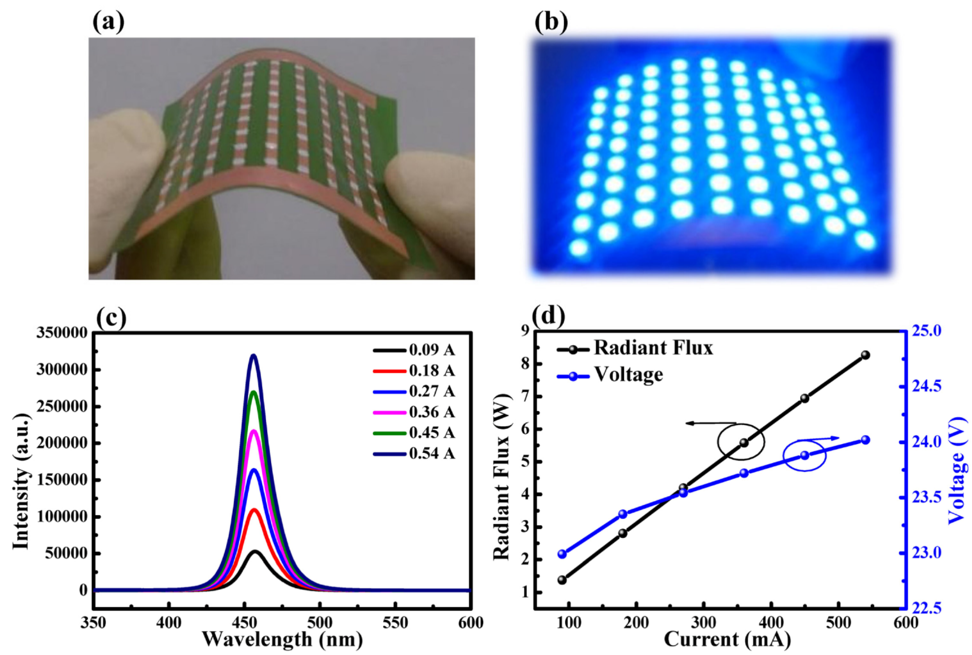

Fig. 4. (a)(b) the pictures of flexible blue LED substrate (c) the EL spectra from 0.09A to 0.54A of injection currents (d) the forward voltage and luminous flux vs. injection currents (from 0.1 to 0.55 A).

The emission spectra of 5000K and 3000K flexible white LED at driving current of 120 mA are shown in Fig. 5(a). As shown in Fig. 5(a), the emission peak wavelength of YAG is occurred at 550 nm with a FWHM of 121 nm in the flexible cool white LED. The flexible warm white LED was composed of blue, yellow, and red emission bands located at 452.5 nm, 550 nm, and 600 nm, respectively, whose peaks belong to the blue LED, YAG, and $CaAlSiN_3$ components in the warm white LED. The luminous flux and the luminous efficiency measured using a calibrated integrating sphere are plotted in Fig. 5(b) and (c) as a function of injection currents ranging from 0 to 1000 mA. The luminous efficiency of cool white LED (5000K of CCT) is 120 lm/W and CRI is 70 whereas the warm white LED (3000K of CCT) can obtain 80 lm/W and CRI value of 81. Moreover, compared to other studies related to large-area lighting source [19–21], the luminous efficiency of the proposed device is compatible and has the potential to use in the flexible lighting application because of high lumen efficiency and low cost. Furthermore, we measure the luminance of the flexible white LED at nine point measurement method and calculate the uniformity with the formula:

$$Uniformity = \left(L_{\min} / L_{\max}\right) \text{x}\, 100\%$$

For flexible white LED, its uniformity is 85% and the best of OLED's can reach 100% [22]. There is certainly room for improvement in our current design, but it demonstrates a good uniform output of light intensity.

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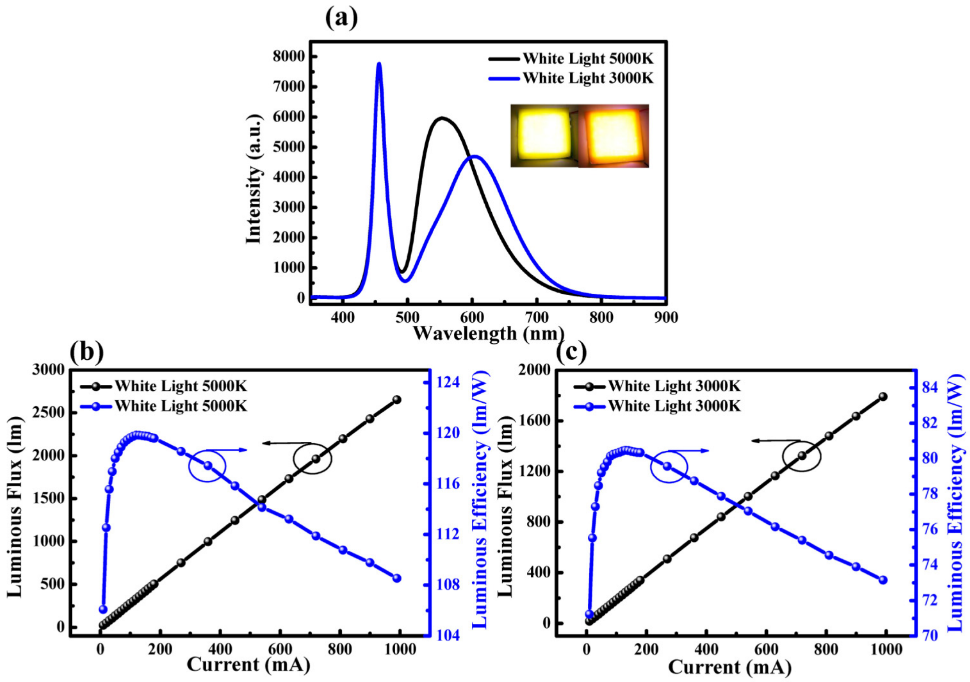

Fig. 5. (a) the flexible white LED's emission spectra in neutral white and warm white. (b)(c) the luminous flux of the flexible white LED structures at 5000K/3000K driven at currents from 0 to 1000 mA.

Once we have the device working in flat condition, it will be important to test the device performance under bending condition. After all, if the bending can seriously change the light output, the device will not be suitable for such application. When the device is flat, the radius of curvature is infinity, and this radius will drop when the device is bent more. As shown in Fig. 6 (a), our flexible LEDs work quite well under different bending curvatures. The size of this flexible white LED is about 5 cm by 5 cm and the total thickness is about 6 mm. As can be seen in the Fig. 6(b), the luminous efficiency as a function of the current show little variation up to a bending diameter of 3 cm. As for the I-V characteristics, the dependence is barely detectable. This result indicates that such large area flexible lighting sources are also suitable for flexible displays and lighting.

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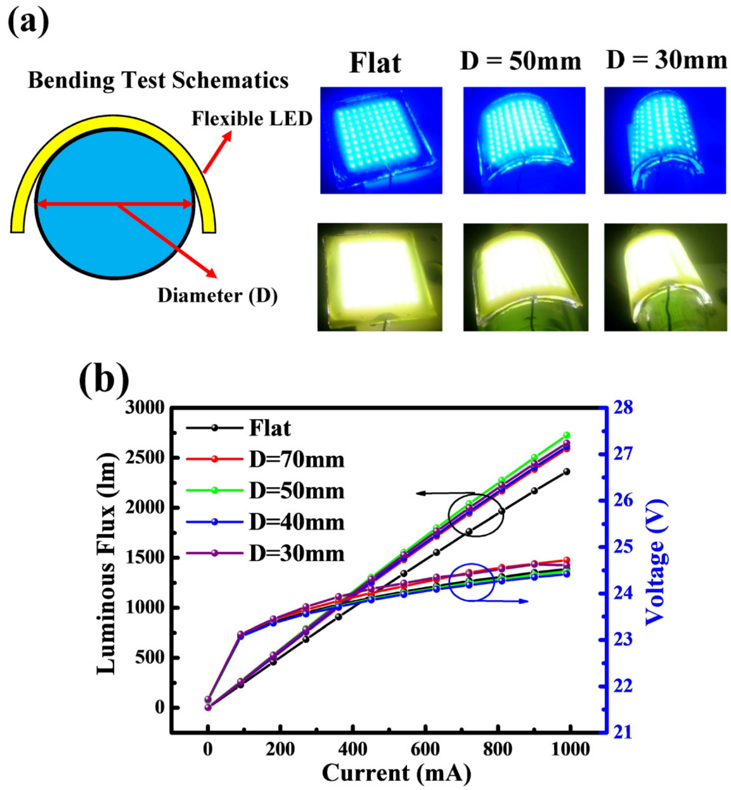

Fig. 6. (a) The picture and (b) the luminous flux and voltage of the flexible white LED for different bending diameters

To discuss about the thermal characteristic of the heat capacity at the thermal interface, the thermal resistance of flexible white LED was measured and shown in Fig. 7. The thermal resistance are related with heat conduction path from the LED junction to die attach and then to the PI substrate [23]. Determination for the thermal resistance (R_{th}) of LED chip can be calculated by using the equation of $R_{th} = \Delta T/(P_e - P_{op})$ [24]. The common thermal resistance of conventional face-up LED with direct eutectic bonding is 5~10 K/W [24]. In our design, the flexible white LED array was equipped with a copper heat spreader to gain better thermal resistance performance. The thermal resistance from junction to package sub-mount is estimated to be about 2.683 K/W where the thermal resistance of the LED chip, bonding metal layer and PI substrate are about 0.156 K/W, 1.016 K/W and 1.511 K/W respectively. Consequently, the thermal resistance of flexible LED is significant lower than conventional face-up LED structure. The results indicated that the copper spreader is useful in thermal resistance reduction of the flexible LEDs. Generally, the thickness of die attach is an important factor to determine the thermal resistances. For flexible LED, the thickness of die attach is about 3 μm and it is thinner than the traditional structure (10 μm). Therefore, these two factors (copper spreader and reduced die attach thickness) are the main reasons which could lower the thermal resistance of flexible white LED structure.

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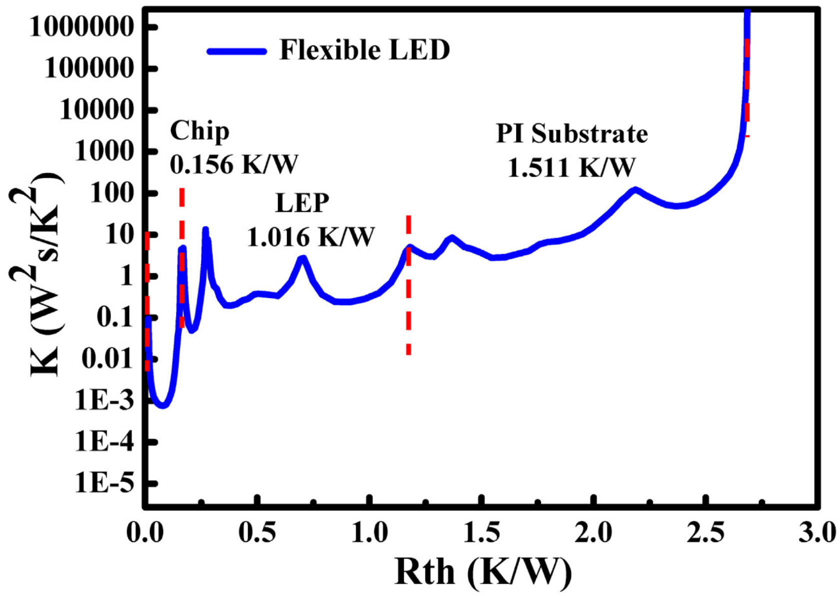

Fig. 7. Thermal resistance of flexible white LED

For our flexible white LED device, we employ the life time test by 1000 hours at room temperature (25 °C). The flexible white LED device's driving current is 120 mA and continue burn in. From Fig. 8, it shows the result of life time test of flexible white LED. The luminous efficiency of flexible white LED decays only 2.5%.

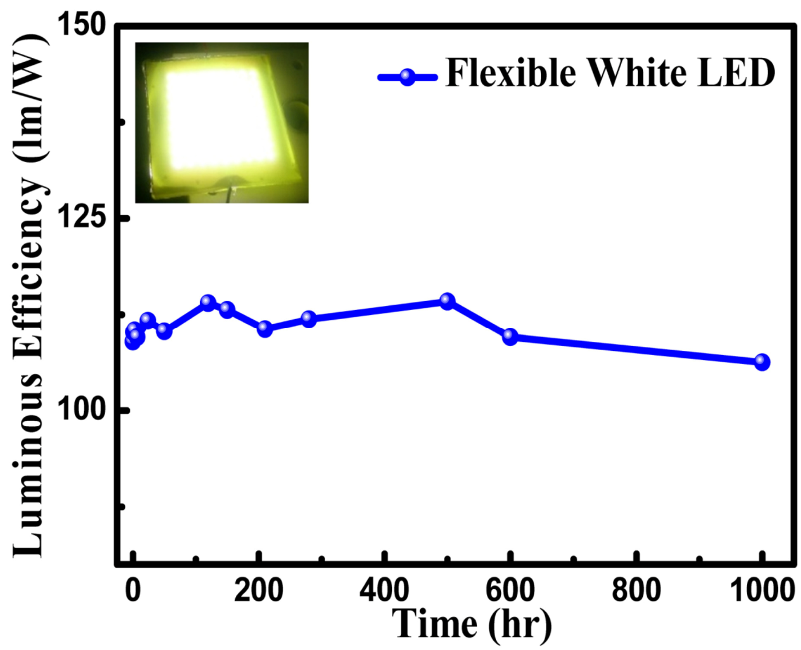

Fig. 8. the life time test of flexible white LED device by 1000 hours

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4. Optical Simulation

From the previous measurement, the luminous uniformity of our flexible LED array still needs improvement. To find out the possible solutions, optical simulation is necessary. To assess the light field uniformity, OptisWorks software based on ray-tracing and Monte Carlo method is employed to simulate the light field of flexible white LED structures [25,26]. In the ray tracing simulation, the total lighting area is 43 mm x 43 mm and total LED chip number is 9 pcs. In the simulation, the refractive indices of different materials are $n_{phosphor}$ = 1.82, $n_{silicone}$ = 1.54, $n_{free\ space}$ = 1.0 (above flexible white LED) and $n_{blue\ chip}$ = 2.4. The copper reflectance at the bottom plate was set as R_{Cu} = 90%. When we calculation the light field of such devices, the pitch between the individual LEDs and the thickness of the phosphor film are the two factors that matter most. It is apparent that the closer the LEDs get, the more uniform field can be generated. However, in our simulation, we found that the thickness of the phosphor film holds the final decision in terms of uniformity. When the thickness of the phosphor film is limited to 0.5 mm, as can be seen in Fig. 9(a), the individual LED element is identifiable under all pitches, and this is not optimal in terms of generating a uniform sheet of light. As the thickness of the middle silicone glue increases, the output light field begins to smear due to extra scattering in the route and more uniform distribution of photons can be seen in Fig. 9(b) With the increase of the height of the silicone glue to 10mm, an even distribution can be obtained due to blue photons from the chip could have the more chances to reflect and to excite with the yellow light. These calculations correspond well to what we observed in the experiment and flexible white LED structure truly needs an optical thickness to scatter and excite the photons from each individual chips. It will help to improve light uniformity from between the thickness of 3 mm and 6 mm samples. But flexible white LED's efficiency is related with the thickness of silicone. When the silicone's thickness is increase 1 mm the efficiency will decrease 1.6%. In theoretical the uniformity can reach 100%. But the thickness is an important part of wearable device. So next step we will use the nanoparticle or microstructures on the surface to improve the uniformity and increase the efficiency.

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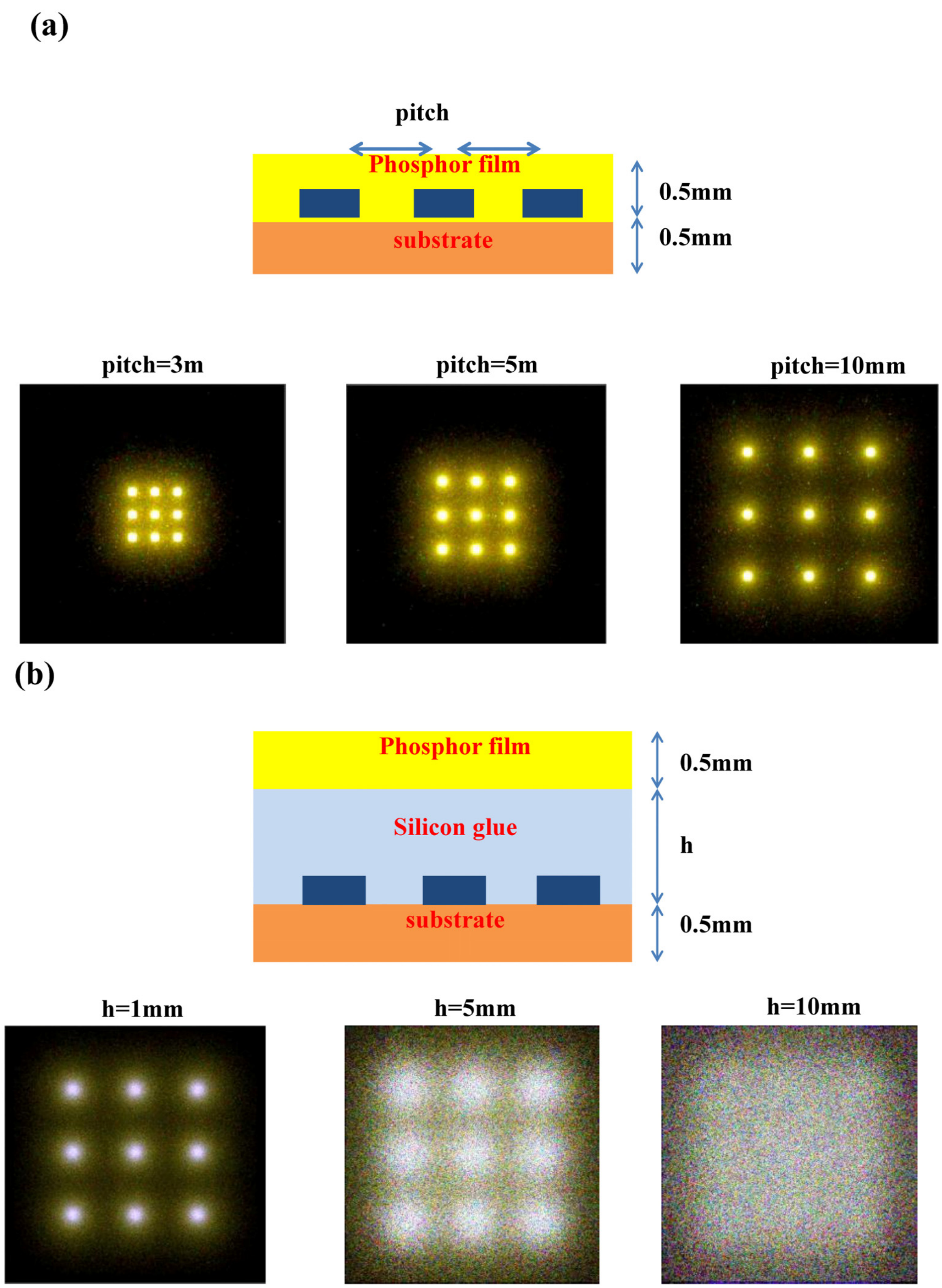

Fig. 9. (a) The simulated results at different chip to chip pitches and (b) at different silicon glue thicknesses.

5. Conclusion

This study demonstrates a uniform and highly efficient flexible white LED structure. In this study, flip chip, polyimides (PI) substrate and spin-coating phosphor film were applied to produce the flexible white LED structure. By controlling the weight percentages of yellow and red phosphors, large-area flexible LEDs with CCTs of 3000K and 5000K can be realized.

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Good light efficiency and uniformity of the flexible LED can be achieved at 120 lm/W and 85% for 5000K of color temperature. We use silicone-based anisotropic conductive adhesive to add flip chip and polyimides (PI) substrate adhesion ability. Further simulation reveals the critical factor for uniform sheet of light output is the thickness of the middle silicone layer which can provide extra scattering and reflection. We believe that the flexible white LED with high lumen efficiency is suitable for various wearable applications in the near future.

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