Supporting Information for

Performance enhancement of white light-emitting diodes using encapsulant semi-solidification method

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1. Dispersibility of YAG phosphor in silicone encapsulant

To investigate the dispersibility of YAG phosphor in silicone encapsulant, the cross-sectional images of the LED encapsulant were acquired by taking optical microscope images at three different levels, *i.e.* the top, middle, and bottom. The number of phosphors which were appeared in the optical microscope image was counted and converted into a percentage. To make comparisons easier, the phosphors appeared in the optical microscope image were marked in green (the phosphors in the conventional encapsulant) or purple (the phosphors in the encapsulant fabricated *via* the semi-solidification process) as shown in **Fig. S1**. The counted number and the converted percentage of phosphors at three different levels were specified in **Table S1**.

Table S1. The number of phosphors obtained at three different levels.[a]

Samples	Top	Middle	Bottom	Total
Conventional	373 (12.6%)	367 (12.4%)	2220 (75.0%)	2960 (100%)
Semi-solidified	526 (32.8%)	532 (33.2%)	545 (34.0%)	1603 (100%)

[a] The figures in parenthesis refer to numerical percentage.

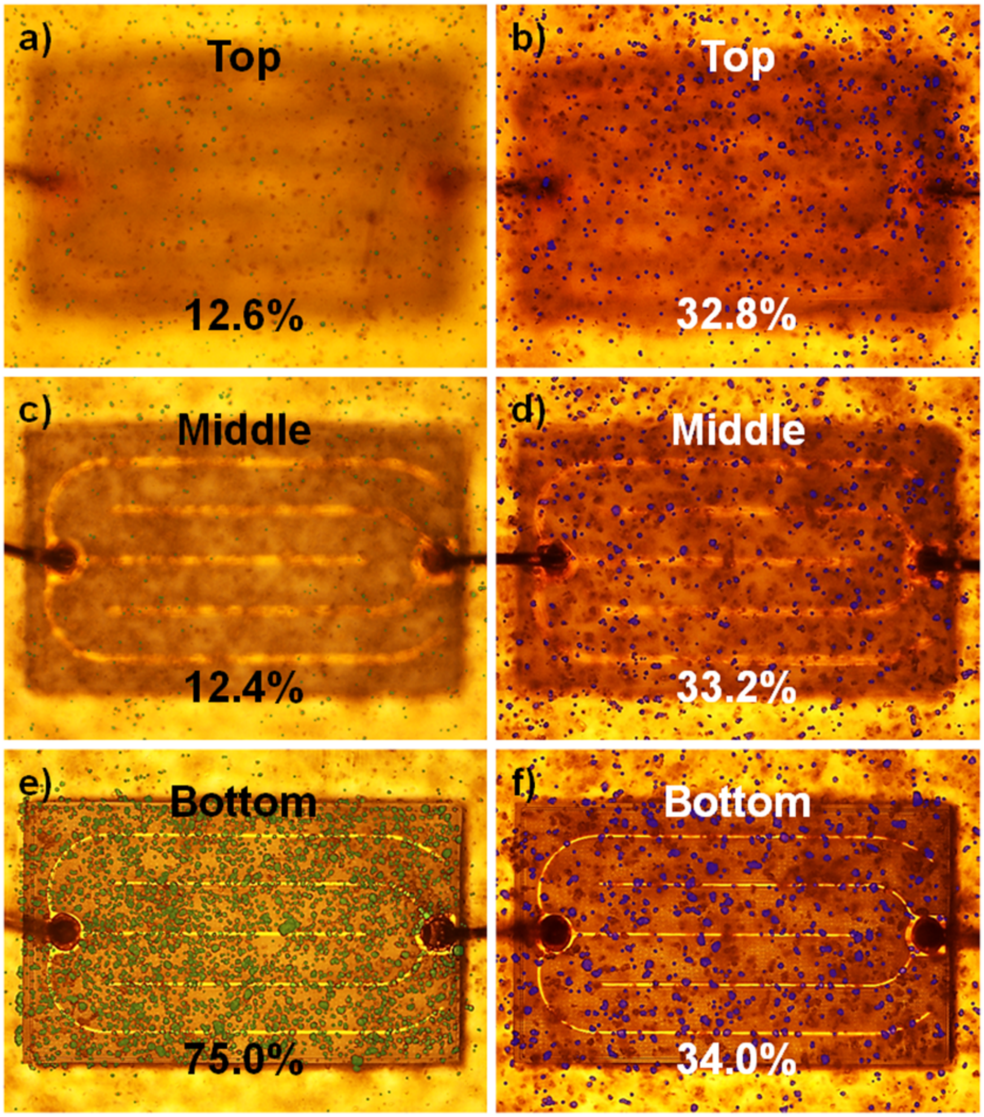

Fig. S1 The optical microscope images of encapsulant fabricated by a conventional curing method taken at a) top, c) middle, and e) bottom. The phosphors appeared in the optical microscope image of the encapsulant prepared by a conventional curing method were marked in green. The optical microscope images of encapsulant prepared *via* the semi-solidification process taken at b) top, d) middle, and f) bottom. The phosphors appeared in the optical microscope image of the encapsulant fabricated by the semi-solidification process were marked in purple.

2. Influence of phosphor concentration

The influence of phosphor concentration was evaluated by measuring the distribution of YAG phosphor in silicone encapsulant and optical properties including luminous flux, efficiency, and color coordinates.

The distribution of YAG phosphor in silicone encapsulant of the LEDs was investigated by varying the contents of phosphor in silicone encapsulant. In addition to the 5wt% phosphor-containing silicone encapsulants which were already evaluated in this work, various concentration (1, 3, 7, and 9 wt%) of silicone encapsulants including phosphor were prepared. To confirm the phosphor distribution in silicone encapsulant, optical microscope images of phosphor-dispersed silicone encapsulant were taken at three different levels, *i.e.* the top, middle, and bottom **(Fig. S2–S5)**. With regard to all the phosphor-containing silicone encapsulants, it was confirmed that the encapsulants prepared through the semi-solidification represented more uniform phosphor distribution than the encapsulants fabricated by the conventional curing method.

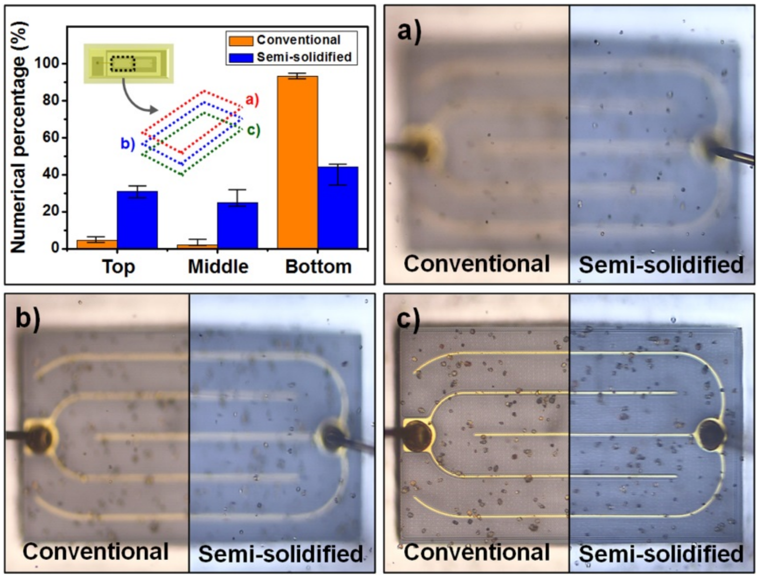

Fig. S2 Distribution of 1 wt% YAG phosphor in silicone encapsulant of the LEDs. The optical microscope images of the encapsulant prepared by a conventional curing method (left image) and semi-solidification process (right image) were obtained at a)top, b) middle, and c) bottom of the encapsulant.

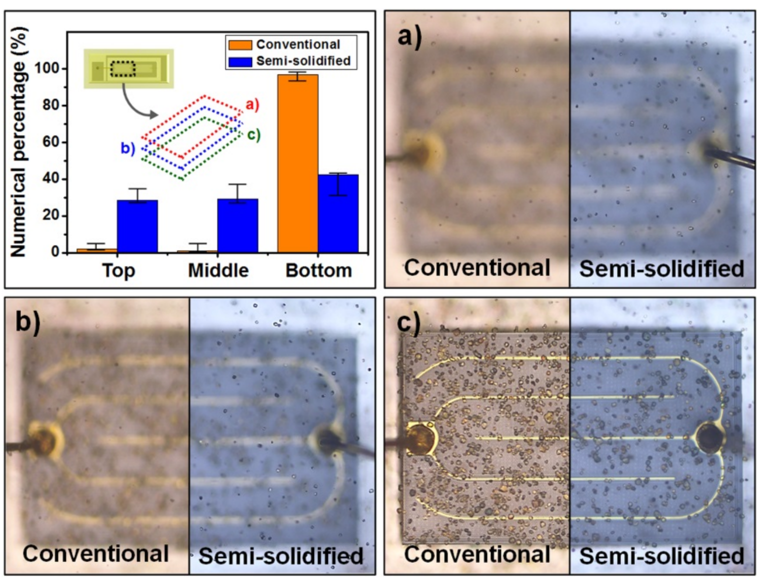

Fig. S3 Distribution of 3 wt% YAG phosphor in silicone encapsulant of the LEDs. The optical microscope images of the encapsulant prepared by a conventional curing method (left image) and semi-solidification process (right image) were obtained at a)top, b) middle, and c) bottom of the encapsulant.

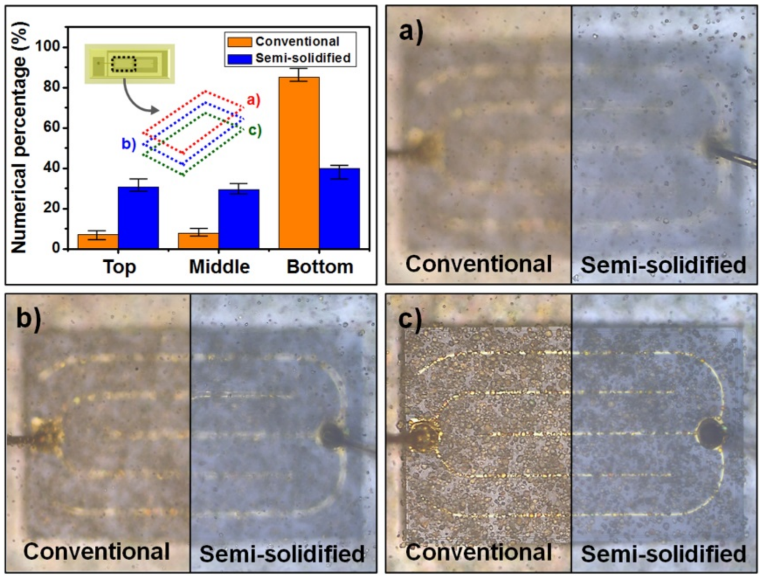

Fig. S4 Distribution of 7 wt% YAG phosphor in silicone encapsulant of the LEDs. The optical microscope images of the encapsulant prepared by a conventional curing method (left image) and semi-solidification process (right image) were obtained at a)top, b) middle, and c) bottom of the encapsulant.

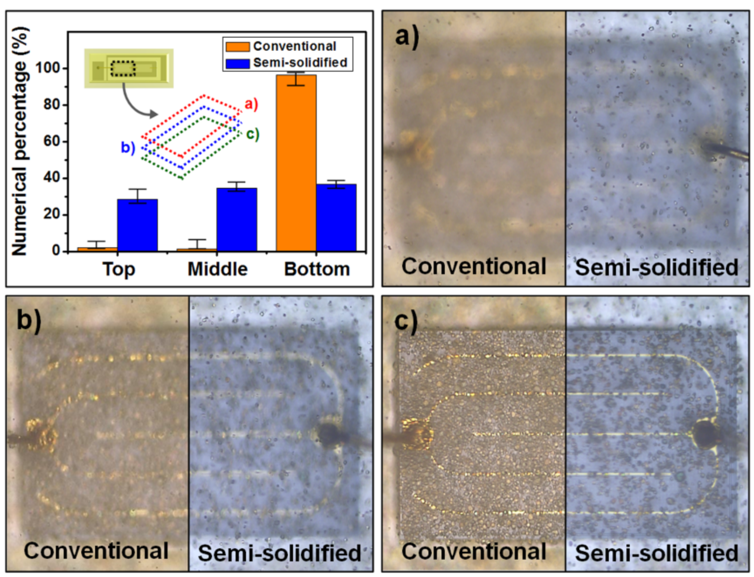

Fig. S5 Distribution of 9 wt% YAG phosphor in silicone encapsulant of the LEDs. The optical microscope images of the encapsulant prepared by a conventional curing method (left image) and semi-solidification process (right image) were obtained at a)top, b) middle, and c) bottom of the encapsulant.

To evaluate the influence of the phosphor concentration in silicone encapsulant on the optical characteristics of the LEDs, the Commission Internationale de L'Eclairage (CIE) 1931 chromaticity coordinates were measured **(Fig. S6)**; the measured values are listed in **Table S2**. Judging from the CIE 1931 color coordinates, the LEDs composed of 1 and 3 wt% phosphor in encapsulant emitted bluish light due to deficient YAG phosphor which plays a role as a color converter. On the other hand, yellowish light was emitted from the LEDs comprised with 5 and 7 wt% phosphor in encapsulant because the blue light which was emitted from the LED chip traveled through the silicone encapsulant rich in yellow phosphors. Accordingly, the optimized concentration of phosphor for white LEDs was 5 wt%.

In addition, it was confirmed that the LEDs with the encapsulant prepared using the semi-solidification process exhibited more uniform color distribution than the LEDs with conventional encapsulant with regard to all the phosphor-containing silicone encapsulants **(Fig. S7)**. The range of color coordinates was definitely reduced by introducing the semi-solidification process. To compare the color distribution of the LEDs, sample variance in the color coordinates was calculated **(Table S2)**. Judging from the calculated sample variance, it is clear that the semi-solidification approach was effective for the improvement of color uniformity.

Table S2. Optical properties of white LEDs comprised of silicone encapsulant with various concentrations of phosphor.[a]

Phosphor contents	Curing method	Voltage	Luminous flux	Efficiency	CIE 1931		Sample variance[b]	
		[V]	[lm]	[lm W^{-1}]	x	y	x [$\times 10^{-4}$]	y [$\times 10^{-4}$]
1 wt%	Conventional	5.84	43.2	77.9	0.2614	0.2069	3.051	1.462
	Semi-solidified	5.84	44.5	80.2	0.2686	0.2107	0.3128	0.9041
3 wt%	Conventional	5.84	54.3	95.4	0.2982	0.2728	1.458	1.205
	Semi-solidified	5.85	55.1	98.3	0.3044	0.2755	0.5286	0.2777
5 wt%	Conventional	5.84	70.1	123.5	0.3245	0.3088	1.126	3.781
	Semi-solidified	5.83	71.9	127.4	0.3326	0.3241	0.1690	0.8734
7 wt%	Conventional	5.84	60.5	105.8	0.3401	0.3402	2.744	3.510
	Semi-solidified	5.84	61.9	110.0	0.3696	0.3915	0.4632	0.9425
9 wt%	Conventional	5.83	56.0	98.7	0.3652	0.3887	2.150	8.424
	Semi-solidified	5.82	57.5	102.8	0.3448	0.3494	0.1780	1.007

[a] Optical properties were measured in conditions provided by CIE-127. Applied current was 100 mA. Temperature was 25.1 ± 0.3 °C and humidity was 51 ± 3% RH. Whole number of devices used for optical property analysis was twenty, and the measured values were averaged.

[b] A sample variance of twenty data for color coordinates was calculated for distribution comparison. Sample variance in the color coordinates was calculated for the distribution comparison.

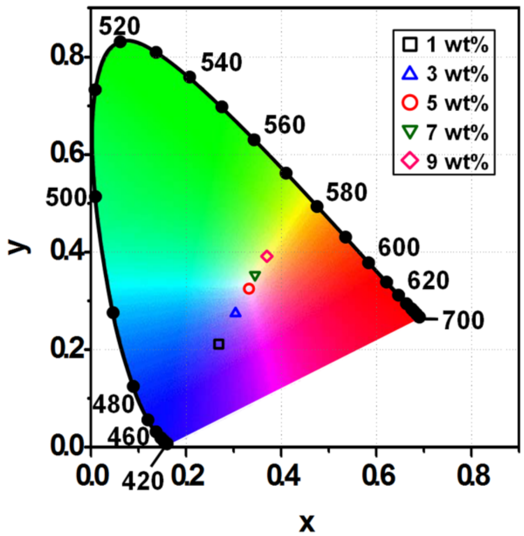

Fig. S6 CIE 1931 color space chromaticity diagram. CIE coordinates for white LED with silicone encapsulant containing various concentrations of YAG phosphor (1, 3, 5, 7, and 9 wt%). The LEDs were fabricated through the semi-solidification process.

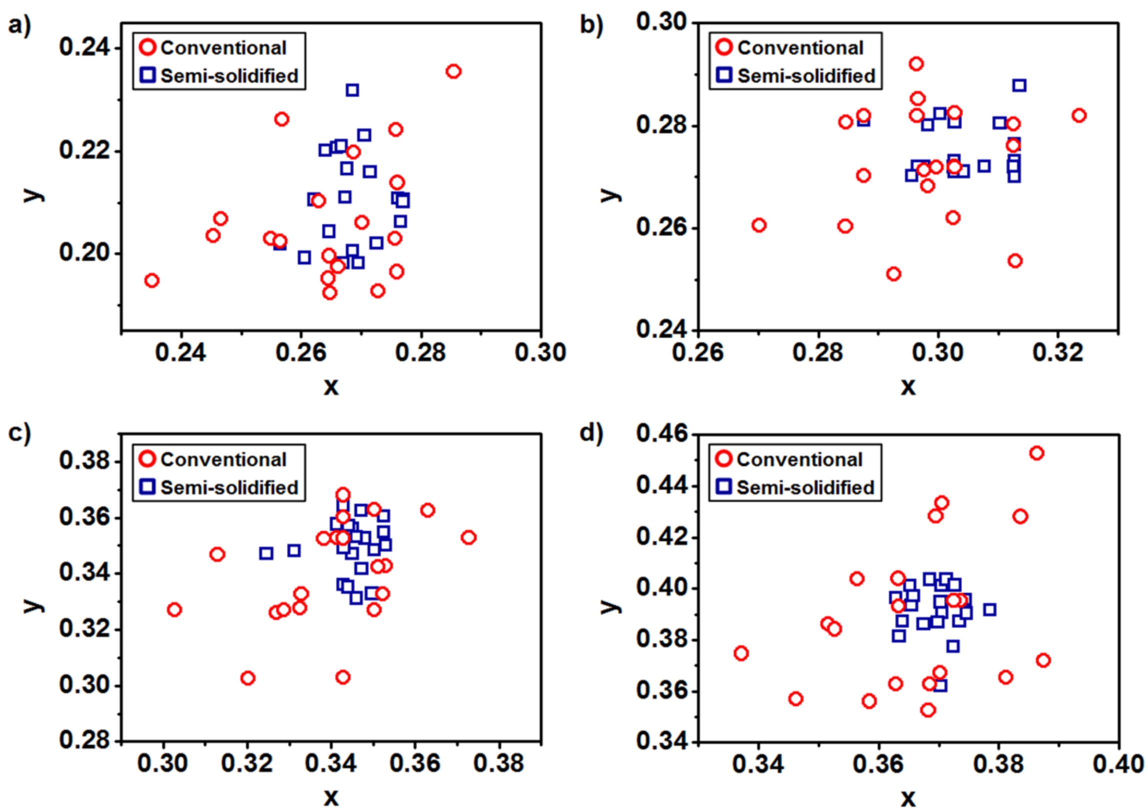

Fig. S7 CIE 1931 color space chromaticity diagram. CIE coordinates for white LED with silicone encapsulant containing a) 1 wt%, b) 3 wt%, c) 7 wt%, and d) 9 wt% of YAG phosphor. The LEDs were fabricated using a conventional curing method and semi-solidification process.

3. Photographs of the LED

The LED package has a dimension of 7 mm × 2 mm × 1 mm. One LED package is composed of two die which has a dimension of 1095 μm × 650 μm × 165 μm. As represented in SEM image, it was confirmed that the average size of YAG phosphor is *ca.* 10 μm.

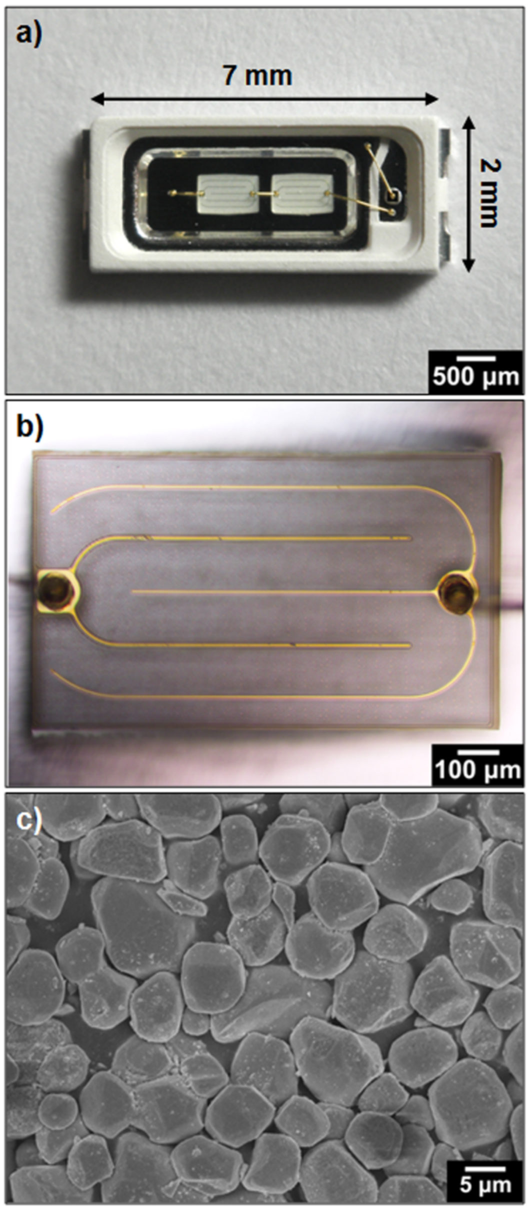

Fig. S8 a) Photograph of the LED package without an encapsulant. b) Optical microscope image of the LED die. One LED package is composed of two die. c) SEM image of YAG phosphor.

Photographs of the LED with the conventional encapsulant and the LED with the encapsulant prepared by the semi-solidification process were taken while the LED was in operation **(Fig. S9)**.

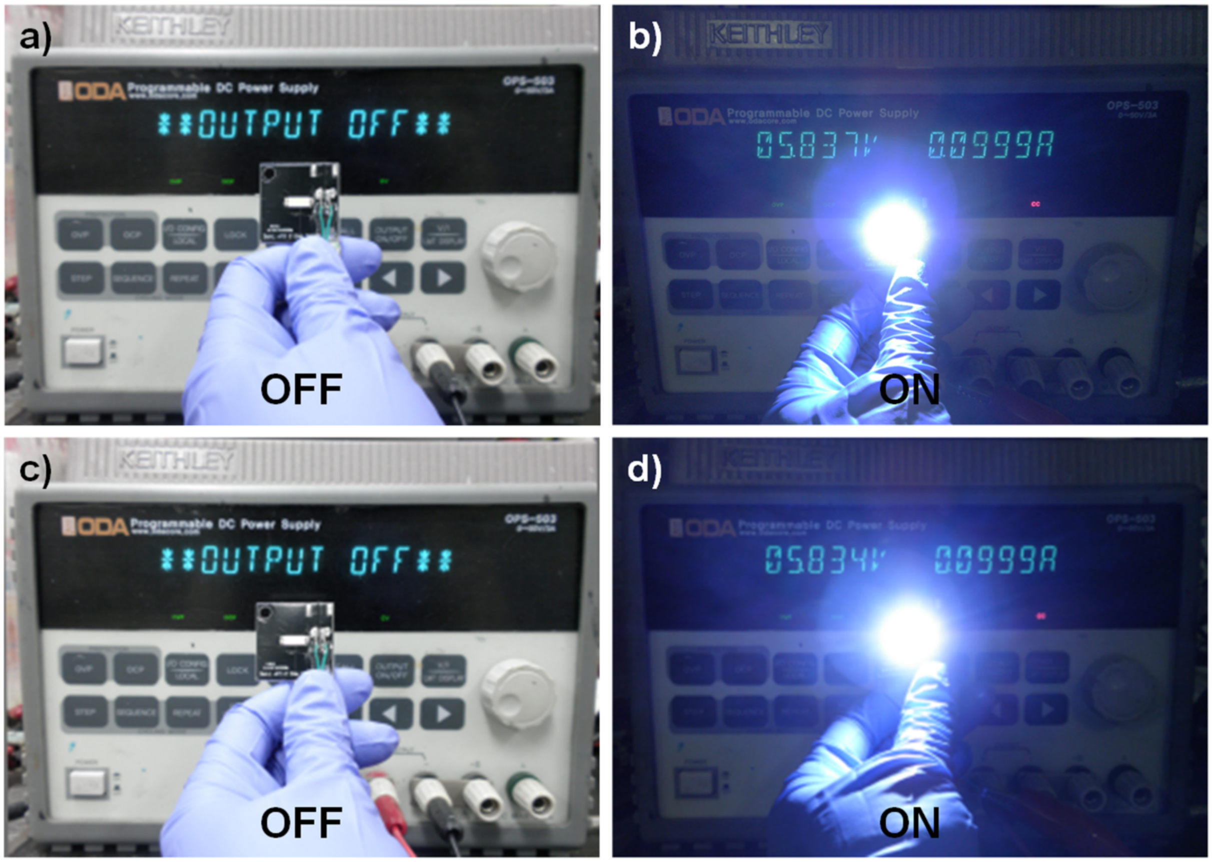

Fig. S9 Photographs of a) the LED with the conventional encapsulant while the light is turned off, or b) turned on, and photographs of c) the LED with the fabricated encapsulant while the light is turned off, or d) turned on.

4. Reliability test of white LEDs

From the reliability test results of the LEDs, it was confirmed that the LED with the new encapsulant exhibits smaller CIE coordinate variation and forward voltage variation as well as smaller variation of relative luminous flux compared with the conventional LED **(Table S3)**.

Table S3. Reliability test results of white light-emitting diode comprised of the encapsulant prepared *via* the conventional curing method or the semi-solidification process.[a]

Test condition	Operating time [h]	Relative luminous flux[b] [%]		CIE coordinate variation (x, y)[c]		Forward voltage variation[d] [%]	
		Conventional	Semi-solidified	Conventional	Semi-solidified	Conventional	Semi-solidified
85 °C, 85% RH, 100 mA	0	100.00	100.00	0.0000, 0.0000	0.0000, 0.0000	0	0
	200	99.998	100.01	–0.0001, –0.0001	–0.0001, –0.0001	0	0
	400	99.960	99.999	–0.0009, –0.0015	–0.0005, –0.0007	0.1	0
	600	99.653	99.983	–0.0012, –0.0020	–0.0005, –0.0008	0.1	0
	800	98.225	99.949	–0.0016, –0.0028	–0.0005, –0.0008	0.1	0.1
	1000	96.207	99.899	–0.0031, –0.0056	–0.0009, –0.0015	0.1	0.1
60 °C, 90% RH, 100 mA	0	99.999	100.01	0.0000, 0.0000	0.0000, 0.0000	0	0
	200	99.984	100.02	–0.0010, –0.0014	–0.0003, 0.0000	0.1	0.1
	400	99.943	99.992	–0.0015, –0.0024	–0.0008, –0.0009	0.3	0.2
	600	99.645	99.958	–0.0025, –0.0041	–0.0015, –0.0021	0.4	0.3
	800	98.206	99.924	–0.0027, –0.0045	–0.0021, –0.0032	0.5	0.4
	1000	95.894	99.727	–0.0045, –0.0078	–0.0029, –0.0047	0.6	0.5

[a] Total operating time was 1000 h and applied current was 100 mA.

[b] Relative luminous flux was estimated by considering the initial luminous flux as *ca.* 100%.

[c] CIE coordinates were analyzed according to CIE 127, and the variation of CIE coordinates were evaluated by regarding the initial value as origin of coordinates.

[d] The initial forward voltage was assumed as zero for evaluating the variation of forward voltage.