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# Enhanced Optical Performance and Thermal Stability of Quantum Dot Convertors for Laser Source

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***Abstract*—Quantum dots (QDs) are a revolution in the field of photoelectric and have a crucial potential for future applications as a color converter in micro/mini-LEDs. However, the reported QD converter efficiency (~20-40%) has not reached the level on par with that of the conventional phosphor color converters (~40-60%). In this study, we fabricate the QD nanowires (NWs) templated in the nanoporous anodic aluminum oxide (AAO) substrate using a combination of inkjet printing and vacuum-deposition. Owing to the light couple and waveguide effect of the nanopores cavity structure, we demonstrate a 1.25-fold enhancement in the luminous flux and a 2.04-fold increase in the photoluminescence (PL) intensity compared with the traditional QD planar converter. Furthermore, the stability test showed a 2.34 times improvement in lifetime resulting from the heat dissipation and moisture protection of the nanopores. The inkjet printing fabrication strategy combined with the nanostructure provides new insights for mass-produce high-quality QD NWs, which is promising for modern lighting applications in the micro/mini-lighting-emitting diodes (LEDs).**



***Keywords—Quantum dots, packaging structure, color converter, thermal and optical performance***


## I. INTRODUCTION

Quantum Dots (QDs) have emerged as promising candidates for highly efficient color conversion layer of micro/mini-LEDs due to high intense photoluminescence quantum yield (PLQY), narrow full-width at half maximum (FWHM), and tunable emission spectra[1-3]. Green and red QDs packaged with micro/mini-LED chips have become the most advanced technique for producing ultra-high-resolution displays[4].

Generally, QDs are dispersed into a transparent polymer matrix to form QD-polymer composites and utilized as color converters[5]. When operated in the heat and flux of the on-chip environment, it is difficult for the QD converter to withstand the continuous high-density power as a result of the poor thermal conductivity of the polymer, leading to the thermal quenching of QDs[6]. The poor thermal stability is one of the crucial obstacles for its commercial applications.

Another one is the low conversion efficiency of the QD converters[7]. Great efforts have been made to increase it by applying various packaging structures and designs. Recently, researchers have found that the utilization of optical microcavity can assure both high photoluminescence quantum yield and outstanding thermal stability of lead halide perovskite quantum dots through the electromagnetic field enhancement from the resonance effect[8]. Besides, some reports reveal that the light extraction with microlens or hollow fiber structures successfully achieves a few times enhancement for OLED performance[9], but this approach has not been adopted for QD converters. Herein, we introduce the nanoporous AAO substrate as a packaging structure of the QD color converter.

In our work, we introduce a facile and scalable method to fabricate QD nanowires (NWs) array within the nanoporous AAO substrate (the Meso QD@AAO). The optical performance tests were conducted to verify the improved light extraction of the Meso QD @AAO compared with the traditional QD film (the QD @PDMS). Finally, the stability comparisons were carried out via the infrared thermal method. The strategy represented here provides a new way to mass-produce QD nanowires of good quality for large-scale lighting applications and highly integrated optoelectronics in the future.

## II. EXPERIMENT

Figure 1 shows the QD NWs fabrication process. First, a nanoporous AAO substrate (2 cm(length)×2 cm(width), purchased from Jiangyin Youkun Experimental Equipment Co., Ltd.) was consecutively cleaned with deionized water with 500 s of sonication. Then, certain amounts of QDs were dissolved in chlorobenzene and ultrasonicated for 300s at room temperature(22℃) to form a uniform and transparent ink, where the QD was fixed at 1 mol/L in solutions.

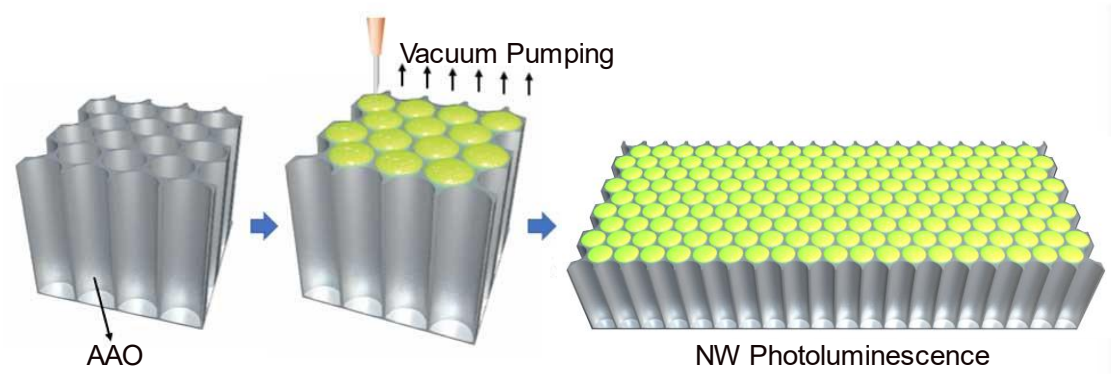


Fig.1. Schematic diagram of the preparation process for Quantum Dots Nanowire in nanoporous AAO for lighting.

Then 0.2 ml QD solutions were slowly inkjet-printed on the AAO substrate until the surface of the AAO substrate was fully covered. After that, vacuum suction was intended on the top of the AAO substrate to accelerate the evaporation of chlorobenzene solution. As the ink dried associated with the evaporation of the chlorobenzene, it reached a saturation state and then induced the crystallization and deposition of QD, thus forming a QD nanowire array embedded in the AAO. The green CdSe/ZnS Quantum Dots used in this paper were purchased from Beijing Beidajubang Science Technology Co., Ltd., and their peak emission wavelength and PLQY were 525 nm and 85%, respectively. The chlorobenzene was supplied from Aladdin.

In previous studies, the QDs were dispersed in organ silicate matrix by the solvent evaporation method[10], therefore, we produced a traditional QD film with the same QD quantity as the QD NWs within the nanoporous AAO to compare the color-converted efficiency between them. First, 0.1 g QDs were dissolved in 2 ml hexane solution and mixed with 1 g polydimethylsiloxane (PDMS) for 5 minutes ultrasonic treatment. After that, the QD slurry was coated on a cleaned sheet of glass(2 cm(length)×2 cm(width)) and cured at 90℃ for 40 min. PDMS, which serves as a QDs dispersion matrix, was purchased from Dow Corning Co., Ltd. All processes were carried out under laboratory conditions at a constant ambient temperature of 22℃.

## III. RESULTS AND DISCUSSIONS

The presence of QD NWs in the AAO nanopores was confirmed by cross-sectional scanning electron microscopy (SEM). Fig. 2(a) is a high-resolution top-view SEM image that showing good filling rate of QDs in the AAO pores, while the inset shows empty nanopores with unprinted AAO substrate. The nanoporous AAO substrate here has a depth of 60 μm and a diameter of 400 nm.

### *A. Optical performance of the QD NWs*

Our previous report has revealed that the strong cluster-induced scattering (AIS) effect of QDs in the silicone matrix results in severe backscattering and reabsorption loss, thus leading to the low efficiency of the LED devices with high QD concentration[6]. Fig. 3(a)(b) schematically demonstrates the QD NWs templated in the nanoporous AAO (Meso QD @AAO) and the traditional QD films (QD @PDMS). With the same amount of QDs, they uniformly dispersed in the nanoporous AAO substrate, while aggregate and form large particles in the PDMS. Due to the large effective size of QDs and the difference in refractive index between the QDs and the silicone matrix (PDMS), the diffraction effect leads to a strong scattering along the edges of the QDs, which causes severe optical loss confirmed by the PL spectra given in Fig. 3(c). The PL intensity of the Meso QD @AAO is much higher than that of the QD @PDMS under the same quantity of QD. It achieves a maximum PL enhancement of 2.04-fold compared with the QD @PDMS.

One reasonable explanation is that the AAO nanopores fundamentally prevent the aggregation of QDs, which is served as the dispensed substrate instead of the PDMS. Another one is that the nanopores in the AAO substrate act as the light coupler. The inner wall of the nanopores of AAO has a high metal reflection index, which helps to focus the light on the QD NWs and to cause more conversion events, thus leading to enhanced light out-extraction. Besides, some QD light can bypass the QDs in the nanopore of the AAO, which

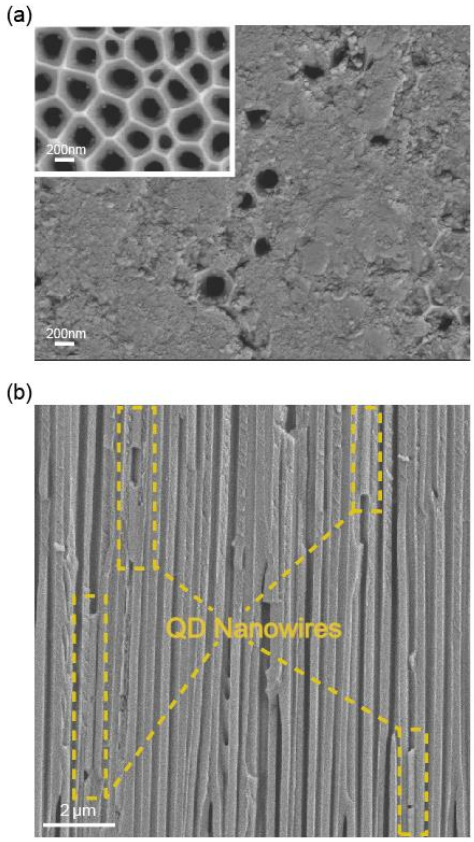


Fig.2. SEM image of the QD NWs in the AAO nanopores. (a) Top view and (b) Cross-sectional SEM image of filled QD NWs in AAO.

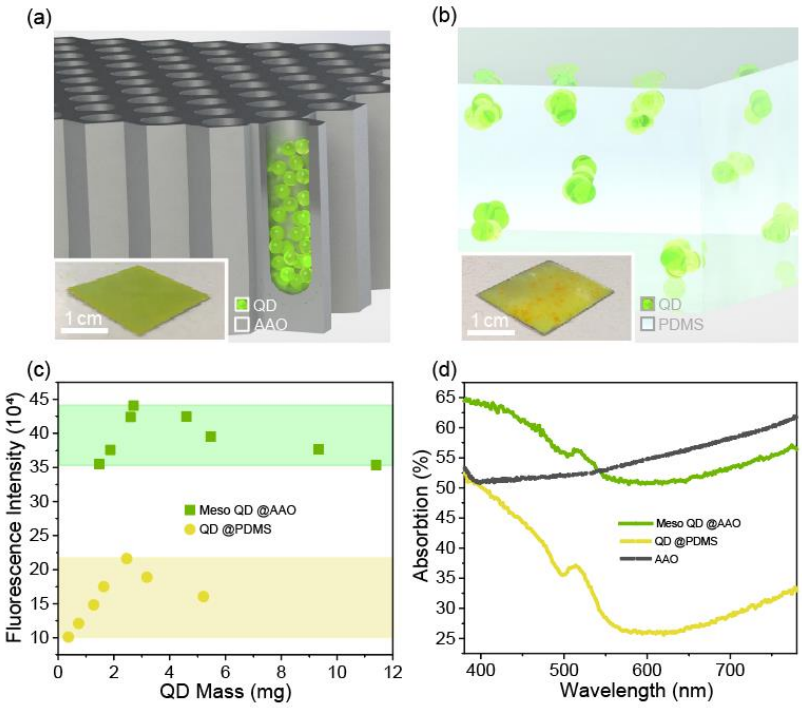


Fig.3. Characterization of the QD NWs templated in nanoporous AAO and the traditional QD films. Cross-sectional views schematic of (a) the Meso QD @AAO and (b) the QD @PDMS. The insets are the photographs of them. (c) PL spectra and (d) Reflection spectra of the Meso QD @AAO and the QD @PDMS, respectively.

successfully reduces the self-reabsorption loss. Another reasonable explanation is the waveguide effect of the nanopores of the AAO substrate. Compared with the QD @PDMS, light can directly enter the QDs in the nanopores of the AAO without passing through an organic matrix interface with a refractive index of 1.41, thus improving the light absorption and utilization. As can be seen from Fig. 3(d), the absorption of the Meso QD @AAO is much higher than that of the QD @PDMS, even the bare AAO substrate does.

However, the PL intensity of the Meso QD @AAO also decreases with the increasing QD mass seen from Fig. 3(c). One explanation is that the propagation direction of QD light is disturbed by the internal scattering effect when the light incident at the boundary of the nanopore. When the characteristic size of the nanopores' boundary is equivalent to the wavelength of the QD light, the strong scattering effect results in greater interference of the QD light and more serious total internal reflection. Even though, the lowest PL intensity of the Meso QD @AAO is still 63.6% higher than the highest one of the QD @PDMS.

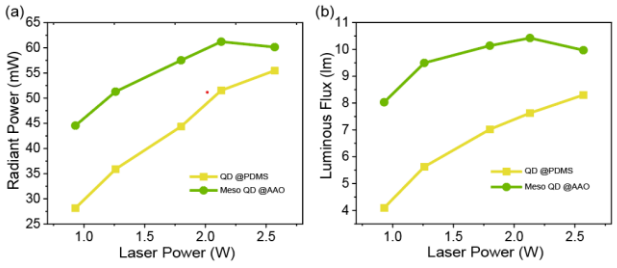


Fig.4. Optical efficiency of the QD NWs templated in AAO nanopores and the traditional QD planar TF CCL under different power excitation. (a) Radiant power. (b) Luminous flux.

Their radiant power and luminous flux under different laser power are compared, as shown in Fig. 4. Intriguingly, the Meso QD @AAO always has higher radiant power than the QD @PDMS. It can be simply attributed to the fact that the waveguide effect of the nanopore of the AAO. Moreover, the luminous flux can be greatly improved by replacing the silicone matrix (PDMS) with the nanoporous AAO, which achieves a maximum luminous flux enhancement of 25.5%.

### *B. Stability of the QD NWs*

Stability is a particularly significant characteristic of the QD converter since the severe thermal quenching phenomenon of QDs easily happens under a high temperature. Therefore, we performed stability tests on two kinds of samples: (i) the QD @PDMS, (ii) the Meso QD @AAO. Fig. 5(a) shows the time-varing maximum temperatures of the QD @PDMS and the Meso QD @AAO excited by the external laser diode at 0.93 W of injected power, respectively. Both are inspired from 0 seconds, and then cease to excite when the maximum temperatures stabilize. As seen from Fig. 5(a), there is a dramatic increase at the beginning, while a dramatic decrease at the end. The maximum temperature of the Meso QD @AAO is 36.974℃, just 0.5-fold that of the QD @PDMS. The nanoporous AAO cavity structure for heat dissipation offers a great amount of heat transfer channels. Fig. 5(b) is the stability under the action of a high-density laser and a harsh closed environment without any heat dissipation. The $T_{half}$ values for the Meso QD @AAO are 11.6664 min, while 4.9998 min for the QD @PDMS, which shows 2.34 times of lifetimes. The enhancement under the continuously high-density laser power stability can be attributed to the cavity on the AAO that helps to against the water and oxygen diffusion.

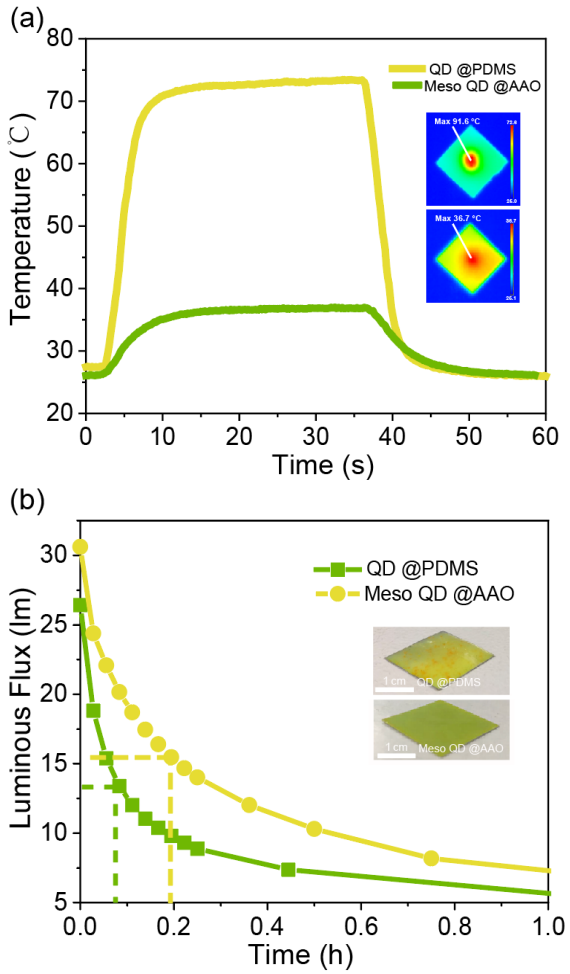


Fig.5. Stability tests of the QD NWs templated in AAO nanopores and the traditional QD planar TF CCL. (a) Time-dependent Surface temperature distributions, the insets are the stable infrared image of the QD @ PDMS and the Meso QD @AAO. (b) Time-dependent Luminous flux, the insets are thee photograph of them. All devices were measured at an injection power of 0.93 W.

## IV. Conclusion

In summary, we proposed a facile strategy to fabricate QD NWs array by inkjet-printing and vacuum-depositing within a nanoporous AAO substrate. The morphology of the AAO nanopores is applied to prevent QDs from aggregation, thus reducing the AIS effect under high concentration. The cavity structure of the AAO nanopores acts as the light coupler, which causes more conversion events and reduces self-reabsorption loss. Furthermore, the waveguide effect of the AAO nanopores improves light utilization and extraction. It achieves a maximum PL enhancement of 2.04-fold compared with the QD @PDMS. Additionally, the AAO nanopores provide heat transfer channels and protection from moisture and oxygen diffusions for the QDs, which contributes to the Meso QD @AAO 2.3334 times the lifetime of the traditional QD film. The study described above provides a strategy for mass-producing QD NWs and simultaneously solves critical issues on optical performance and thermal stability, which suggests a general guide for future designs on the QD converters integrated with other intelligent equipment, such as micro/mini-LED.

## Acknowledgment

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