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Mesh Patterned Silver Electrode via Electrohydrodynamic Printing for Transparent and Flexible Quantum-Dot Light-Emitting Diodes

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Abstract

A precise and efficient patterning method for mesh-structured electrodes is crucial for fabricating Transparent and Flexible Quantum-Dot Light Emitting Diodes (TF-QLEDs). In this study, we present an Electrohydrodynamic (EHD) printing method to directly pattern Ag mesh electrodes on flexible QLED devices, eliminating the need for sacrificial layers or chemical etching. By investigating the printing parameters, we achieved Ag mesh electrodes with excellent optical transparency exceeding 84%T, electrical conductivity with a sheet resistance of less than 8 Ω/sq and mechanical stability with less than 5% variation after over 2000 bending cycles. These mesh-patterned electrodes demonstrated superior characteristics compared to conventional electrodes. Additionally, the device efficiency of mesh-patterned electrodes was comparable to that of conventional planar electrodes, making them highly suitable for flexible electronic devices. This method offers significant advantages in transparency, flexibility and cost-efficiency, presenting a promising approach for the fabrication of next-generation flexible displays.

Author Keywords

flexible QLED; transparent electrode; EHD printing; mesh pattern; solution-processing; silver nanoparticles;

1. Introduction

The demand for transparent and flexible displays is rapidly growing, driven by advancements in the Internet of Things (IoT) and wearable electronics. Indium Tin Oxide (ITO) is commonly used as a transparent electrode due to its excellent properties. However, it suffers from brittleness, which limits its use in flexible displays that require repeated bending or deformation[1]. In contrast, metal mesh structures offer enhanced mechanical durability by effectively distributing tensile stress and preventing crack propagation[2], thanks to their flexible and non-planar architecture[3]. Additionally, metal meshes achieve both high optical transparency and excellent electrical conductivity, making them an ideal candidate for flexible, transparent electrodes.

When it comes to fabricating mesh structures, methods such as lithography[4] and wet etching[5] offer distinct benefits but also have limitations. The printing method, however, stands out for its combination of precision, scalability, and cost-efficiency. It allows for drop-on-demand patterning, ensuring precise material deposition with minimal waste, enhancing both economic and environmental sustainability[6]. Additionally, printing operates at lower temperatures, eliminating the need for complex setups, which reduces production costs and simplifies the fabrication process. These advantages make it a promising solution for transparent electrode fabrication in commercial applications.

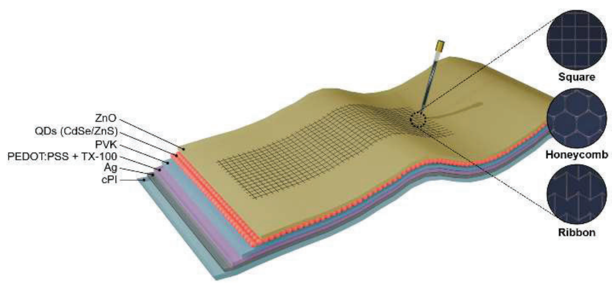

Figure 1. Schematic illustration of TF-QLED with Ag mesh-patterned electrode fabricated via EHD printing.

Among various printing methods, inkjet printing is valued for its adaptability across diverse inks and substrates[7], but its resolution is insufficient for the precise patterning required in metal mesh structures[8]. In contrast, EHD printing excels with its exceptional precision and high-resolution, leveraging advanced mechanisms to produce fine details such as transparent mesh patterns that remain invisible to the human eye. By direct printing electrodes without additional processes like stamping, laminating[9] or etching, EHD printing significantly enhances cost efficiency. This is achieved by reducing process complexity and material waste, while ensuring scalability and environmental sustainability. These advantages make EHD printing a reliable and efficient solution for fabricating metal mesh structures tailored to transparent and flexible displays.

In this study, we suggest an EHD printing method for directly printing mesh-patterned electrode on TF-QLEDs. The detailed structure is illustrated in **Figure 1**. AgNPs (Silver Nanoparticles) were chosen as the material for the mesh structure due to their excellent transparency, electrical conductivity and flexibility[10]. The printed Ag mesh electrode was used as the top electrode in TF-QLEDs and successfully integrated onto QLEDs fabricated on flexible substrates, including cPI (Colorless Polyimide) and PEN (Polyethylene Naphthalate). For the bottom electrode, a 12 nm-thick Ag layer was thermally evaporated onto the cPI substrate, ensuring both transparency and conductivity required for transparent device fabrication[11]. The thickness of the Ag layer was carefully optimized to achieve a balance between electrical and optical performance, making the electrode appear transparent to the human eye. All common layers were spin-coated to utilize the cost-effectiveness and mask-free capabilities of solution processing. We used PEDOT:PSS (Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) as the HIL (Hole Injection Layer) with 0.3wt% Triton X-100 (p-tert-octyl-phenoxy (9.5) polyethylene ether) added to enhance wetting properties and mechanical stabilities[12]. The concentration of Triton X-100 was adjusted to ensure that the hole injection characteristics of PEDOT:PSS were not compromised. Sequential layers were spin-coated as well, including PVK (Poly(9-vinylcarbazole) in chlorobenzene (7mg/ml) as the HTL (Hole Transport Layer),

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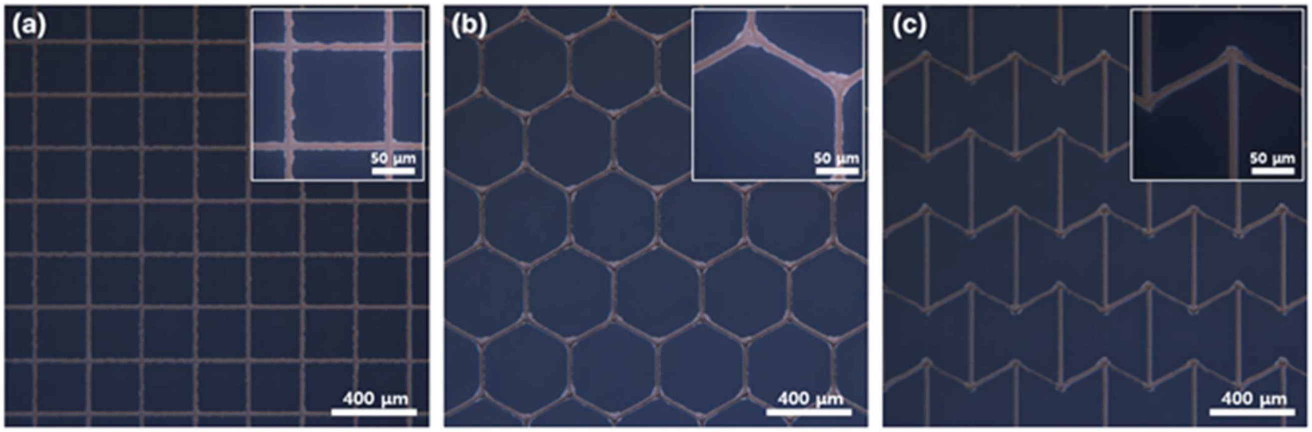

Figure 2. EHD printing results of mesh pattern on ZnO coated glass (a) Square (b) Honeycomb (c) Ribbon mesh pattern

QDs (Quantum dots) dispersed in octane (20 mg/ml) as EML (Emission Layer) and ZnO (Zinc Oxide) in butanol (40 mg/ml) as the ETL (Electron Transport Layer). In the final steps, the Ag mesh-patterned electrode was directly printed onto the ETL. This streamlined fabrication approach enables the production of highly transparent and flexible displays while minimizing material waste and reducing process complexity.

2. Result and Discussion

Performance of Optimized Mesh Patterns: The Ag mesh-patterned electrodes demonstrated significant advantages over conventional electrodes in terms of flexibility, transparency, and conductivity. Using the printing method, we were able to precisely control the mesh pattern and customize characteristics such as shape, pitch, line width, and thickness. To evaluate the performance of the customized patterns, we optimized three designs: square, honeycomb and ribbon as shown in **Figure 2(a)-(c)**. All patterns were printed on ZnO coated glasses with a line spacing of 225 µm pitch in order to construct the same conditions with direct printing on QLEDs. The printing process involved stacking 30 layers, resulting in a line width of approximately 20 µm. Compared to flexible ITO films which exhibited a sheet resistance above 30 Ω/sq, all mesh-patterned structures demonstrated higher conductivity. Among them, the honeycomb pattern showed the lowest sheet resistance at approximately 7 Ω/sq as shown in **Figure 3(a)**. Additionally, all patterns showed excellent transmittance, exceeding 84%T at 550 nm wavelength. To further evaluate the electrodes, we calculated the FoM (Figure of Merit) defined as T10/Rs following Haacke's methodology[13]. Here, T represents the transmittance at 550 nm,

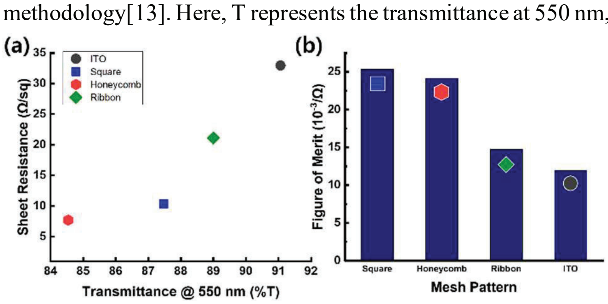

Figure 3. Comparing the characteristics of ITO and mesh patterns on ZnO coated glass (a)Transmittance and sheet resistance of ITO and mesh patterns (b) FoM of ITO and mesh patterns.

and Rs denotes the sheet resistance. As shown in **Figure 3(b)**, the square and honeycomb patterns both achieved a high FoM of approximately 25x10-3/Ω, significantly outperforming the flexible ITO film, which had a FoM of around 12x10-3/Ω, even lower than the ribbon mesh pattern. These results suggested he exceptional properties of metal mesh structures, particularly in their ability to combine high conductivity and transparency, making them a promising alternative to flexible ITO films for electrode applications.

Mechanical Stability of Mesh Patterns: The Ag mesh-patterned electrodes exhibited superior mechanical stability compared to both thermally evaporated planar Ag electrodes and flexible ITO films, making it suitable flexible electrode applications. We conducted a bending test to evaluate the mechanical stability of various electrodes. All mesh-patterned electrodes were fabricated by printing on ZnO coated PEN film with dimension of 1.6 x 24 mm. We measured the resistance change rate as the bending radius was gradually decreased. As shown in **Figure 4(a)**, the flexible ITO film was too brittle to

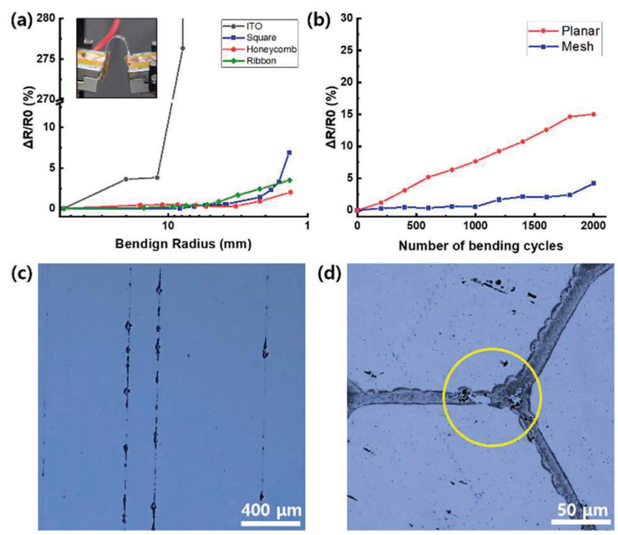

Figure 4. Result of mechanical stability test (a) Resistance change rate of ITO and mesh patterns during bending test (b) Resistance change rate of planar and mesh electrode during bending cycle test (c) Crack on ITO surface (d) Crack on mesh structure

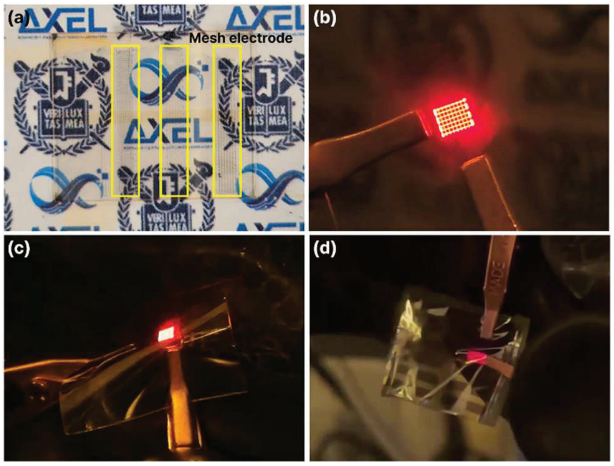

Figure 5. TF-QLED devices in each state (a) Transparent mesh electrodes enabling to see the logo underneath the device (b) Emitting light following the mesh pattern (c) Maintaining light in bent state (d) Emitting light on cPI substrate under crumpled state

withstand bending state, so when the bending radius dropped below 8 mm, the resistance increased by more than 300%. In contrast, the Ag mesh-patterned electrodes maintained a stable resistance change rate of less than 10%, even at a bending radius of 1 mm. Among these, the honeycomb pattern exhibited the highest mechanical stability, with a resistance change rate of nearly 2%. To further examine long-term mechanical stability, we conducted a bending cycle test comparing the mesh-patterned electrodes to planar Ag electrodes fabricated via thermal evaporation with a thickness of 100 nm. After 2000 bending cycles at a bending radius of 1.3 mm, the mesh-patterned electrodes exhibited a resistance change rate of around 5% as shown in **Figure 4(b)**. In contrast, the planar Ag electrode showed a resistance change rate of 15%, highlighting the superior mechanical durability of the mesh structure. Additionally, we observed that the crack occurred in the direction of the bending test on the ITO surface as shown in **Figure 4(c)**. Although we also found crack on the mesh-patterned electrodes, the unique structure effectively hindered crack propagation as shown in **Figure 4(d)**. These results indicate that Ag mesh-patterned electrodes are highly appropriate for use in flexible displays, offering enhanced flexibility and long-term durability, which can withstand extensive bending cycles without significant degradation in performance.

Implementation of Mesh Electrodes in TF-QLEDs: We successfully fabricated TF-QLEDs by directly printing the Ag mesh pattern as the top electrode onto the ETL of the QLEDs. The devices were constructed on cPI and PEN, demonstrating that this printing method is applicable to various flexible substrates. As shown in **Figure 5(a)**, the Ag mesh electrode exhibited excellent transparency, allowing the underlying logo to be easily seen with the naked eye. When voltage was applied, the TF-QLED emitted bright and uniform light following the printed mesh pattern. This emission was observable through both the transparent top and bottom side, as presented in **Figure 5(b)**. Moreover, as seen in **Figure 5(c)**, the device maintained stable light emission when the substrate was bent, confirming its functionality as a flexible device. Notably, this device continued to emit light reliably even under irregular deformation on ultra-thin substrates like cPI, demonstrating its versatility and mechanical durability as shown in **Figure 5(d)**. These results indicate that the Ag mesh-patterned top electrode, fabricated via our direct printing method is highly suitable for the TF-QLED devices. Furthermore, the method can be extended to various flexible substrates, making it a promising approach for next-generation flexible displays.

Impact of Fabrication Method and Electrode Structure on Device Efficiency: We analyzed the impact of fabrication method and electrode structure on device efficiency to evaluate the feasibility of mesh-patterned electrodes as an alternative to conventional planar electrodes in flexible QLEDs. The electrode conditions were categorized into three types: a thermally evaporated planar Ag electrode with a thickness of 100 nm, an inkjet-printed planar Ag electrode, and an EHD-printed mesh-patterned Ag electrode with a 225 μm pitch. First, we compared the thermal evaporation and printing methods. As shown in **Figure 6(a)-(c)**, the thermally evaporated planar Ag electrode provided a smooth, uniform surface ensuring consistent emission. In contrast, the inkjet-printed planar Ag electrode exhibited surface irregularities due to sequential deposition of ink droplets, leading to localized thickness variations. These surface irregularities increase sheet resistance and hinder charge transport efficiency[14]. However, EHD mesh printing enables precise control over ink deposition, preventing overflow and minimizing ink usage. As a results, it effectively reduces surface irregularities, leading to a more uniform morphology. Next, we compared the electrode structures, focusing on the performance of planar versus mesh-patterned electrodes. As shown in **Figure 6(d)**, the mesh-patterned electrode achieved a luminance of 811.24 cd/m^2 at 5 V, normalized to a fill factor of 0.099. Additionally, its current efficiency and power efficiency at 5 V were 2.87 cd/A and 1.76 lm/W respectively, which were comparable to those of the thermally evaporated electrode (2.57 cd/A and 1.61 lm/W), as shown in **Figure 6(e)**. As noted earlier, the inkjet-printed electrode showed the lowest current and power efficiency due to its surface non-uniformity. While the mesh-patterned electrode demonstrated comparable brightness and efficiency to the conventional electrodes, it also offered transparency as a leu advantage. This characteristics make it particularly advantageous for applications in flexible and transparent displays. These results demonstrate the potential of EHD-printed mesh electrodes, offering excellent performance

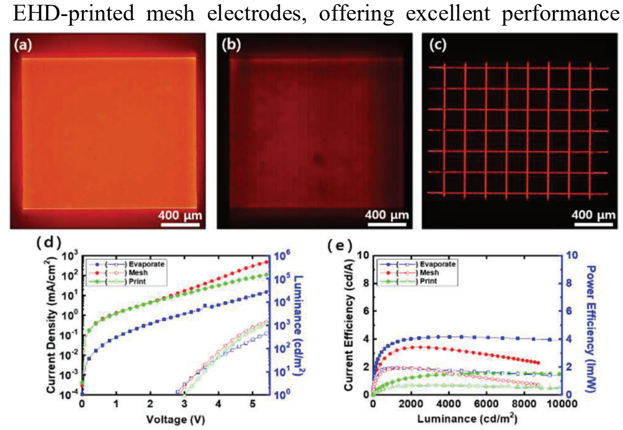

Figure 6. Device performance based on electrode structure and fabrication method (a) Thermally evaporated planar Ag electrode (b) Inkjet-printed planar Ag electrode (c) EHD-printed mesh printed Ag electrode. Emission images were captured at 0.5 mA with 33.33 ms exposure. (d) Current density and luminance (e) Current efficiency and power efficiency.

with superior scalability, simplified fabrication, and enhanced transparency, positioning them as a promising alternative to conventional planar electrodes for next-generation flexible and transparent displays.

3. Conclusion

In this study, we successfully developed a direct electrode printing method using EHD printing for TF-QLED devices. By investigating parameters such as shape, pitch, line width and layer count, we achieved Ag mesh electrodes with excellent optical transparency, electrical conductivity and mechanical stability. The mesh-patterned electrodes demonstrated superior flexibility and long-term durability compared to commonly used flexible ITO electrodes. Moreover, this direct printing method simplified the fabrication process and reduced material waste. Importantly, the versatility of this approach enables the production of TF-QLED devices on various flexible substrates, including ultra-thin materials. These features position our method as a promising solution for advancing next-generation flexible display technologies.

4. Author Contributions

†These authors contributed equally to this work.

5. Acknowledgements

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