

High-resolution intrinsically stretchable quantum-dot displays through thermally assisted intaglio transfer printing

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Supplementary Methods

Tensile testing of free-standing QD nanocomposite films on a water surface

Water surface, characterized by high surface tension (73 mN m^{-1}) and low viscosity ($1.002 \text{ mPa}\cdot\text{s}$), was employed as a tensile test platform of QD nanocomposite thin films. The high surface tension stably supports the films without sagging or tearing, while the low viscosity enables nearly frictionless in-plane sliding, minimizing mechanical interference. This configuration allows for accurate assessment of the film's intrinsic mechanical properties by effectively eliminating substrate-induced constraint. A high-resolution load cell (model LTS-50GA, KYOWA, Japan) and a linear actuator (model M-111.1DG, Physik Instrumente, Germany) were mounted on an anti-vibration table and symmetrically aligned with the floating specimen. The films were gripped at both ends using PDMS-coated silicon supports to ensure uniform load transfer and minimize edge effects. A constant displacement rate of 0.002 mm s^{-1} was applied under ambient conditions (25°C , 20% RH). Axial force was recorded in real time by the load cell, while tensile strain was simultaneously tracked using a CCD-based digital image correlation (DIC) system. Through this process, stress-strain curves were obtained, enabling quantitative evaluation of the mechanical behaviour of the nanocomposite thin films.

Elemental analysis

Elemental analysis was performed using powder samples obtained by scraping the composite films from the substrate. The QD:OA ratio in the SEBS-g-MA (10 wt%) QD nanocomposite was determined from thermogravimetric analysis data (**Supplementary Fig. 39**). For the untreated composite, the composition was assumed to be QD 75.3 wt%, OA 14.7 wt%, and SEBS-g-MA 10.0 wt%.

For simplicity, given the low MA content in SEBS-g-MA ($\sim 1 \text{ wt\%}$), ligand exchange was assumed to occur predominantly through the displacement of OA by MPA, while the

contribution from SEBS-g-MA was considered negligible in the calculation. The OA:MPA ratio was estimated from the measured C/S atomic ratio using the following equation:

$$\frac{C}{S} = \frac{18(\frac{m_{OA,0}}{282.47} - n_{MPA}) + 0.86\frac{m_{SEBS-g-MA}}{12.011} + 3n_{MPA}}{n_{S,ZnS} + n_{MPA}}$$

In this calculation, 282.47 is the molecular weight of OA, 12.011 is the atomic weight of carbon, and 0.86 is the carbon mass fraction of SEBS-g-MA. $m_{OA,0}$ is the initial mass of OA, $m_{SEBS-g-MA}$ is the mass of SEBS-g-MA, $n_{S,ZnS}$ is the number of moles of sulfur originating from the QDs, and n_{MPA} is the number of moles of MPA.

The value of $n_{S,ZnS}$ was first determined from the C/S ratio of the untreated composite. The amount of MPA in the LIFT-composite and the MPA composite was then calculated based on the elemental analysis results, and the OA:MPA ratio was subsequently determined from the calculated MPA content. The LIFT-composite shows a lower MPA ratio than the MPA composite, supporting the partial ligand displacement.

Cyclic voltammetry measurements

To investigate the effect of MPA surface treatment on the energy level, and to determine whether the MPA treatment was confined to the surface of the composite, cyclic voltammetry (CV) measurements were conducted on the untreated composite, the LIFT-composite, and the MPA composite sample. CV measurements were performed using the same potentiostat in a standard non-aqueous three-electrode configuration. The electrolyte consisted of a 0.1 M solution of TBAP in acetonitrile. The working electrode was prepared by spin-coating the QD nanocomposite solution onto an indium tin oxide (ITO) substrate at 2000 r.p.m. for 15 seconds, followed by mounting it in a glassy carbon electrode holder. To fabricate MPA composite and LIFT-composite films, the concentration of the QD nanocomposite solution and amount of MPA solution were adjusted to control the extent of MPA-functionalisation. A platinum (Pt) wire was

used as the counter electrode. A silver/silver ion (Ag/Ag^+) reference electrode was prepared in an acetonitrile solution containing 0.1 M TBAP and 0.01 M AgNO_3 . Prior to each measurement, argon gas was bubbled through the electrolyte for 30 min to minimize oxygen interference. The CV scans were conducted within a potential range of 2.5 to $-2.0 \text{ V}_{\text{Ag}/\text{Ag}^+}$ at a scan rate of 30 mV s^{-1} . The conduction band minimum (CBM) of the QDs was determined from the position of the first reduction peak (E_{red}) using the following equation^[S1,S2]:

$$E_{\text{CBM}} = -[E_{\text{red}} - E_{\text{Fc}/\text{Fc}^+} + 4.8]$$

The first reduction peaks for the untreated composite, LIFT-composite, and MPA composite were found at -0.93 V , -1.01 V , and -1.40 V , respectively (**Supplementary Fig. 13**). Based on these values, the calculated CBM positions were -3.62 eV , -3.54 eV , and -3.15 eV , respectively. The optical bandgap (E_g) of the untreated composite, LIFT-, and MPA composites, derived from the photoluminescence emission peak at 527 nm (**Supplementary Fig. 12**), was approximately 2.35 eV according to the relation $E_g = h\nu$ ^[S3]. The valence band maximum (VBM) was calculated using the CBM derived from CV measurements and optical bandgap obtained from PL emission, according to the equation shown below^[S3].

$$E_{\text{VBM}} = E_{\text{CBM}} - E_g$$

Substituting the corresponding bandgap values into the equation yields VBM (HOMO level) energies of -5.97 eV , -5.89 eV , and -5.50 eV , respectively. These results indicate that MPA treatment effectively modulates the HOMO level, thereby facilitating more efficient hole injection.

Mott–Schottky measurements

Mott–Schottky (M–S) measurements were performed using the same potentiostat in a three-

electrode setup. The M–S measurements were conducted over a frequency range of 10^5 to 10^{-2} Hz with an AC amplitude of 5.0 mV. The carrier concentration (N) was calculated from the slope of the M–S plot using the following equation^[S4]:

$$N = \left(\frac{2}{e\epsilon\epsilon_0} \right) \left[\frac{d(\frac{1}{C^2})}{dV} \right]^{-1}$$

where e is the elementary charge (1.6×10^{-19} C), ϵ is the relative dielectric constant of the semiconductor (5.8 for CdSe QDs), ϵ_0 is the vacuum permittivity (8.8×10^{-14} F cm⁻¹), V (V) is the applied potential, and C (F cm⁻²) is the interfacial capacitance.

Fabrication of QLEDs with LIFT-composites

The ITO-coated glass substrate was sequentially cleaned by sonication in detergent solution, deionized water, and isopropyl alcohol, followed by UVO treatment for 10 min. PEDOT:PSS (Clevios VP AI 4083) was then spin-coated at 2,000 r.p.m. and annealed at 150 °C for 30 min in ambient atmosphere. Subsequently, TFB (Lumtec, 0.5 wt% in chlorobenzene) was spin-coated at 2,000 r.p.m. and thermally annealed at 150 °C for 30 min. The LIFT-composite film was transfer-printed onto the TFB layer. For the integration of pre-stretched EMLs, the QD/SEBS-g-MA nanocomposite film was first picked up using a low-modulus PDMS stamp. After LIFT process, the EML was mechanically pre-stretched on the PDMS stamp to the desired strain level and subsequently transfer-printed onto the TFB layer of the device architecture. The applied strain levels (from 0 to 100%) were controlled by mechanical elongation of the PDMS stamp prior to transfer, enabling systematic evaluation of the deformation-dependent optoelectronic properties of the EML. ZnO nanoparticles dispersed in butanol was spin-coated and annealed at 85 °C for 30 min. Then, 100-nm-thick Al cathode was thermally evaporated under high vacuum. All processes conducted after the PEDOT:PSS deposition were conducted

inside a nitrogen-filled glovebox.

Finite element analysis

Thermo-mechanical strain and stress distributions during trench-assisted transfer of QD/elastomer composite films were simulated using commercial finite element software (Abaqus 2022, Dassault Systèmes, France) through a sequentially coupled thermal–mechanical approach. A two-dimensional plane strain model was constructed to represent the cross-sectional geometry of the PDMS stamp, QD composite layer, and underlying trench. The geometry was discretized using 4-node bilinear plane strain quadrilateral elements with reduced integration (CPE4R) for the mechanical analysis and corresponding 4-node heat transfer elements (DC2D4) for the thermal analysis. The final mesh consisted of 4,446 elements and 4,566 nodes, with locally refined meshing near the trench corner to accurately capture steep strain gradients. To realistically account for localised annealing, a steady-state heat transfer analysis was first performed, where a constant temperature corresponding to the annealing condition (60–120 °C) was prescribed at the trench region. Because the actual PDMS stamp thickness (~1 cm) is substantially larger than the modeled thickness (1 μm) used for computational efficiency, the truncated top surface of the PDMS domain was treated using an equivalent surface film boundary condition defined as $h_{eq} = k_{PDMS}/L_{omitted}$, where k_{PDMS} is the thermal conductivity of PDMS and $L_{omitted}$ represents the unmodeled bulk thickness. This approach approximates conductive heat dissipation into the bulk PDMS and enables formation of a physically realistic temperature gradient. The resulting nodal temperature field was extracted from the thermal analysis and imported into a subsequent static mechanical step as a predefined temperature field. An initial uniform temperature of 25°C was assigned as the stress-free reference state, and thermal strain was incorporated through isotropic thermal expansion, $\epsilon_{th} = \alpha(T - 25^\circ\text{C})$. Mechanical boundary conditions were applied to prevent rigid body

motion while allowing thermally induced deformation. Strain localisation near the trench edge was evaluated by extracting the maximum in-plane principal strain and comparing it with the far-field strain within the PDMS bulk to assess the influence of annealing temperature on deformation contrast governing pattern transfer.

Interfacial adhesion calculations of different QD nanocomposite films on SiO₂ intaglio trench

The interfacial interactions between various QD nanocomposite films and SiO₂ intaglio trench were quantified using the Fowkes method to calculate the work of adhesion ($W_{A/B}$), based on the surface energy components of each layer^[S5,S6]. The dispersive (γ^d) and polar (γ^p) contributions to surface energy were derived from contact angle measurements using water and glycerol, applying the Owens-Wendt-Kaelble equation (**Supplementary Table 3**)^[S7]:

$$\gamma_l(1 + \cos\theta) = 2[\gamma_l^d \gamma_s^d]^{\frac{1}{2}} + 2[\gamma_l^p \gamma_s^p]^{\frac{1}{2}}$$

In this equation, γ_l , γ_l^d , γ_l^p , γ_s^d , and γ_s^p represent the total, dispersive, and polar components of the surface free energy of the liquid (l) and solid (s), respectively. Using these values, the work of adhesion ($W_{A/B}$) between the SiO₂ intaglio trench (A) and each QD nanocomposite films (B), including untreated composite, LIFT-composite with MPA, and LIFT-composite with propanethiol, was calculated as follows^[S8]:

$$W_{A/B} = 4\left(\frac{\gamma_A^d \gamma_B^d}{\gamma_A^d + \gamma_B^d} + \frac{\gamma_A^p \gamma_B^p}{\gamma_A^p + \gamma_B^p}\right)$$

The results indicate that the LIFT-composite incorporating MPA significantly enhances adhesion to the trench surface compared to the others (**Fig. 3d, Supplementary Fig. 23**).

Fabrication of stretchable double-layer AgNWs electrodes

Stretchable double-layer AgNW bottom electrodes were fabricated via sequential spray-

coating of pristine and ligand-exchanged AgNW solutions onto an ODTs-treated Si wafer using a patterned shadow mask. For the first layer, AgNWs solution (0.07 wt% in IPA) was uniformly spray-coated onto the substrate. The second layer, ligand-exchanged AgNWs solution, was prepared by modifying a previously reported ligand exchange process^[S9]. 1-decanethiol (Sigma Aldrich) was added to AgNW solution and stirred for 24 hours, followed by multiple washes and redispersion in IPA. Following the sequential spray-coating of both AgNW layers, a PUA resin was drop-cast onto the AgNW-coated substrate and UV cured. The electrode was delaminated from the Si substrate for the fabrication of intrinsically stretchable QLEDs.

Supplementary Table 1 | Elemental analysis of untreated, LIFT-, and MPA QD nanocomposite films.

Sample	C wt%	S wt%	C/S ratio	OA:MPA
Untreated composite	16.81	12.83	3.49	1:0
LIFT-composite	16.80	14.89	3.01	1:0.32
MPA composite	14.25	18.66	2.03	1:3.55

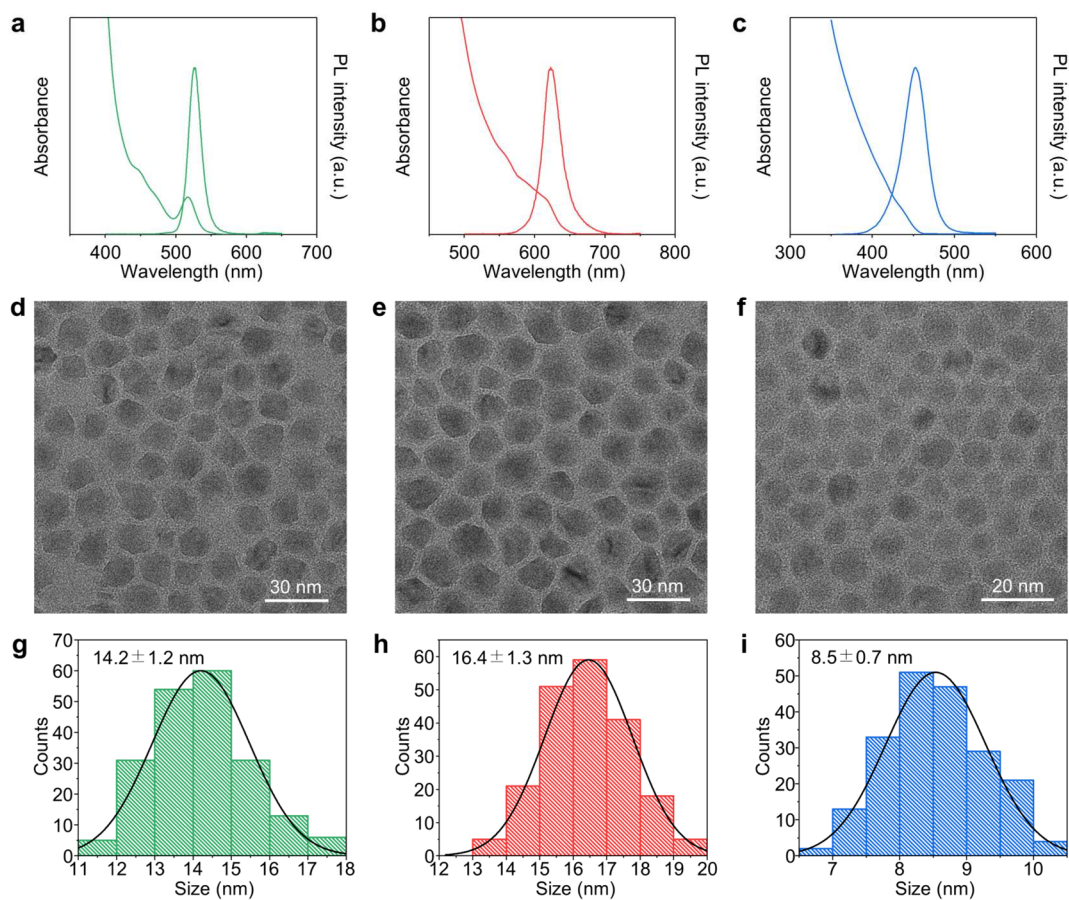
Supplementary Table 2 | Impedance analysis result of devices fabricated via transfer printing and LIFT.

	R_s [Ω]	R_{ct} [$k\Omega$]
Transfer printing	42.5	77.3
LIFT	36.4	56.2

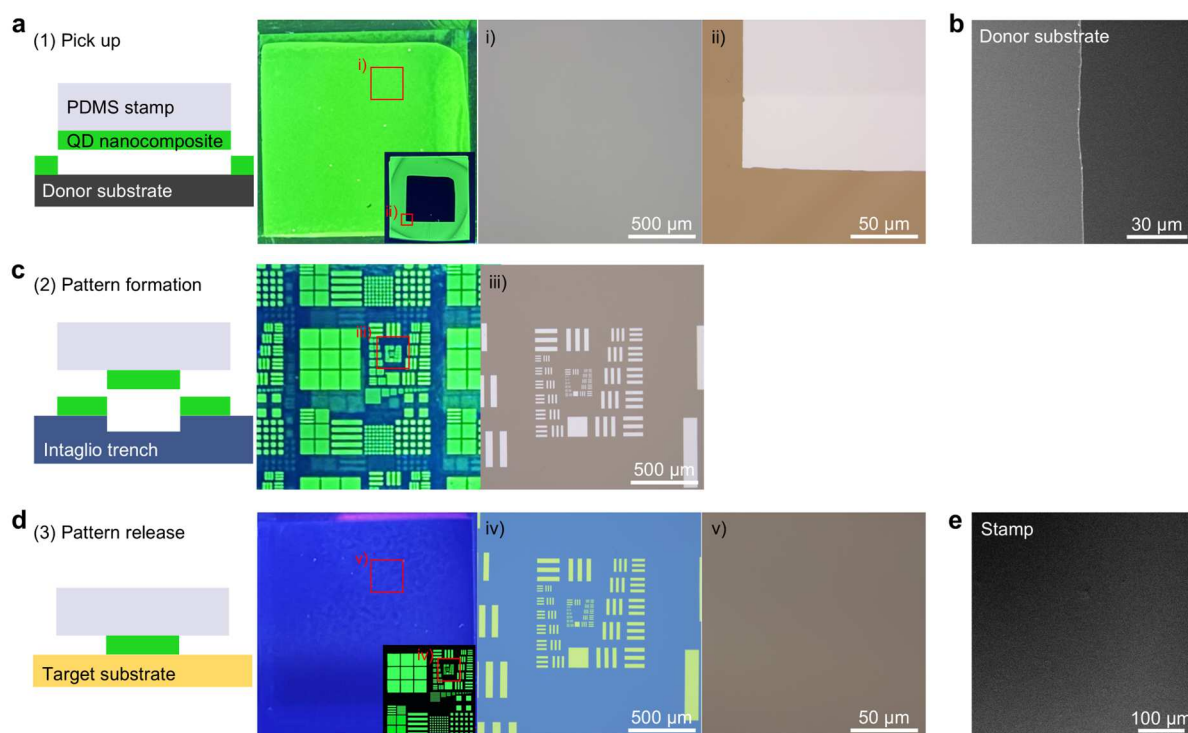
Supplementary Table 3 | Contact angles and surface energies of different QD nanocomposite films and intaglio trench.

	Contact angle [°] ^{a)}		γ_s^d (Dispersion	γ_s^p (Polar
	DI water	Glycerol	components) [mJ m ⁻²]	components) [mJ m ⁻²]
Untreated	99.4	87.4	19.4	1.9
LIFT-composite using MPA	86.5	84	6.0	14.5
LIFT-composite using propanethiol	93.9	88.1	9.3	7.6
SiO ₂	64.0	56.3	17.2	21.4

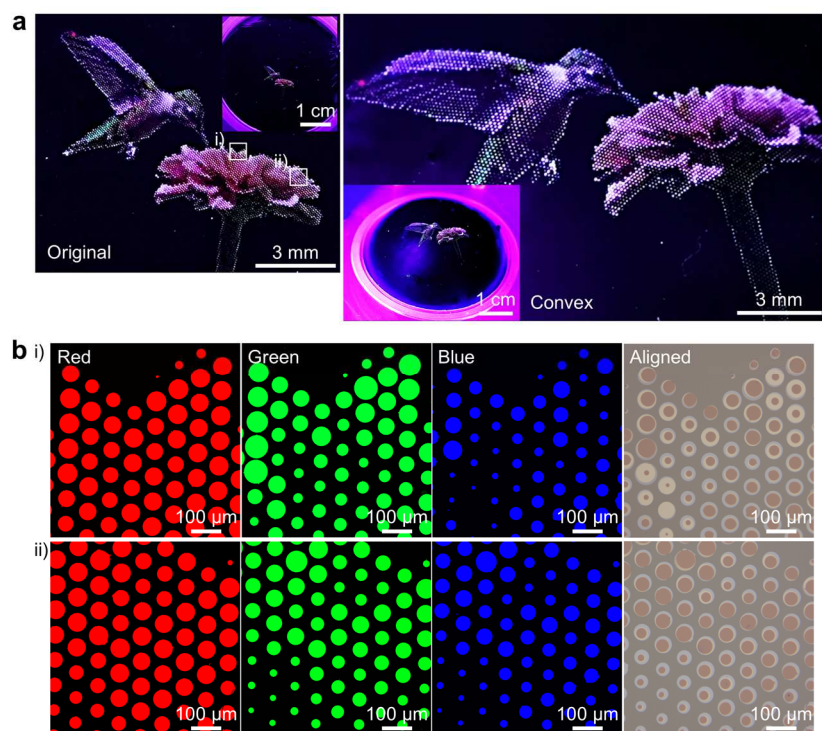
a) The contact angles of droplets were measured using a contact angle analyzer (SmartDrop, Femtobiomed).



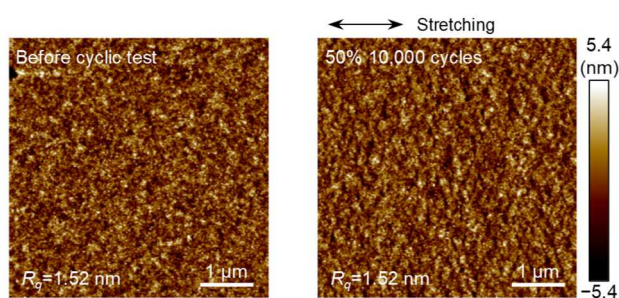
Supplementary Fig. 1 | Characterisation of green, red, and blue QDs. a–c, Absorption and PL spectra of green (a), red (b), and blue (c) QDs. **d–f,** Transmission electron microscopy images of green (d), red (e), and blue (f) QDs. **g–i,** Histograms showing the size distributions of green (g), red (h), and blue (i) QDs ($n = 200$).



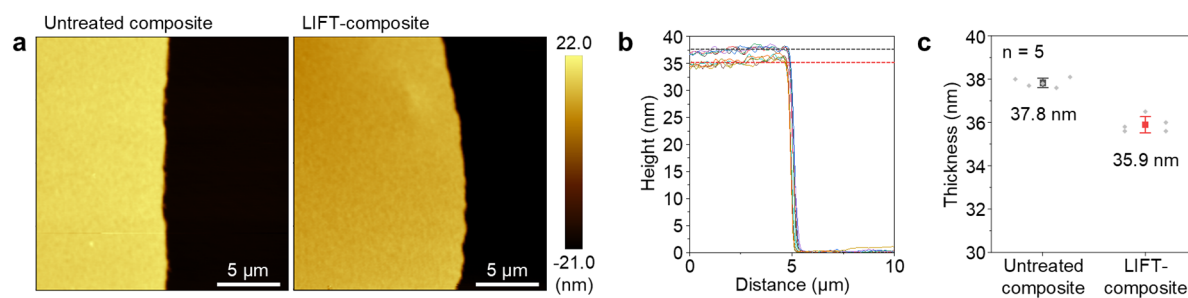
Supplementary Fig. 2 | **a**, Schematic illustration of the QD composite pick-up process (left), PL images of the PDMS stamp (middle) and the donor substrate (middle, inset) after pick up, and the corresponding optical microscope images (i, ii). **b**, SEM image of the donor substrate after the pick-up step, confirming the absence of residual material. **c**, Schematic illustration of the pattern formation process (left), PL image of the PDMS stamp after pattern formation (middle), and the corresponding optical microscope images (iii). **d**, Schematic illustration of the pattern release process (left), PL images of the PDMS stamp (middle) and the receiver substrate (middle, inset) after release, together with the corresponding optical microscope images (iv, v). **e**, SEM image of the PDMS stamp after pattern release, confirming clean transfer without residual QD nanocomposite.



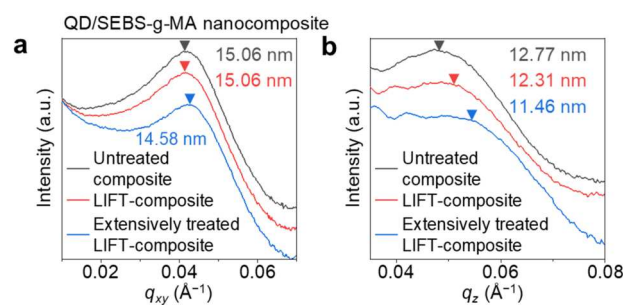
Supplementary Fig. 3 | a, PL images of high-definition full-colour QD pixel arrays (318PPI) under planar (left) and convex (right) deformation. A stretchable SEBS/carbon black composite is used as the substrate. **b**, Magnified fluorescence images of the RGB subpixels from the boxed region in (a) and the corresponding optical microscope image of the vertically stacked RGB subpixels (right).



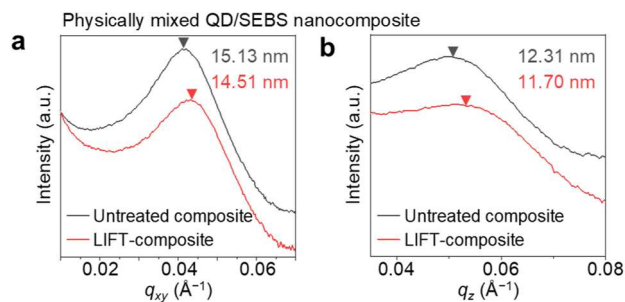
Supplementary Fig. 4 | AFM images of QD nanocomposite films before (left) and after (right) 10,000 cycles of 50% uniaxial stretching.



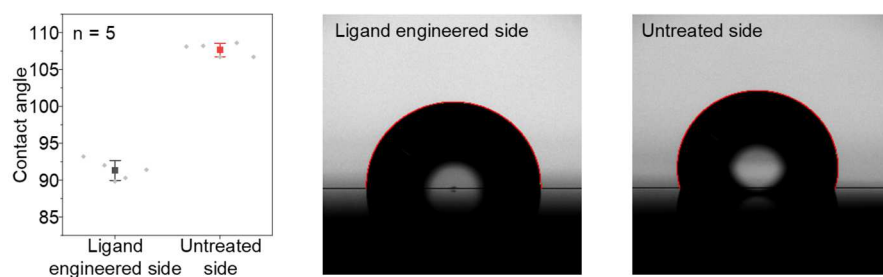
Supplementary Fig. 5 | **a**, AFM images of untreated (left) and LIFT- (right) composite films. **b**, Corresponding height profiles from (a). **c**, Comparison of the film thickness before and after ligand engineering. Data are presented as mean and standard deviation from five independent samples.



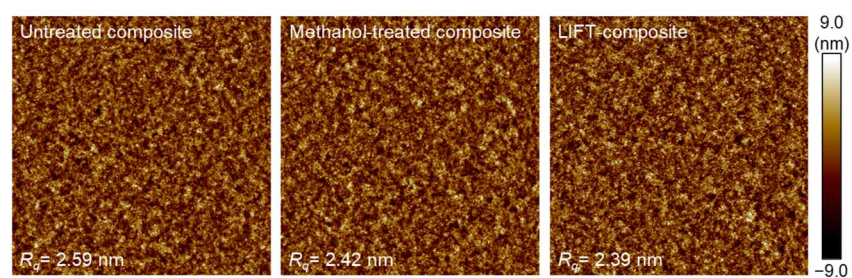
Supplementary Fig. 6 | GISAXS line profiles along the in-plane (a) and out-of-plane (b) directions for untreated composite, LIFT-composite, and extensively treated LIFT composite under harsher ligand engineering conditions ($10\times$ MPA concentration and $5\times$ reaction time). In conventional QD solids, film-state ligand exchange with short-chain ligands such as MPA typically induces contraction of the interparticle spacing through replacement of long-chain native ligands. By contrast, the QD/SEBS-g-MA nanocomposite shows largely unchanged interparticle spacing after the standard LIFT treatment, whereas the extensively treated LIFT-composite exhibits pronounced spacing contraction.



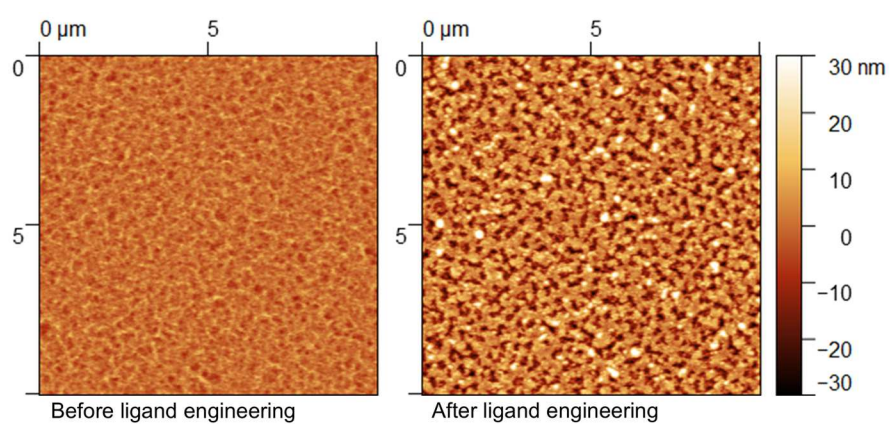
Supplementary Fig. 7 | GISAXS line profiles along in-plane (a) and out-of-plane (b) directions for untreated and LIFT-composite based on QD/SEBS nanocomposites. Unlike the chemically bonded QD/SEBS-g-MA nanocomposite, the physically mixed QD/SEBS nanocomposite exhibits a pronounced reduction in interparticle spacing after LIFT treatment.



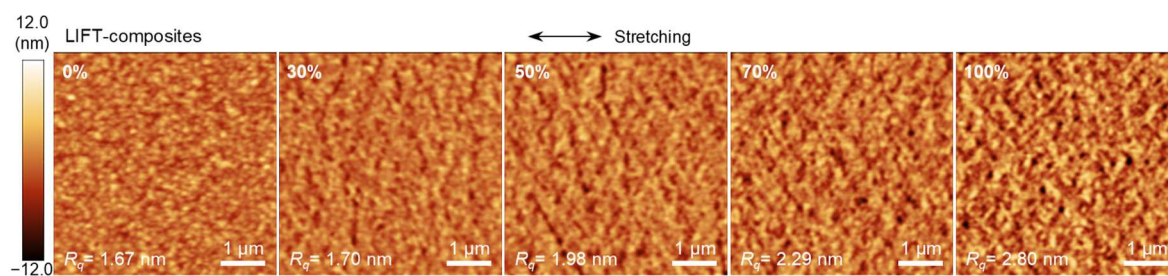
Supplementary Fig. 8 | Contact angles measured on the ligand engineered side and the opposite untreated side of the LIFT-composite. Data are presented as mean and standard deviation from five independent samples.



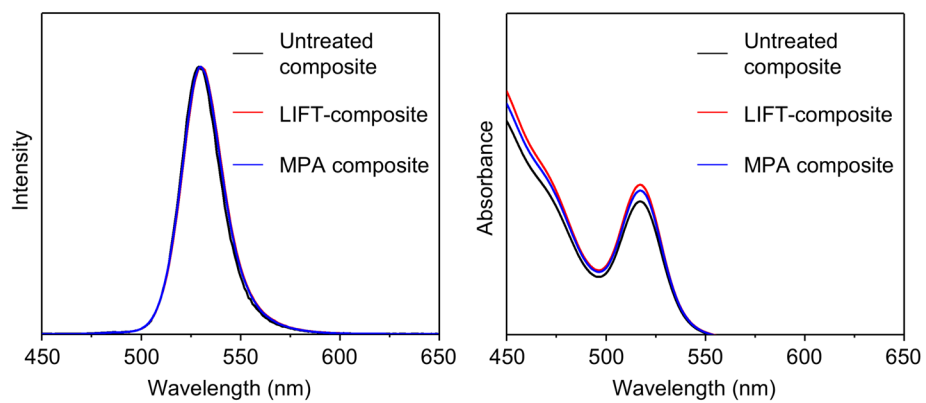
Supplementary Fig. 9 | AFM images of untreated (left), methanol-treated (middle), and LIFT-composites (right).



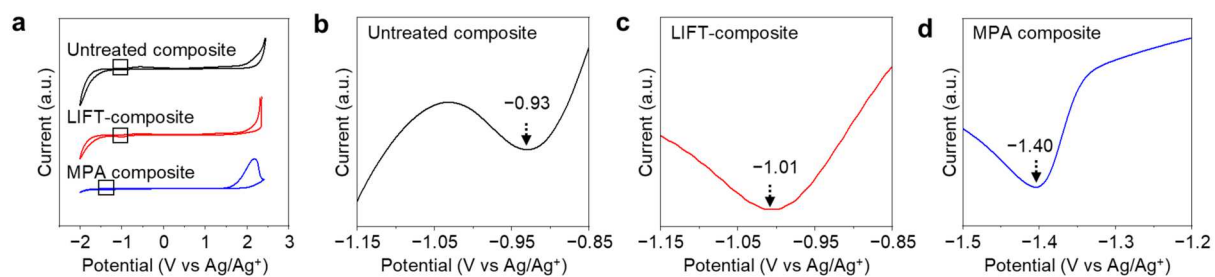
Supplementary Fig. 10 | AFM images of bare QD films before (left) and after (right) ligand engineering.



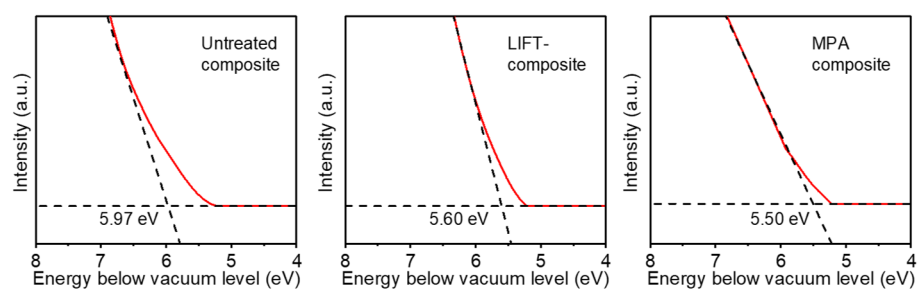
Supplementary Fig. 11 | AFM images of LIFT-composites under different tensile strains (0%, 30%, 50%, 70%, and 100%).



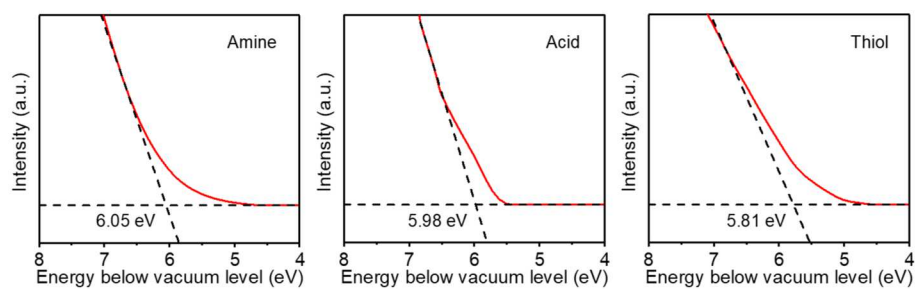
Supplementary Fig. 12 | PL (left) and absorption (right) spectra of untreated, LIFT-, and MPA QD nanocomposite films.



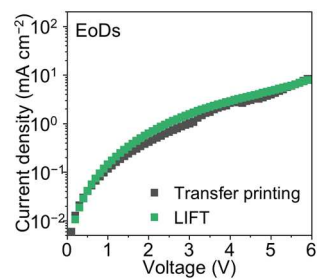
Supplementary Fig. 13 | CV analysis of untreated, LIFT-, and MPA QD nanocomposite films. a, CV curves of QD nanocomposite films. **b–d**, Magnified CV curves highlighting the reduction potentials for untreated (b), LIFT- (c), and MPA (d) QD nanocomposite films.



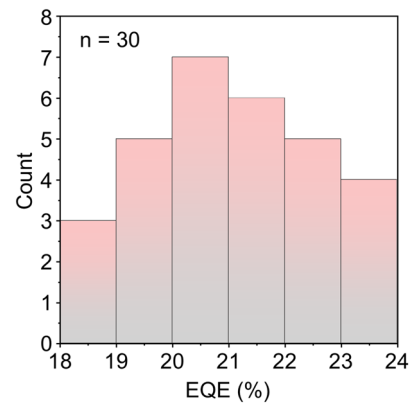
Supplementary Fig. 14 | UPS results of untreated (left), LIFT- (middle), and MPA (right) composites.



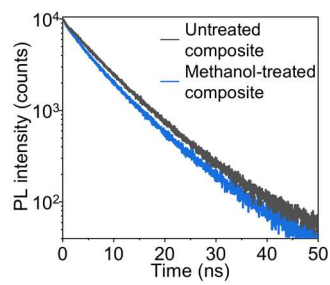
Supplementary Fig. 15 | UPS results of LIFT-composites treated with amine (propanamine), carboxylic acid (butyric acid), and thiol (propanethiol)-containing ligands.



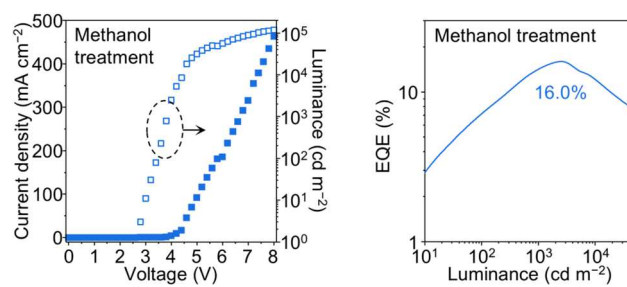
Supplementary Fig. 16 | J - V characteristics of EoDs (EoDs; ITO/ZnO/QD nanocomposite/ZnO/Al) fabricated by transfer printing and LIFT process.



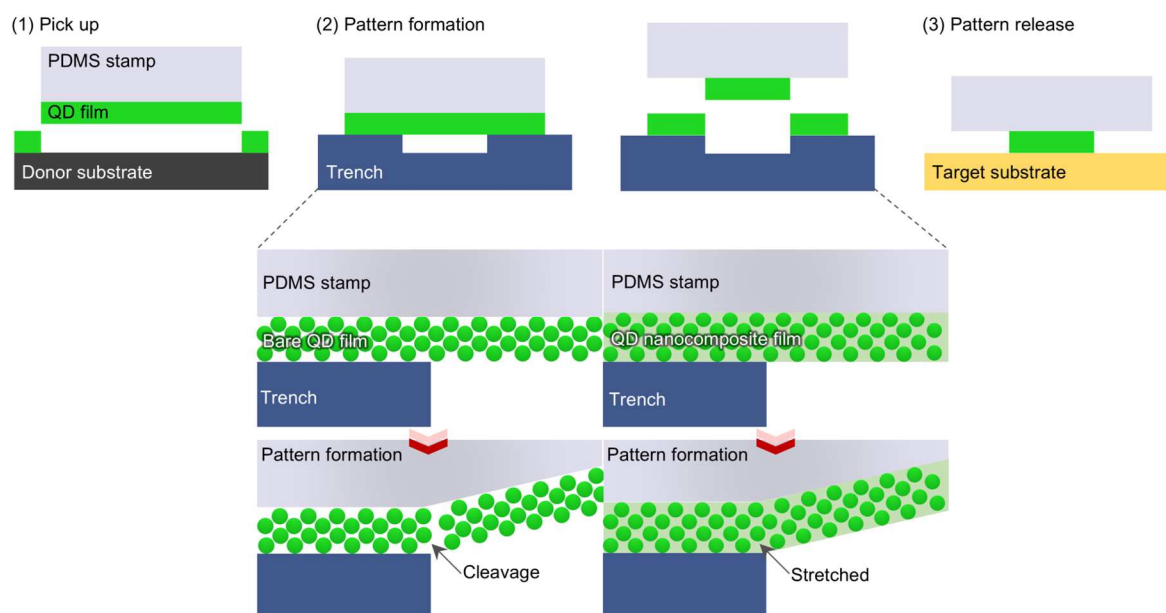
Supplementary Fig. 17 | Histogram of EQE distribution for QLED fabricated via LIFT process (n = 30).



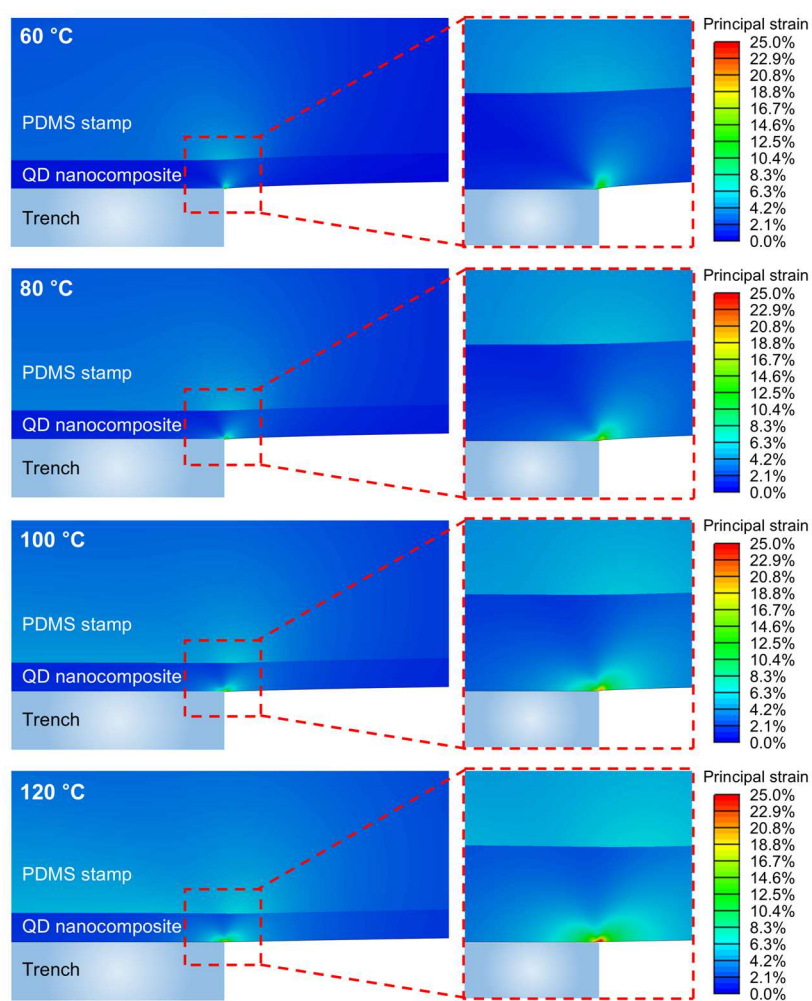
Supplementary Fig. 18 | TRPL decay profiles of untreated and methanol-treated composites.



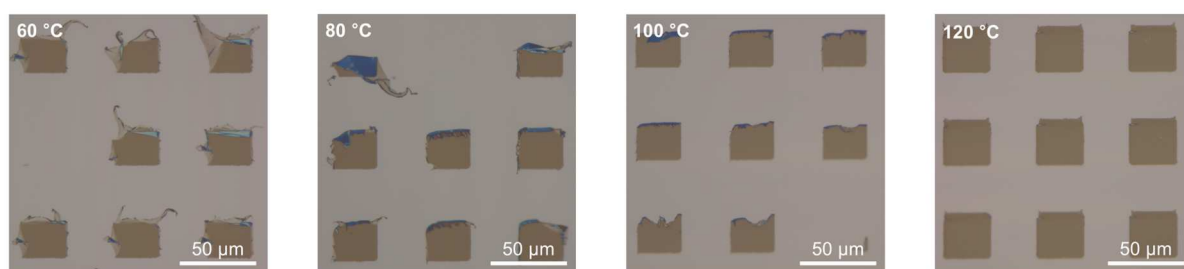
Supplementary Fig. 19 | J – V – L (left) and EQE– L (right) characteristics of QLED fabricated with methanol-treated composite.



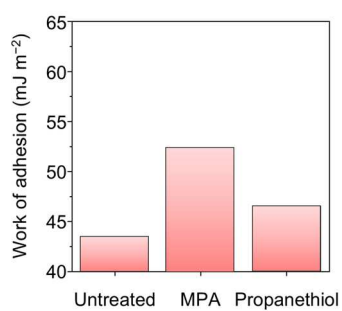
Supplementary Fig. 20 | Comparison of intaglio patterning for bare QD films (bottom left) and QD nanocomposite films (bottom right).



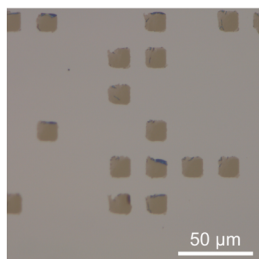
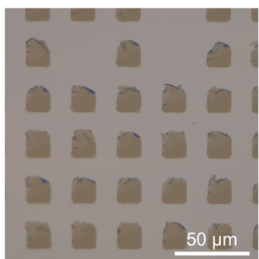
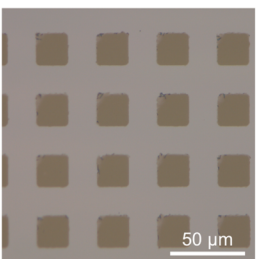
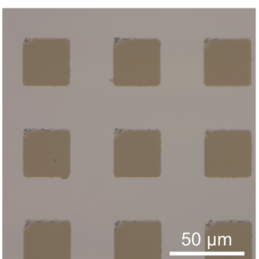
Supplementary Fig. 21 | Finite element analysis of localised strain distribution at trench edges during pattern formation under different processing temperatures.



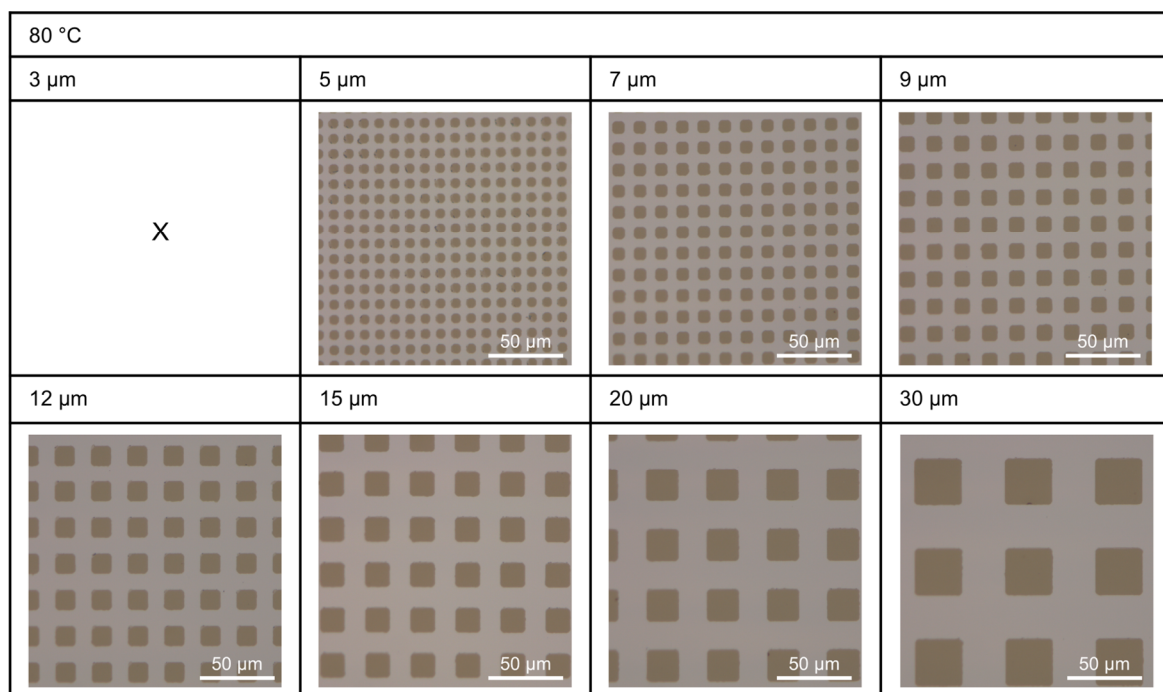
Supplementary Fig. 22 | Optical microscope images showing the temperature-dependent evolution of pattern fidelity in QD nanocomposite films processed at 60, 80, 100, and 120 °C.



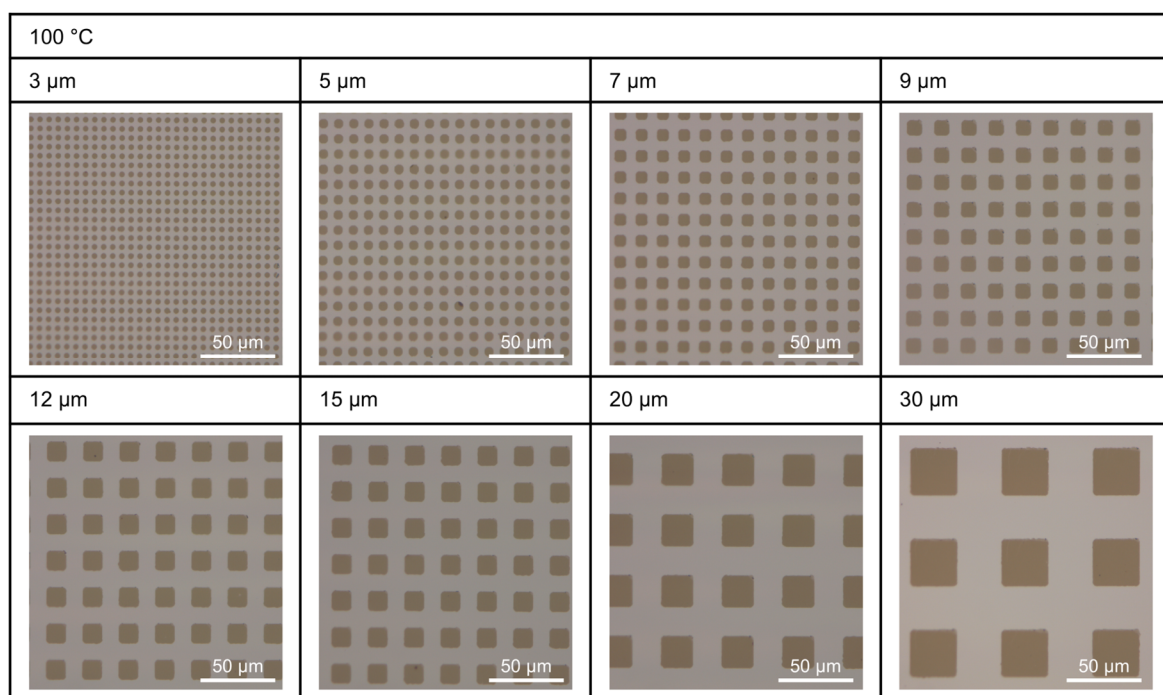
Supplementary Fig. 23 | Work of adhesions between SiO₂ trench and QD nanocomposite films with different ligand engineering materials.

60 °C			
3 μm	5 μm	7 μm	9 μm
X	X	X	X
12 μm	15 μm	20 μm	30 μm
			

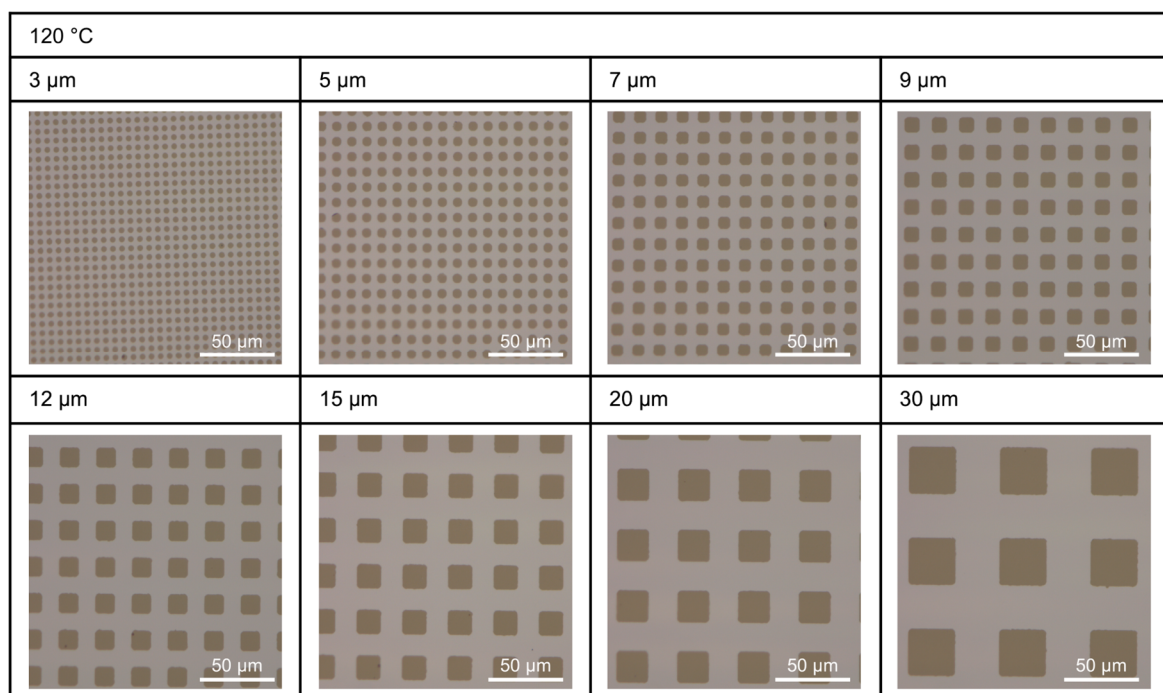
Supplementary Fig. 24 | Optical microscope images showing the effect of feature size on pattern fidelity in QD nanocomposite films processed at 60 °C.



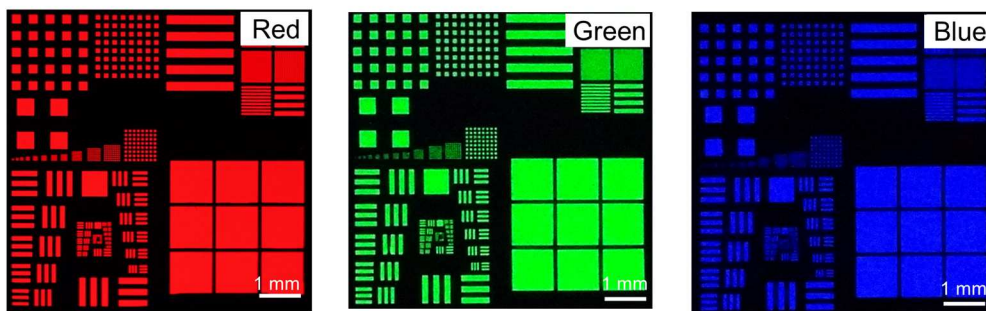
Supplementary Fig. 25 | Optical microscope images showing the effect of feature size on pattern fidelity in QD nanocomposite films processed at 80 °C.



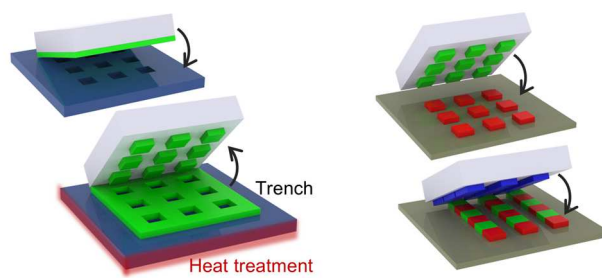
Supplementary Fig. 26 | Optical microscope images showing the effect of feature size on pattern fidelity in QD nanocomposite films processed at 100 °C.



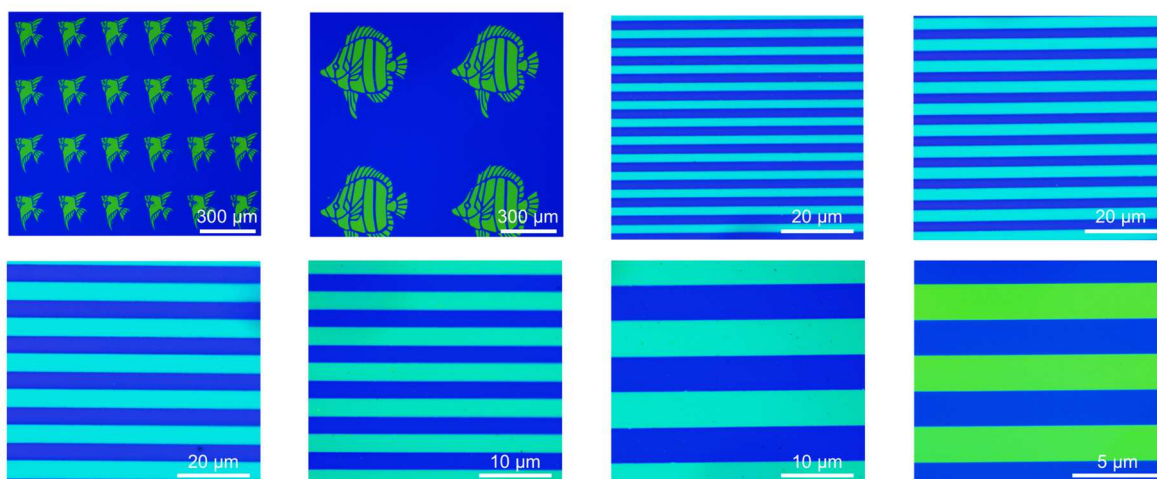
Supplementary Fig. 27 | Optical microscope images showing the effect of feature size on pattern fidelity in QD nanocomposite films processed at 120 °C.



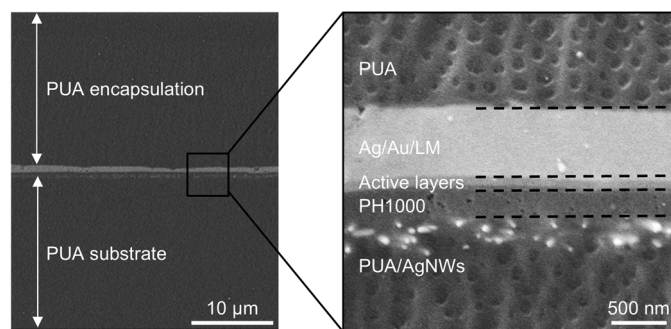
Supplementary Fig. 28 | Photographs of monochromatic QD nanocomposite patterns in red (left), green (middle), and blue (right).



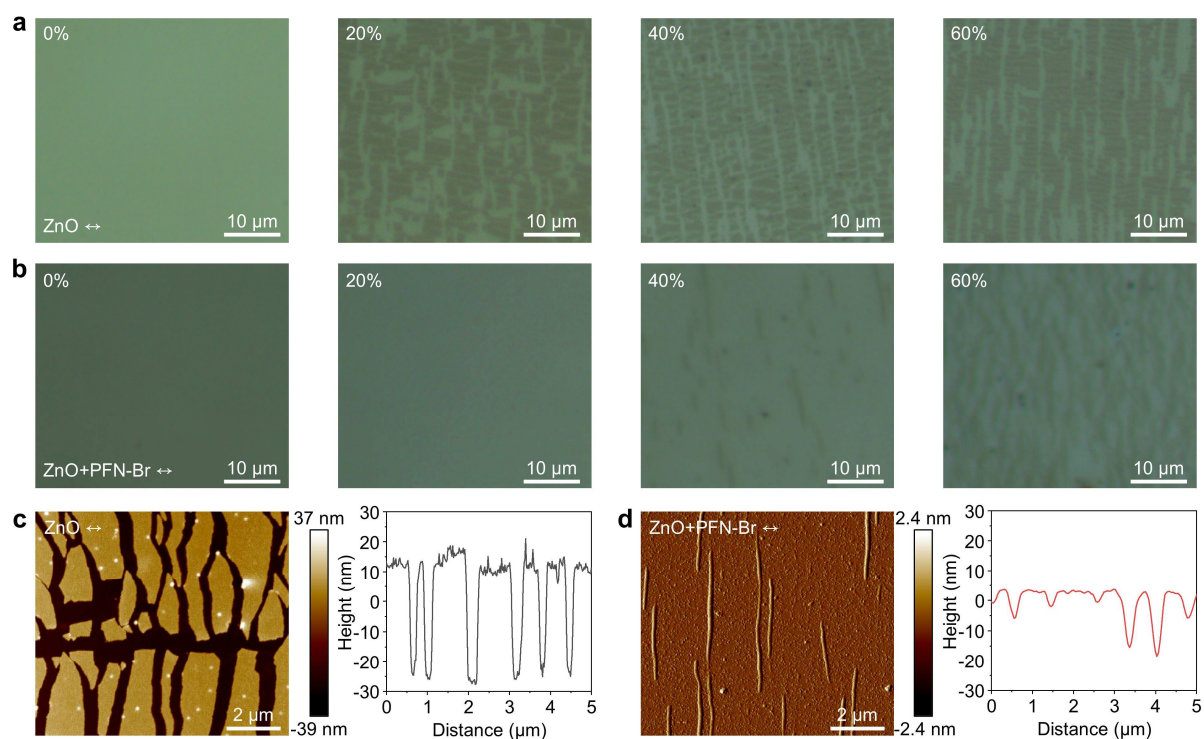
Supplementary Fig. 29 | Schematic illustrations of multicolour aligned pattern formation process.



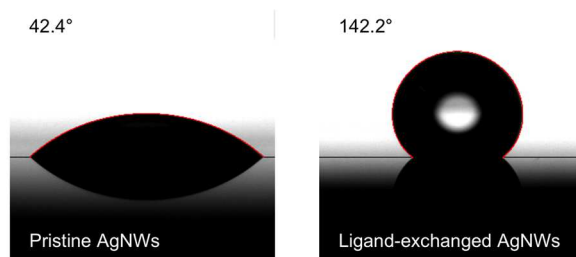
Supplementary Fig. 30 | Optical microscope images of monochromatic QD nanocomposite patterns with various shapes and sizes.



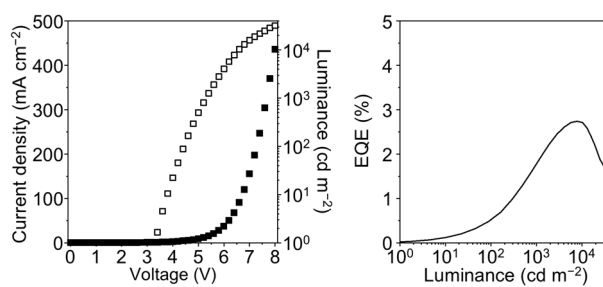
Supplementary Fig. 31 | Cross-sectional SEM images of the intrinsically stretchable QLED in different magnifications.



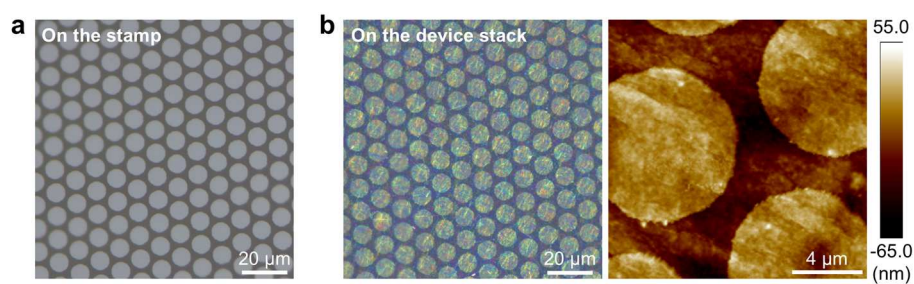
Supplementary Fig. 32 | Mechanical stretchability of ETL layers. **a**, Optical microscope images of bare ZnO ETL layers under different tensile strains. **b**, Optical microscope images of ZnO/PFN-Br hybrid ETL layers under different tensile strains. **c,d**, AFM images of ZnO (c) and ZnO/PFN-Br hybrid ETL layers (d) under 40% tensile strain, with corresponding height profiles (right).



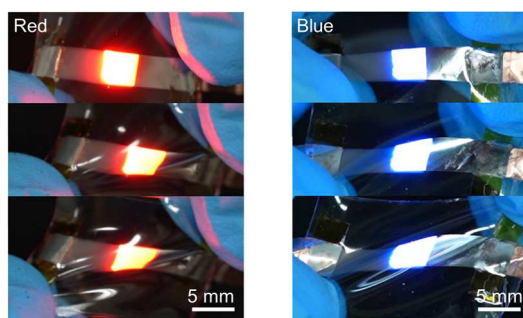
Supplementary Fig. 33 | Contact angles of water droplet on pristine (left) and ligand-exchanged AgNWs (right) film surfaces.



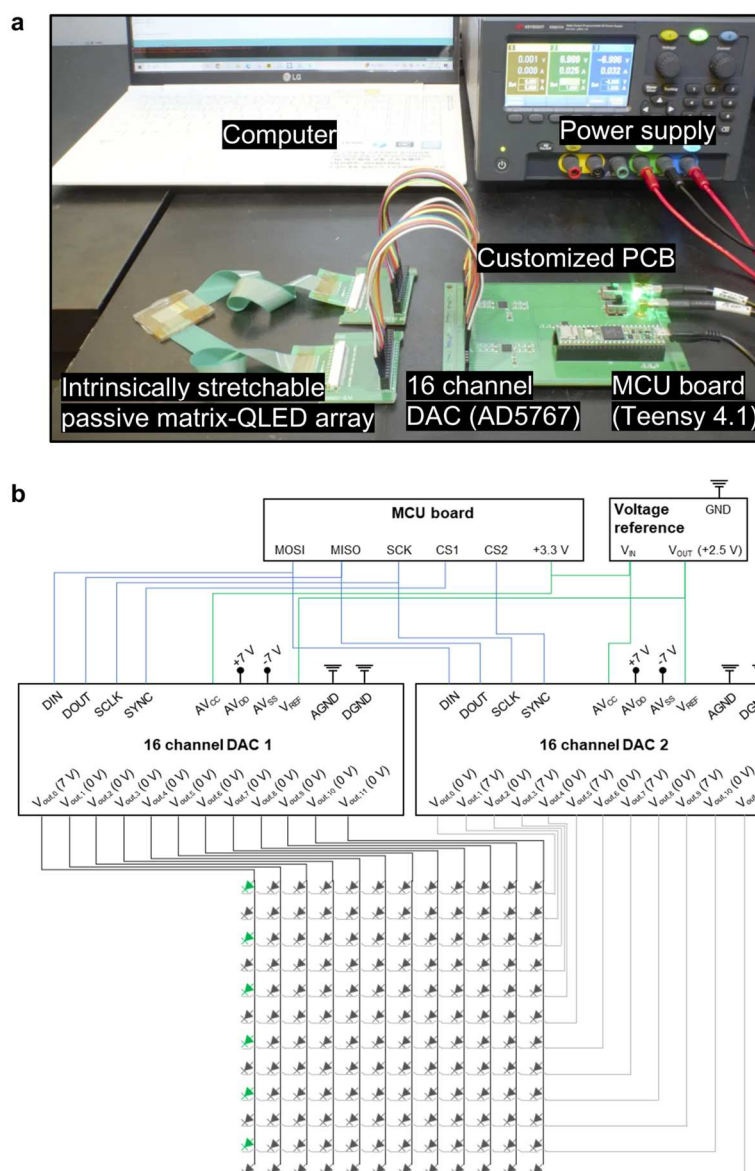
Supplementary Fig. 34 | J - V - L (left) and EQE- L (right) characteristics of intrinsically stretchable QLED fabricated by spin-coating.



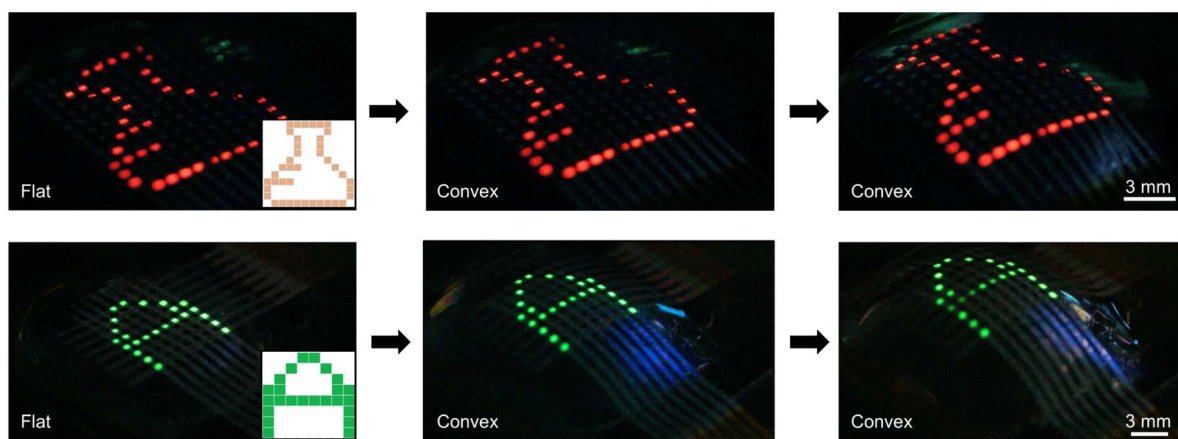
Supplementary Fig. 35 | a,b, Optical microscope images of high-resolution pattern arrays on the stamp (a) and after transfer onto the device stack (b), demonstrating preservation of pattern fidelity during device integration. The corresponding AFM image of the transferred pattern is shown to the right of panel (b).



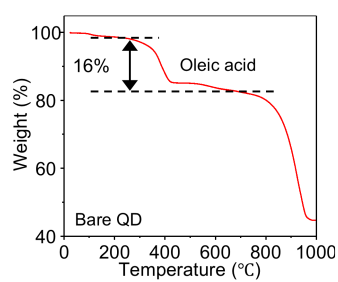
Supplementary Fig. 36 | Photographs of red-emitting (left) and blue-emitting (right) stretchable QLEDs under diagonal stretching.



Supplementary Fig. 37 | Customized setup for operation of intrinsically stretchable passive matrix QLED array fabricated via LIFT process. a, Photograph of the experimental setup used to operate the intrinsically stretchable passive matrix QLED array. **b**, Schematic diagram of the driving circuit. A customized printed circuit board integrated with microcontroller unit board (Teensy 4.1) and 16 channel digital-to-analog converter (AD5767) was used in the setup.



Supplementary Fig. 38 | Convex deformation of red and green QLED arrays, displaying beaker (top), an alphabet ‘A’ (bottom).



Supplementary Fig. 39 | Thermogravimetric analysis results of bare QD.

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