Supplementary Information for

Development of Fin-LEDs for Next-generation Inorganic Displays using Face-selective Dielectrophoretic Assembly

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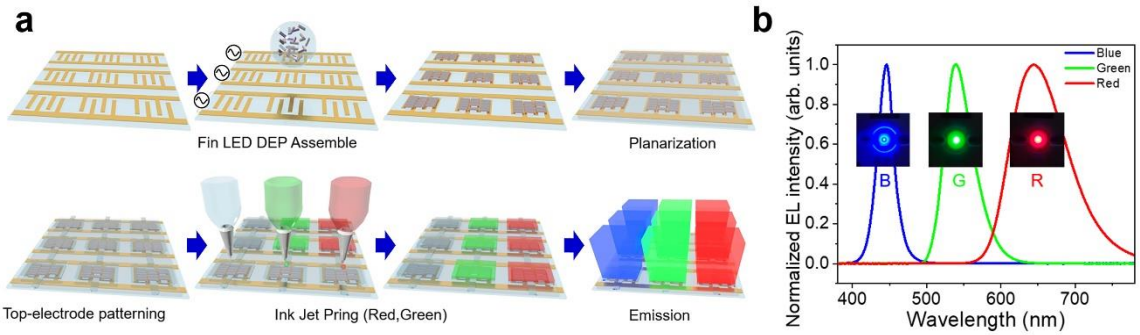
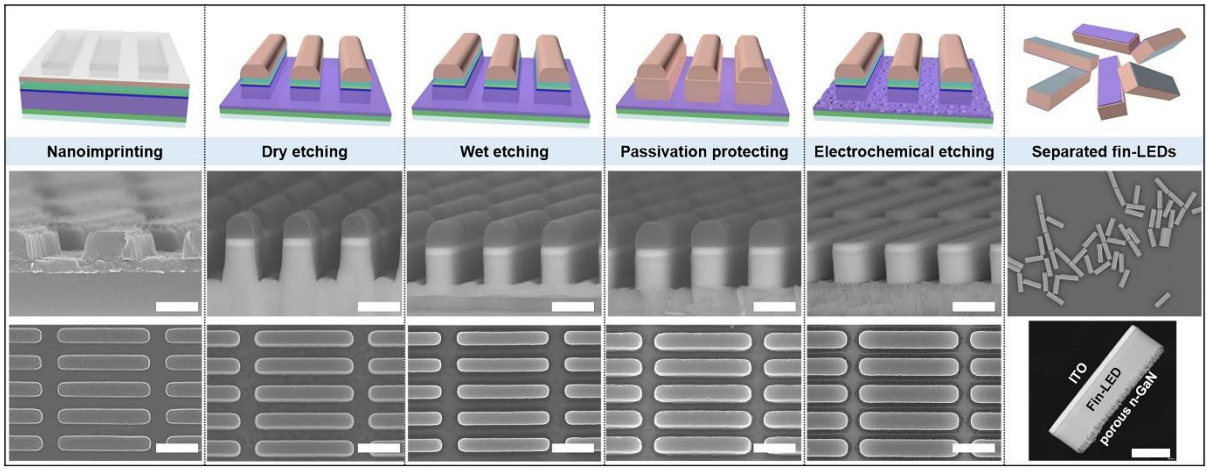


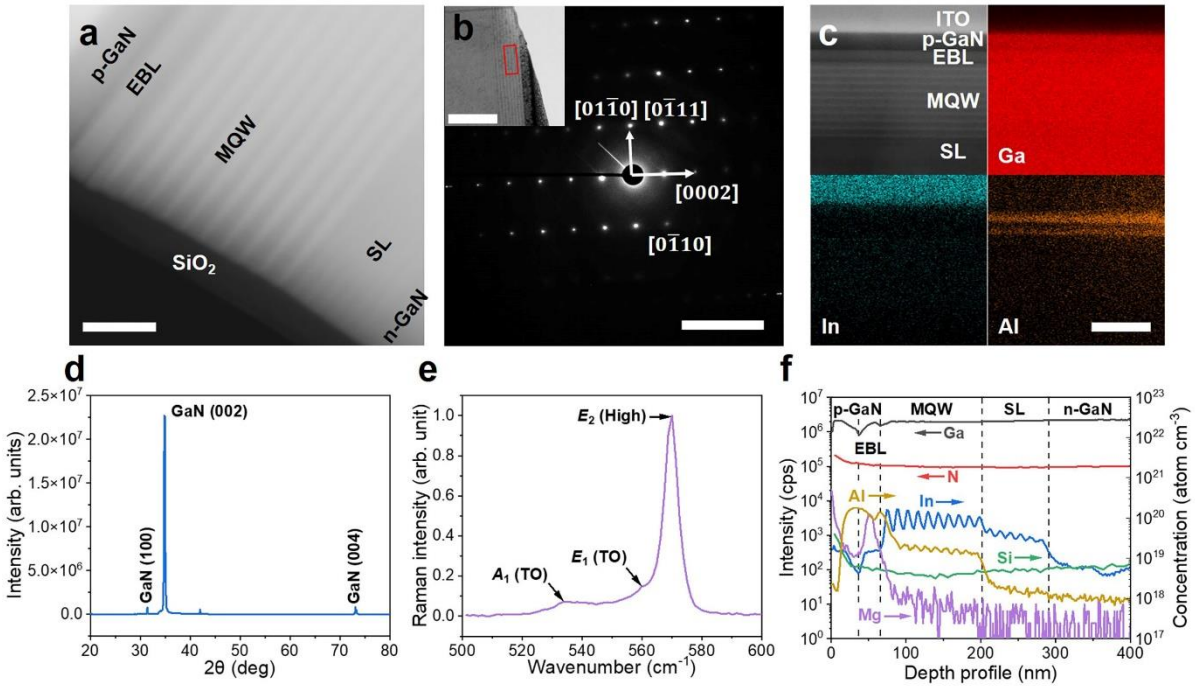
Supplementary Fig. 1 | Schematic of implementing a full-color fin-LED Display

a Schematic of full-color fin-LED display. **b** Fin-LED color conversion RGB EL spectrum (Blue: fin-LED, Green: fin-LED@InP QDs color film, Red: fin LED@R6832 phosphor color film.



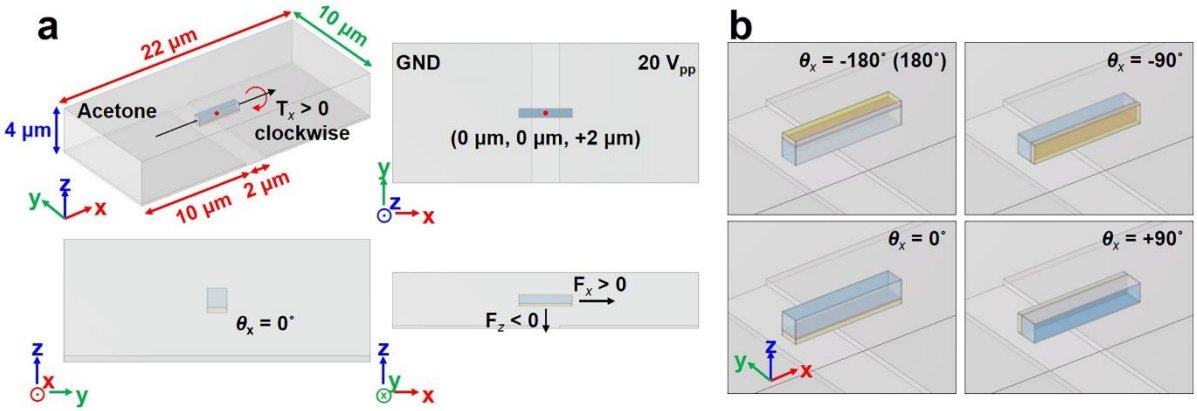
Supplementary Fig. 2 | Schematic diagram of fin-LED fabrication process

Electron microscopy images of each step of fabrication process of individually separated fin-LED. All scale bars represent 1 μm.



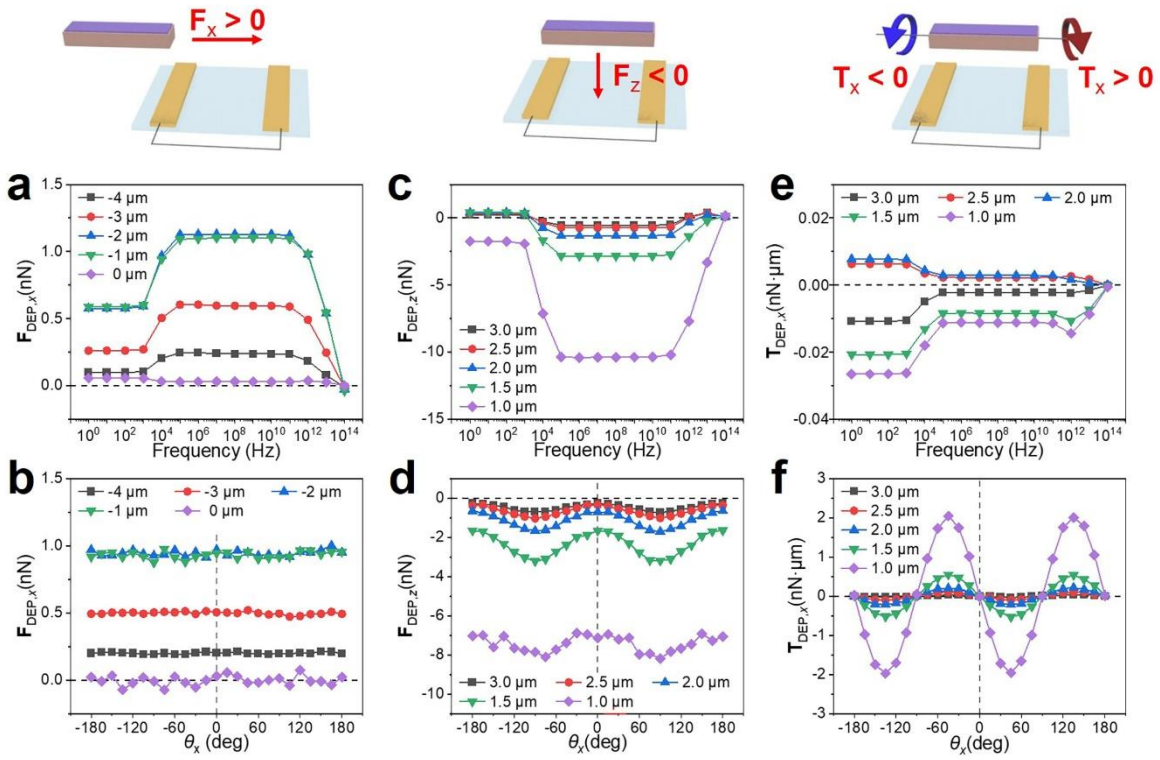
Supplementary Fig. 3 | Additional analysis data for individually separated fin-LED

a High-angle annular dark-field (HAADF)-STEM image of ITO/p-GaN/MQW/n-GaN@SiO_2 structured fin-LED. **b** Selected area electron diffraction (SAED) patterns of MQW of fin-LED. (Insect TEM image of fin-LED) **c** Energy-dispersive X-ray spectroscopy (EDX) images of fin-LED. **d** X-ray diffraction (XRD) spectrum of fin-LED. **e** Raman spectrum of fin-LED. **f** Dynamic-secondary ion mass spectroscopy (SIMS) depth profiles of fin-LED. EBL, electron blocking layer; MQW, multiple quantum well; SL, superlattice.



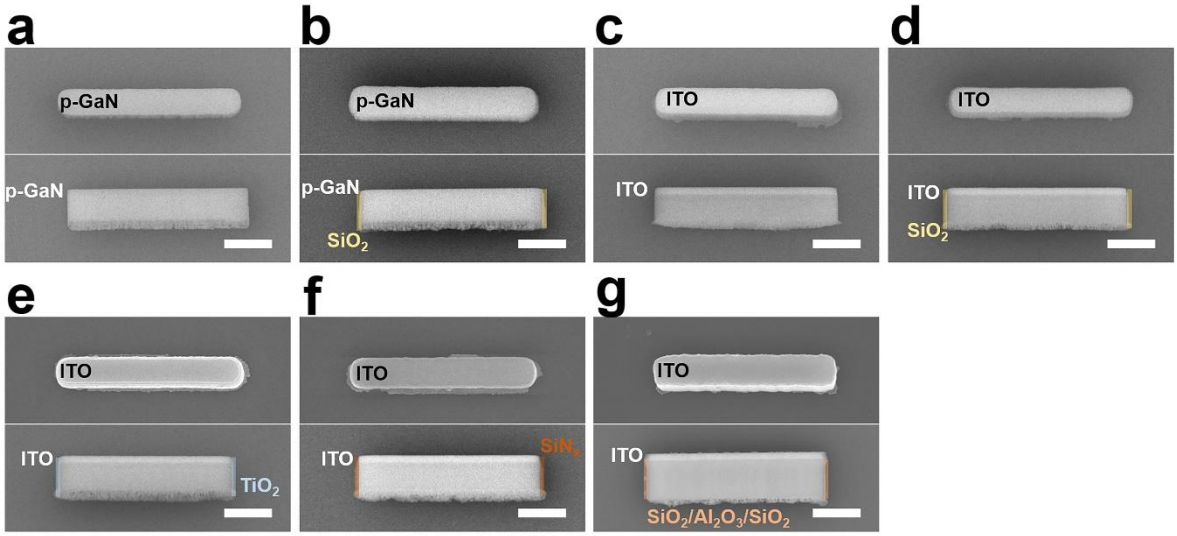
Supplementary Fig. 4 | Schematic of 3D model for finite element simulation (FEM)

a A pair of 10 μm × 10 μm electrodes were placed on the bottom with a 2 μm gap on the entire domain size of 22 μm × 10 μm × 4 μm. The center coordinates of a GaN-based light-emitting diode (LED) were arranged to be (0 μm, 0 μm, +2 μm). The remaining area except for the electrodes and LED was composed of solvent (acetone). **b** Schematic diagram according to x-axis rotation angle of the LED. It was set to 0˚ when the n-GaN was facing upward. The n- and p-GaN, ITO, and the shell layer on the side of the LED (SiO_2) are expressed in blue, red, yellow, and white, respectively.



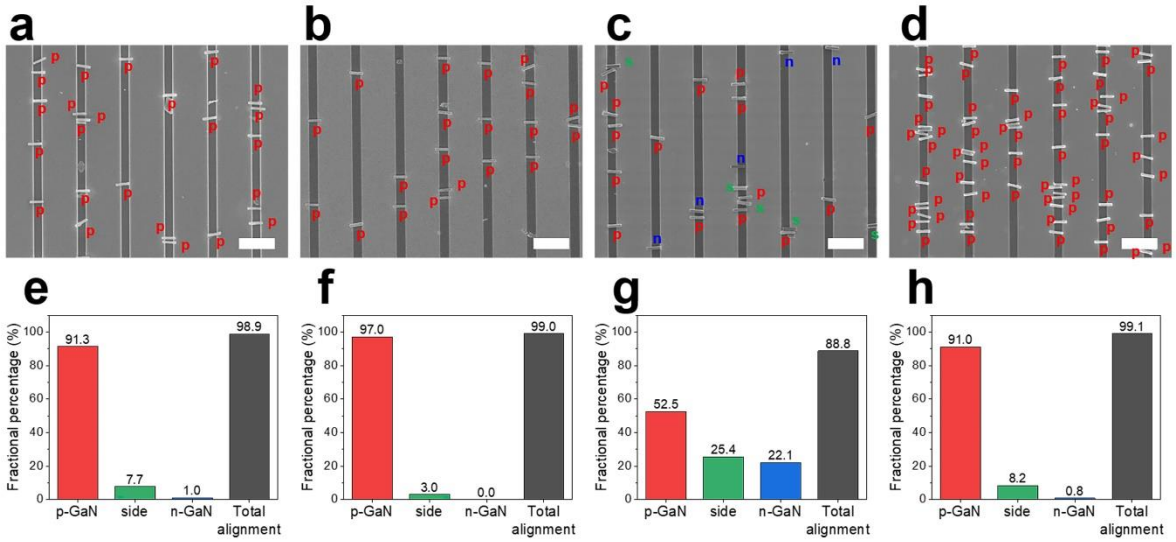
Supplementary Fig. 5 | FEM simulation results of ITO/fin-LED@SiO_2 LED

a,**b** The x-axis dielectrophoretic (DEP) force as a function of frequency of the LED with an x-angle of 0˚ and as a function of x-angle of the LED with a frequency of 10 kHz when the central coordinates of LED changed from (–4 μm, 0 μm, +2 μm) to (0 μm, 0 μm, +2 μm). **c**,**d** The z-axis DEP force as a function of frequency of the LED with an x-angle of 0˚ and as a function of x-angle of the LED with a frequency of 10 kHz when the central coordinates of LED changed from (0 μm, 0 μm, +3 μm) to (0 μm, 0 μm, +1 μm). **e**,**f** The x-axis DEP torque as a function of frequency of the LED with an x-angle of 0˚ and as a function of x-angle of the LED with a frequency of 10 kHz when the central coordinates of LED changed from (0 μm, 0 μm, +3 μm) to (0 μm, 0 μm, +1 μm).



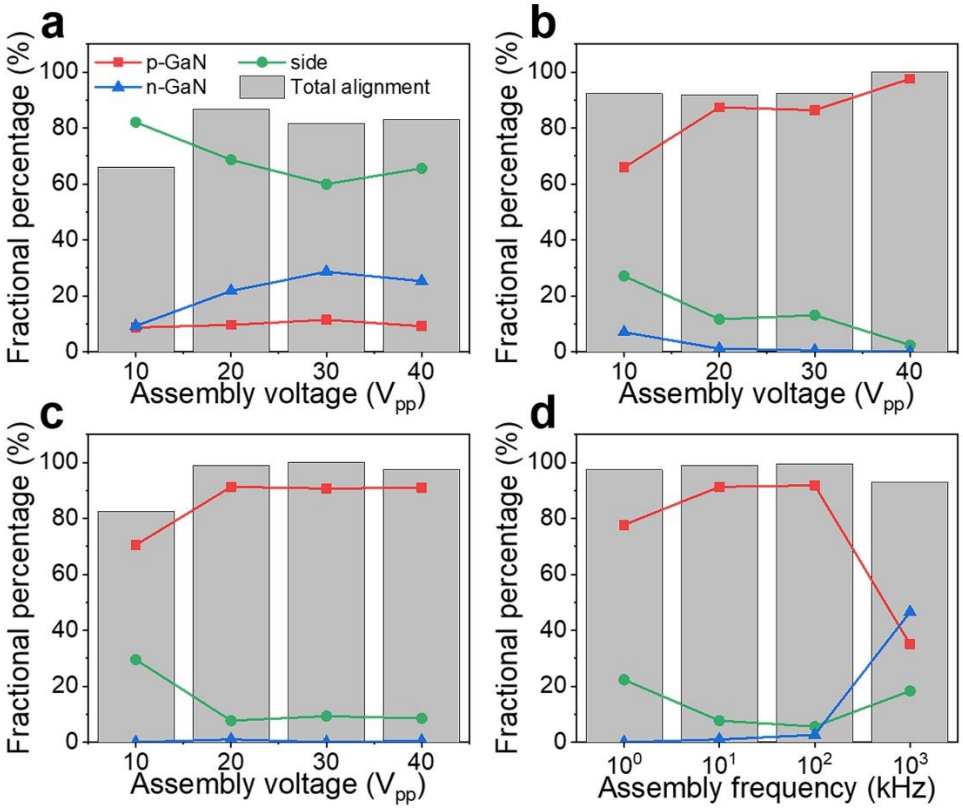
Supplementary Fig. 6 | SEM images of fin-LED with different structures

The upper images are the top view of the fin-LEDs and the lower images are the cross-sectional view of the fin-LEDs obtained in backscattered electron (BSE) mode. **a** fin-LED. **b** fin-LED@SiO_2. **c** ITO/fin-LED. **d** ITO/fin-LED@SiO_2. **e** ITO/fin-LED@TiO_2. **f** ITO/fin-LED@SiN_x. **g** ITO/fin-LED@SiO_2/Al_2O_3/SiO_2. All scale bars represent 1 μm.



Supplementary Fig. 7 | Self-assembly results of different structured fin-LED by DEP force

a–d SEM image of ITO/fin-LED@SiO_2, ITO/fin-LED@SiN_x, ITO/fin-LED@TiO_2, and ITO/fin-LED@SiO_2/Al_2O_3/SiO_2 structures. To align the fin-LEDs of all structures, a sinusoidal function with a voltage of 20 V_{pp} and a frequency of 10 kHz was applied to the electrodes. To indicate the contact surface between the fin-LEDs and electrodes, different colored letters were marked on the individual LEDs: red p, p-GaN contact; blue n, n-GaN contact; green s, side contact. All scale bars represent 10 μm. **e–h** Fractional ratio of different contact of ITO/fin-LED@SiO_2, ITO/fin-LED@SiN_x, ITO/fin-LED@TiO_2, and ITO/fin-LED@SiO_2/Al_2O_3/SiO_2 structures. All scale bars represent 10 μm.



Supplementary Fig. 8 | Fractional ratio of different ITO/fin-LED@SiO_2 with solvent

a–c Fractional ratio in hexane, isopropyl alcohol (IPA) and acetone depending on the voltage with an applied frequency of 10 kHz (sinusoidal wave function). **d** The ratio in acetone depending on the frequency with an applied voltage of 20 V_{pp}. All legends in the graphs are identical to those expressed in **a**.

a

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
A	39	39	38	41	39	40	38	40	35	36	34	32	34	32	29	36	34	31	36	32	37	29	28	18	34	30	32	37
B	36	37	32	39	44	31	29	38	33	37	34	30	32	33	30	25	30	33	31	30	32	27	28	35	33	34	36	41
C	35	37	28	30	38	36	29	29	33	34	37	34	28	33	26	25	34	32	33	32	24	33	31	33	34	34	36	46
D	28	36	33	30	30	30	29	34	33	30	35	33	26	33	27	28	33	33	33	27	28	32	33	30	33	25	30	28
E	29	34	31	29	31	32	29	35	34	30	32	30	38	27	27	30	35	33	32	37	25	29	30	27	32	29	27	33
F	36	24	40	24	27	32	28	28	33	33	39	28	24	27	36	28	28	34	27	34	23	23	29	29	27	28	28	35
G	32	29	41	30	33	29	34	27	38	34	34	26	30	30	29	33	25	32	34	32	32	33	28	29	29	35	34	35
H	36	36	30	27	38	36	22	35	29	33	31	27	26	35	22	26	32	33	34	29	22	32	29	28	34	34	32	38
I	29	31	33	34	32	35	29	29	32	36	24	33	32	28	20	30	20	32	25	27	35	34	27	28	34	33	32	29
J	27	28	30	37	32	26	32	25	34	32	35	27	24	30	30	31	27	30	35	25	27	35	35	31	35	33	35	26
K	32	27	29	25	30	29	32	25	23	21	31	33	30	28	29	29	27	36	28	32	31	24	33	35	26	36	32	42
L	35	33	25	32	27	27	27	33	29	22	26	23	23	28	32	22	29	29	30	26	28	28	25	26	29	35	36	38
M	36	32	26	31	29	31	30	38	26	28	22	23	27	29	27	30	30	30	28	34	27	30	30	32	29	30	46	36
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O	26	28	25	23	27	27	27	30	27	30	33	29	31	29	28	31	34	31	33	32	31	29	31	33	28	31	37	41
P	30	33	29	30	24	23	37	28	34	30	31	31	27	28	29	27	30	32	28	28	28	31	28	30	29	33	36	36
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R	30	31	26	33	28	25	29	30	30	32	29	28	29	29	29	32	27	30	29	29	26	31	31	27	29	40	28	27
S	32	32	32	33	28	29	28	23	34	31	27	30	27	31	27	28	35	29	25	27	28	27	28	33	29	28	33	27
T	30	29	29	30	25	26	29	30	27	32	25	32	30	27	28	30	30	26	30	32	35	29	27	33	31	28	39	30
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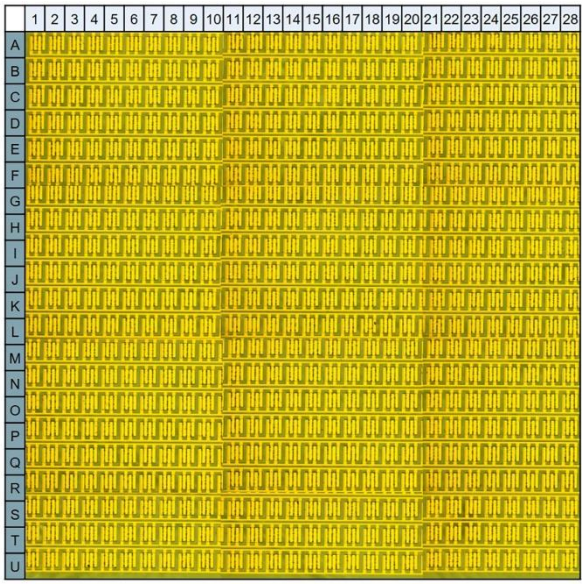

b

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A	47	43	32	38	35	34	37	28	36	37	35	33	34	33	28	36	37	36	31	33	35	31	23	31	25	32	23	41
B	37	34	32	32	30	34	33	31	29	20	20	26	33	31	34	27	28	26	43	32	42	43	27	28	31	18	20	27
C	40	22	20	11	26	39	25	23	28	25	17	26	23	22	21	36	31	26	29	25	29	31	26	32	29	23	21	37
D	28	36	31	34	23	28	20	28	24	27	28	20	27	24	27	21	35	32	40	23	36	32	35	32	25	24	26	45
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G	15	25	30	28	31	34	32	23	20	24	29	35	29	23	29	23	36	24	34	33	21	39	32	25	34	26	29	41
H	33	22	41	38	46	37	31	26	29	23	24	32	29	26	27	36	28	33	34	39	33	26	26	37	26	22	29	46
I	30	36	37	31	35	37	32	33	39	26	22	29	25	27	26	34	30	29	31	26	28	29	41	37	22	25	29	36
J	40	43	44	32	28	32	28	37	34	32	33	29	27	23	28	35	35	28	31	36	30	28	32	32	22	23	26	48
K	28	34	31	29	29	28	33	37	38	28	34	26	29	29	31	32	28	38	27	36	27	31	34	36	32	31	31	34
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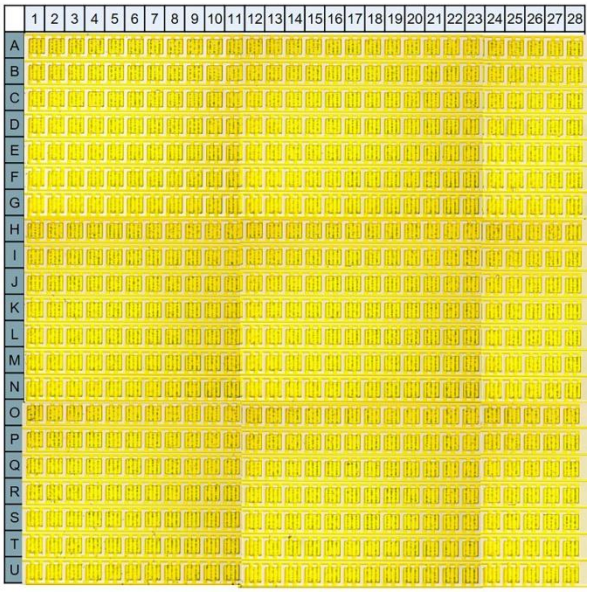

c

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C	44	40	42	33	39	30	33	29	36	40	36	26	40	35	41	34	38	44	37	34	39	35	29	33	39	38	35	33
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R	31	25	23	26	23	27	22	24	30	31	29	22	21	27	34	31	31	24	19	30	26	27	31	29	31	27	33	22
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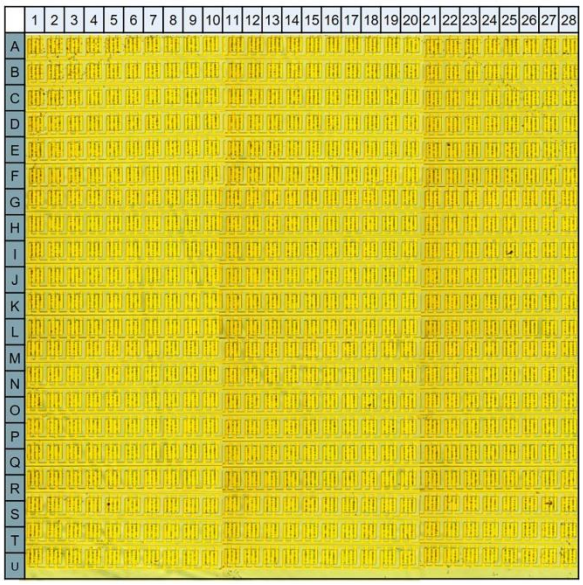

d

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B	32	39	36	30	21	23	23	32	27	36	32	36	39	32	29	26	20	32	27	45	34	32	34	43	36	36	38	47
C	31	34	24	20	23	30	27	18	25	32	26	32	25	28	33	27	29	29	30	31	29	38	29	32	31	40	33	46
D	29	27	17	29	24	24	24	19	20	23	32	21	31	22	21	21	32	35	45	36	45	52	34	29	26	27	34	50
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G	36	32	24	28	28	27	22	23	31	18	17	32	32	26	24	20	37	22	32	25	21	33	34	29	28	27	40	53
H	29	23	27	24	58	24	27	23	24	31	29	19	28	31	29	23	25	25	21	21	20	29	36	27	18	28	36	37
I	25	31	32	44	52	30	25	27	25	26	23	25	22	28	25	23	22	28	32	20	34	30	32	25	29	33	42	29
J	39	35	33	28	29	32	29	16	20	33	22	28	24	22	21	23	15	24	29	28	20	22	25	29	25	19	26	40
K	38	29	29	24	24	30	22	27	30	17	29	46	37	27	25	25	29	27	59	30	37	27	25	20	25	26	23	36
L	29	30	26	25	24	33	30	35	24	28	22	32	33	22	20	34	35	49	58	27	23	26	25	31	22	30	28	31
M	32	29	34	18	26	21	23	30	26	26	20	23	35	25	32	40	32	34	34	32	33	43	32	39	29	35	34	52
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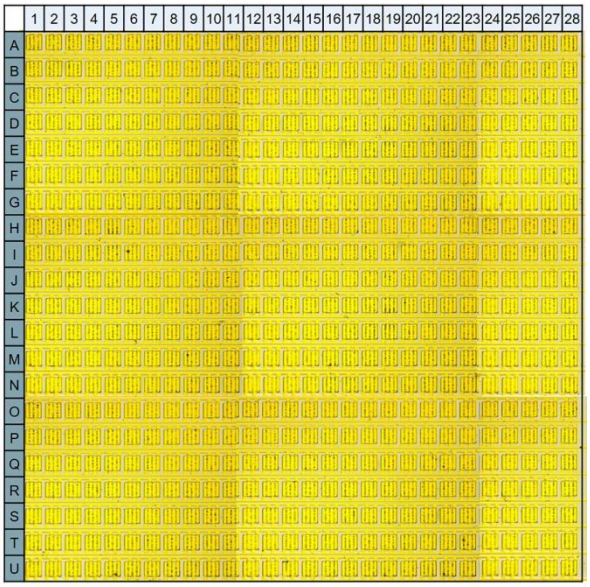
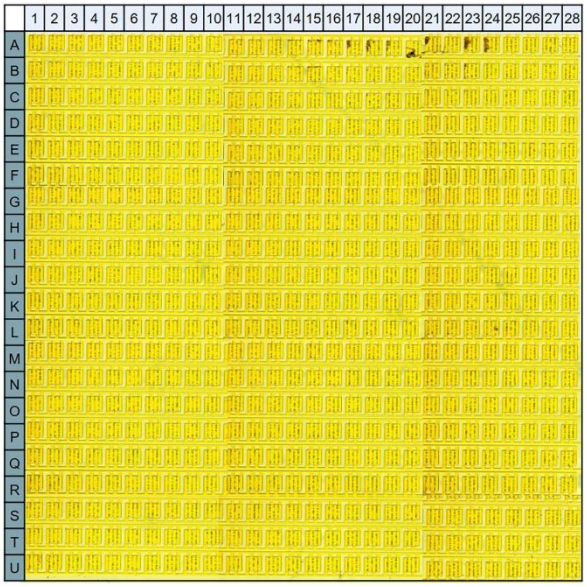
R	34	28	20	32	23	21	21	20	31	20	29	30	26	27	23	29	32	29	30	25	28	38	29	26	22	20	23	37
S	28	28	26	23	25	28	17	22	30	34	33	37	28	34	27	20	36	23	29	29	29	30	25	26	25	34	31	42
T	49	43	26	35	33	25	31	26	25	33	27	25	29	36	35	30	30	32	28	38	26	28	30	34	28	29	28	47
U	34	45	37	34	40	43	34	36	42	35	33	40	42	43	39	46	40	41	30	30	43	32	32	35	44	43	37	46

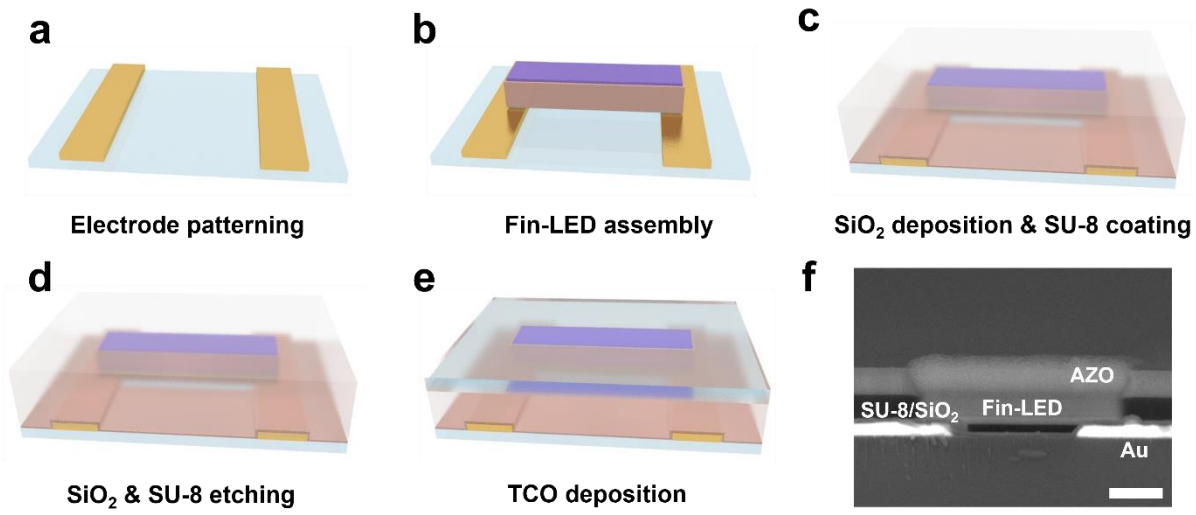


e

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
A	33	22	29	27	31	32	31	35	34	20	22	27	36	26	31	34	32	32	26	23	39	38	41	33	39	41	43	44
B	26	21	29	27	29	32	21	30	29	23	31	26	27	28	35	29	25	28	29	32	34	38	42	34	41	29	29	31
C	32	33	21	24	23	19	21	29	30	25	22	19	39	30	34	39	33	27	37	35	33	25	41	34	35	29	35	44
D	27	28	26	30	22	30	24	28	21	20	24	23	32	28	24	26	34	32	37	29	30	35	32	28	28	28	35	41
E	28	24	26	29	27	28	29	24	31	26	21	24	31	24	30	40	33	30	32	24	31	34	39	27	35	37	37	34
F	22	32	17	24	20	23	21	12	26	22	26	26	29	28	28	28	31	27	33	36	27	37	38	45	44	43	39	38
G	24	26	36	22	24	26	31	32	27	32	35	21	29	27	35	39	38	30	25	33	36	34	27	34	31	34	30	38
H	31	29	18	27	22	23	21	20	23	25	19	37	27	34	32	32	33	36	36	24	39	32	34	32	40	43	39	33
I	27	23	28	24	31	35	32	23	31	25	19	28	25	37	26	32	37	34	34	35	27	35	41	36	40	37	41	35
J	31	26	24	34	23	20	21	27	24	25	26	29	29	28	31	34	25	33	39	42	32	34	35	34	39	34	33	36
K	35	23	26	25	30	34	29	24	28	28	25	33	28	33	22	25	33	33	32	29	30	32	27	37	32	37	29	38
L	30	26	27	24	23	24	41	29	30	31	25	26	28	29	30	39	33	43	34	34	33	34	31	22	39	30	28	28
M	27	26	28	29	23	22	30	30	24	25	28	18	31	41	37	31	33	31	34	24	39	36	41	38	39	36	31	37
N	28	20	21	21	33	20	27	25	24	29	26	25	28	39	27	27	41	43	35	31	41	32	39	34	40	31	33	30
O	25	19	20	23	30	28	26	30	23	34	36	30	28	31	29	32	27	25	38	34	37	31	31	29	38	32	26	36
P	23	27	31	24	27	24	20	23	25	22	32	30	31	31	31	35	28	32	28	34	36	35	31	33	35	31	32	39
Q	25	29	27	24	25	33	27	34	28	24	26	31	27	32	28	35	27	31	29	32	30	30	40	30	33	35	31	31
R	35	35	21	18	29	17	27	21	22	30	31	22	25	23	30	27	42	33	29	27	36	33	41	40	37	33	34	36
S	29	23	39	25	27	28	30	29	32	28	25	33	34	36	29	34	23	33	29	28	36	29	35	35	43	30	35	36
T	27	24	22	24	35	28	28	25	25	33	25	32	24	32	35	31	38	29	34	32	39	33	34	36	37	34	45	33
U	31	40	33	33	25	28	32	35	42	32	27	27	33	34	34	34	36	35	39	37	37	38	46	41	41	37	47	36



Supplementary Fig. 9 | Optical microscope image of five fin-LED array devices with 588 subpixels **a** Panel-1, mean: 30.47, standard deviation (σ): 4.16. **b** Panel-2, mean: 31.06, σ: 6.40. **c** Panel-3, mean: 31.27, σ: 5.35. **d** Panel-4, mean: 30.44, σ: 7.97. **e** Panel-5, mean :30.50, σ :5.82 (Total subpixel: 2,940, Assembly accuracy: 99.93%).



Supplementary Fig. 10 | Schematics of fabrication of EL device based on the fin-LEDs

a Fabrication of electrode. **b** Fin-LEDs DEP assembly. **c** SU-8 planarization coat & SiO_2 anchor deposition. **d** TCO deposition. **e** SEM image of fin-LEDs EL Device. Scale bar represents 1 μm

Assembly	Transfer method	Chip size (μm^2)	Chip cost	Transfer Cost	Transfer speed	Transfer yield (%)	Ref
Pick up	Elastomer stamp	~1,256.00	Middle	High	1M hr^{-1}	99.50	[1,2]
	Laser	~1.00	Low~Middle	Middle~High	100M hr^{-1}	99.80	[1,2]
Fluidic assembly	Wave energy	~1,256.00	Middle	Middle	NR	97.00	[3]
	Gravity and capillary force	~1,256.00	Middle	Middle	1M hr^{-1}	99.90	[4]
	Vander walls force	1,256.00	Middle	Middle	54K hr^{-1}	99.99	[5]
	Molten solder	706.50	Middle	Middle	1M hr^{-1}	99.88	[6]
	magnetic-force-assisted dielectrophoretic self-assembly technology	~980.20	Middle	Middle	NR	99.50	[7]
	Dielectricphoresis	~0.19	Low	Low	NR	99.98	[8~13]
		2.80	Low	Low	1M hr^{-1}	99.93	Our works

Supplementary Table 1 | Comparison for micro-LED mass transfer method

Volume (μm^2) Shape	Area of MQW (μm^2)	Orientation selective ratio (%)	Aligned direction	Wavelength (nm)	Brightness ($cd\ m^{-2}$)	EQE (%)	Ref
0.49, rod	0.20	NR	Horizontal	515	2,130 (20V)	NR	[8]
0.66, rod	0.23	74.4	Horizontal	515	NR	NR	[9]
0.97, rod	0.22	NR	Horizontal	448	NR	8.9~20.2	[10]
1.32, rod	0.26	NR	Horizontal	445	NR	9	[11]
1.32, rod	0.26	NR	Horizontal	460-464	NR	19.6~22.2	[11]
2.36, rod	0.50	NR	Horizontal	440	NR	2.6	[12]
7.64, rod	1.79	NR	Horizontal	445	NR	NR	[13]
0.86, dot	0.79	NR	Vertical	448	1,070.40 (10 V)	6.21	[14]
2.17, fin	2.28	91.3	Vertical	448	8,640 (5 V)	9.1	Our works

*NR Non-reported

Supplementary Table 2 | Comparison for micro-LED electric properties in sizes below 10 μm^2

	Dielectric constant (ε_0)	Electrical conductivity (S m^{-1})	Reference
n-GaN	8.9	20×10^3	[7]
p-GaN	8.9	2.38×10^{-3}	[15]
ITO	3.2	10^6	[15]
SiO_2	3.9	1×10^{-12}	[16]
Acetone	20.7	20×10^{-6}	[17]

Supplementary Table 3 | Physical properties of materials used in FEM simulation

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