Supplementary information

Conformal ALD of tin-doped indium oxide transparent p-ohmic contacts for micro- and nano-LEDs

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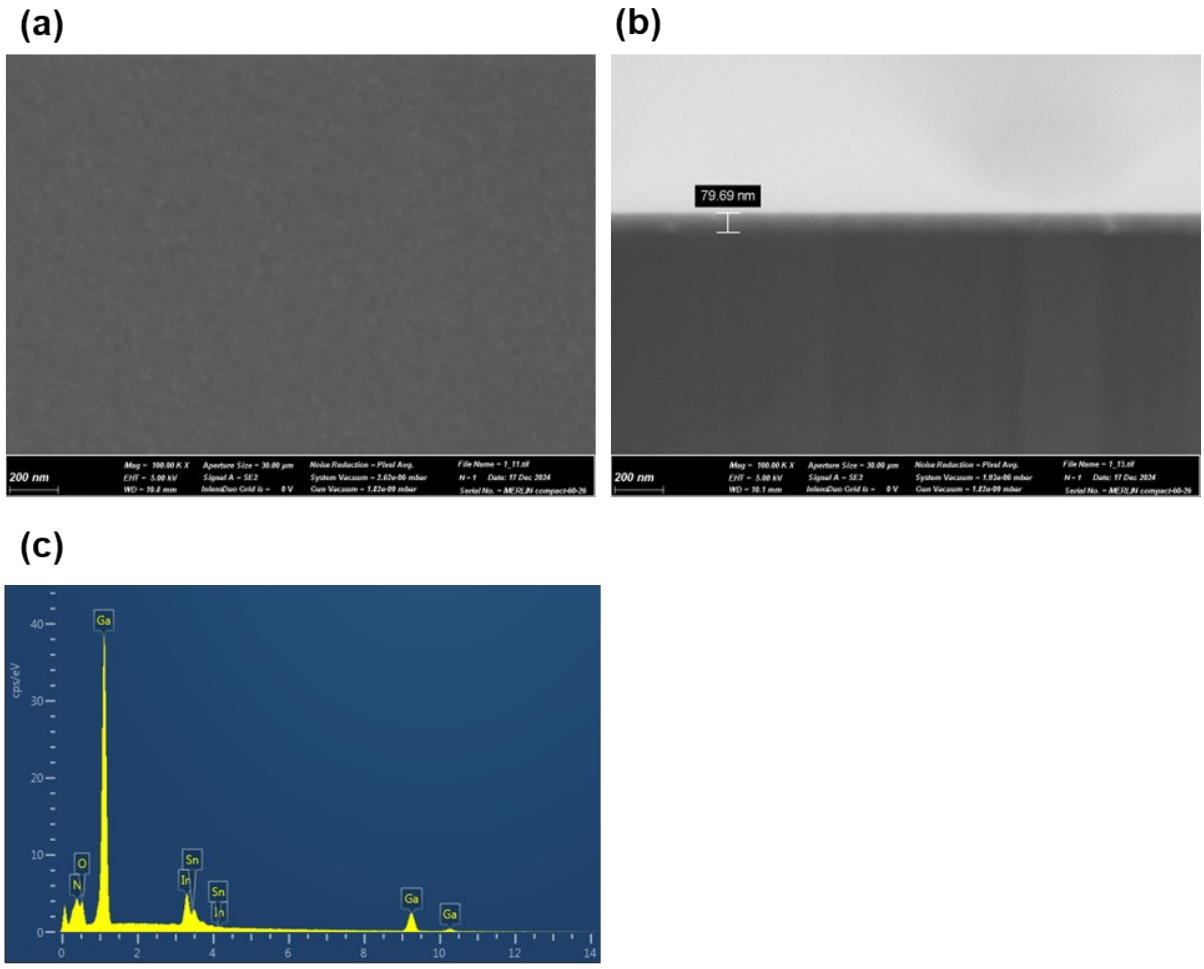


Fig. S1 SEM images of ALD-deposited ITO/In_2O_3 on a p-GaN substrate: (a) plan view, (b) cross-sectional view, and (c) SEM-EDS spectra corresponding to a point in (a).

Table S1. The quantitative analysis of the SEM-EDS point analysis.

	Apparent concentration	Wt%	Wt% sigma	Atomic%	Line
N	46.83	14.17	2.00	40.06	K series
O	10.73	7.97	0.43	19.73	K series
Ga	74.45	60.09	1.46	34.11	L series
In	24.96	16.15	0.51	5.57	L series
Sn	2.24	1.61	0.39	0.54	L series
Total		100.00		100.00	

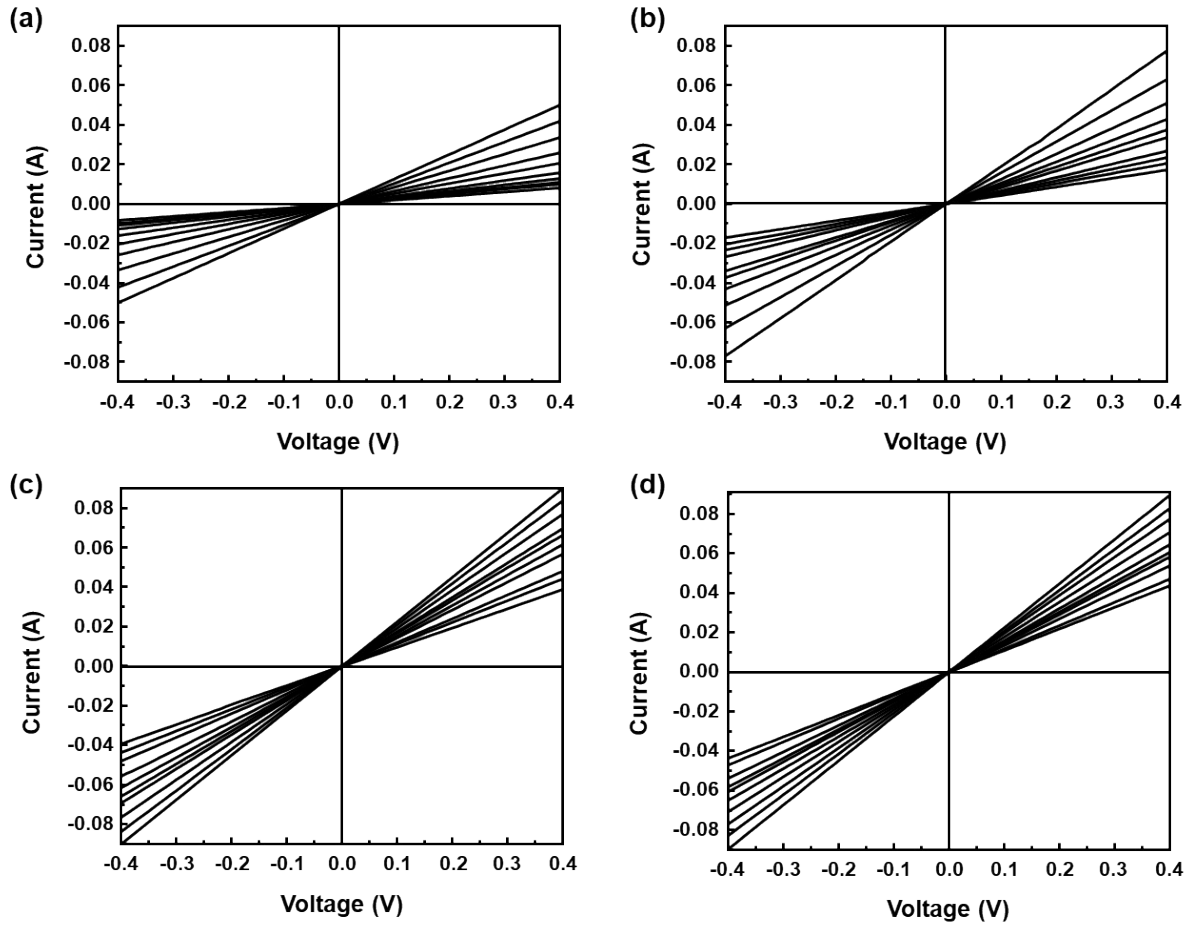


Fig. S2 *I-V* plot of CTLM measurements for (a) pristine, (b) 400 °C, (c) 500 °C, and (d) 600 °C annealed ITO on p-GaN with increasing gap sizes.

Table S2. CTLM extracted sheet resistance, and effective specific contact resistivity

	Sheet resistance R_s (Ω/sq)	Effective specific contact resistivity $\rho_{c,\ effective}$ (Ω·cm^2)
Bare	351	1.8×10^{-3}
400	140	5.6×10^{-4}
500	38.4	5.5×10^{-5}
600	27.9	2.8×10^{-5}

Table S3. Fringe constant of UV-Vis transmittance spectra for PEALD ITO and bilayer ITO on GaN/sapphire.

	PEALD ITO	**Bilayer ITO**
GaN	0.0745	0.0852
Pristine	0.0614	0.0685
400 °C	0.0614	0.0664
500 °C	0.0578	0.0662
600 °C	0.0558	0.0620

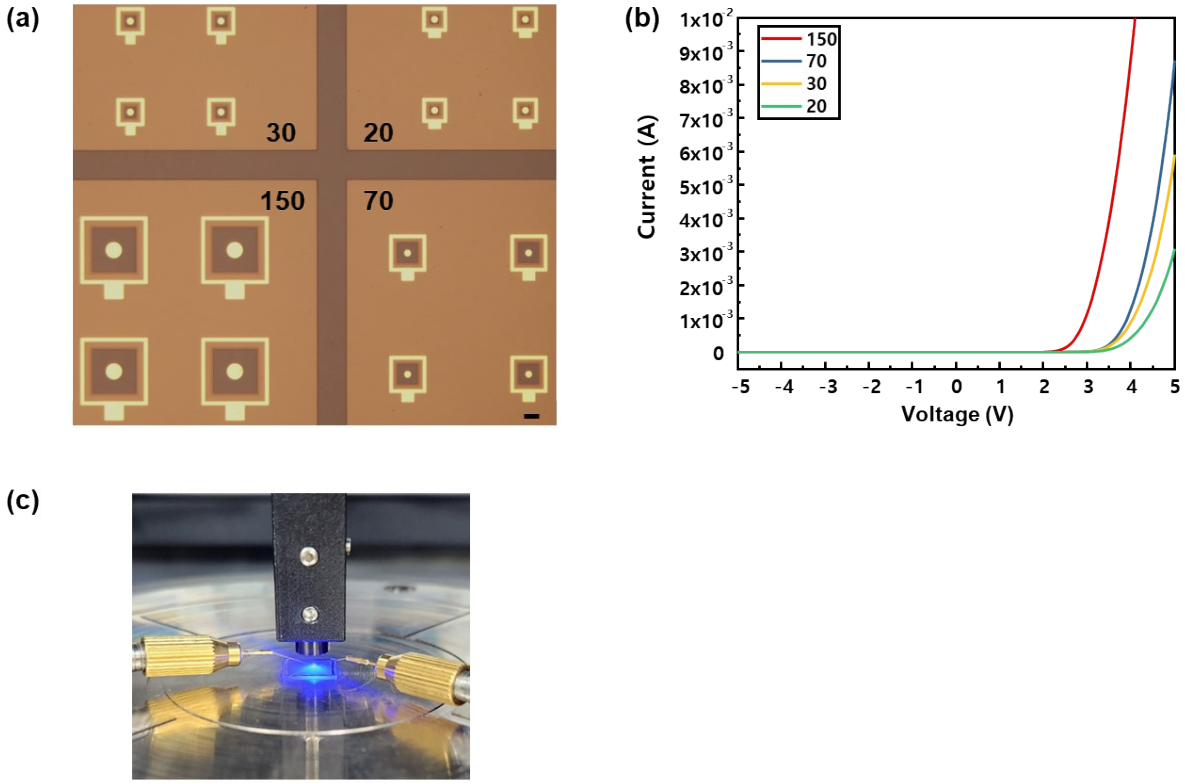


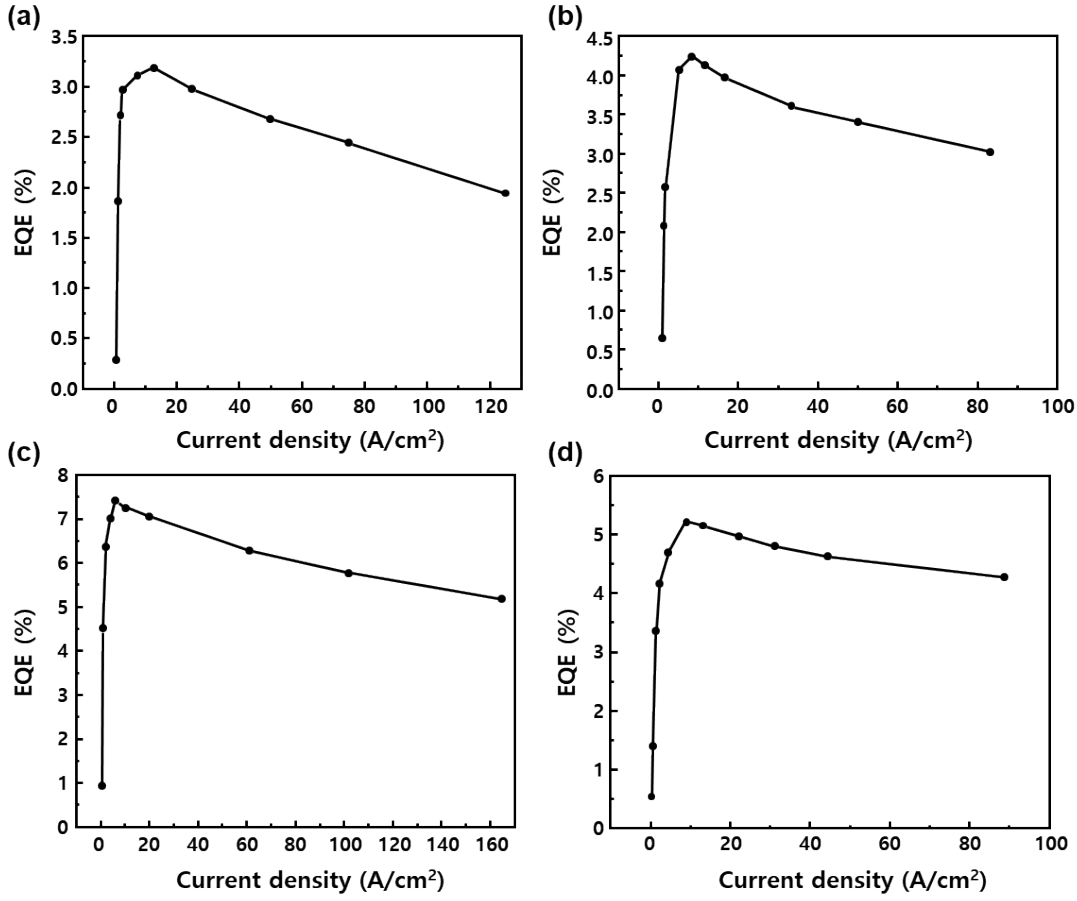
Fig. S3 (a) OM image of the micro-LEDs with dimensions of 30 × 30 μm^2, 20 × 20 μm^2, 150 × 150 μm^2, and 70 × 70 μm^2. The scale bar indicates 50 μm. (b) *I-V* characteristics of the micro-LEDs measured without compliance current. (c) Optical image of EL probestation system with electroluminescence from a micro-LED device.

Supplementary Note 1. External quantum efficiency calculation

EQE is defined as the ratio of the number of photons emitted per second to the number of electrons injected into the LED per second. EQE was determined by measuring the luminosity power (P_{out}) with a fiber-optic spectrometer connected to a photometer, and a source measure unit:

$$EQE = \frac{P_{out}}{P_{in}} \times \frac{hc}{e\lambda} \quad (1)$$

where h is Planck's constant, c is the speed of light, e is the elementary charge, and λ is the wavelength of the emitted light. P_{in} is the electrical input power, calculated as the product of voltage



and current**.**

Fig. S4 External quantum efficiency (EQE) of the micro-LEDs with dimensions of (a) 20 × 20 μm², (b) 30 × 30 μm², (c) 70 × 70 μm², and (d) 150 × 150 μm².

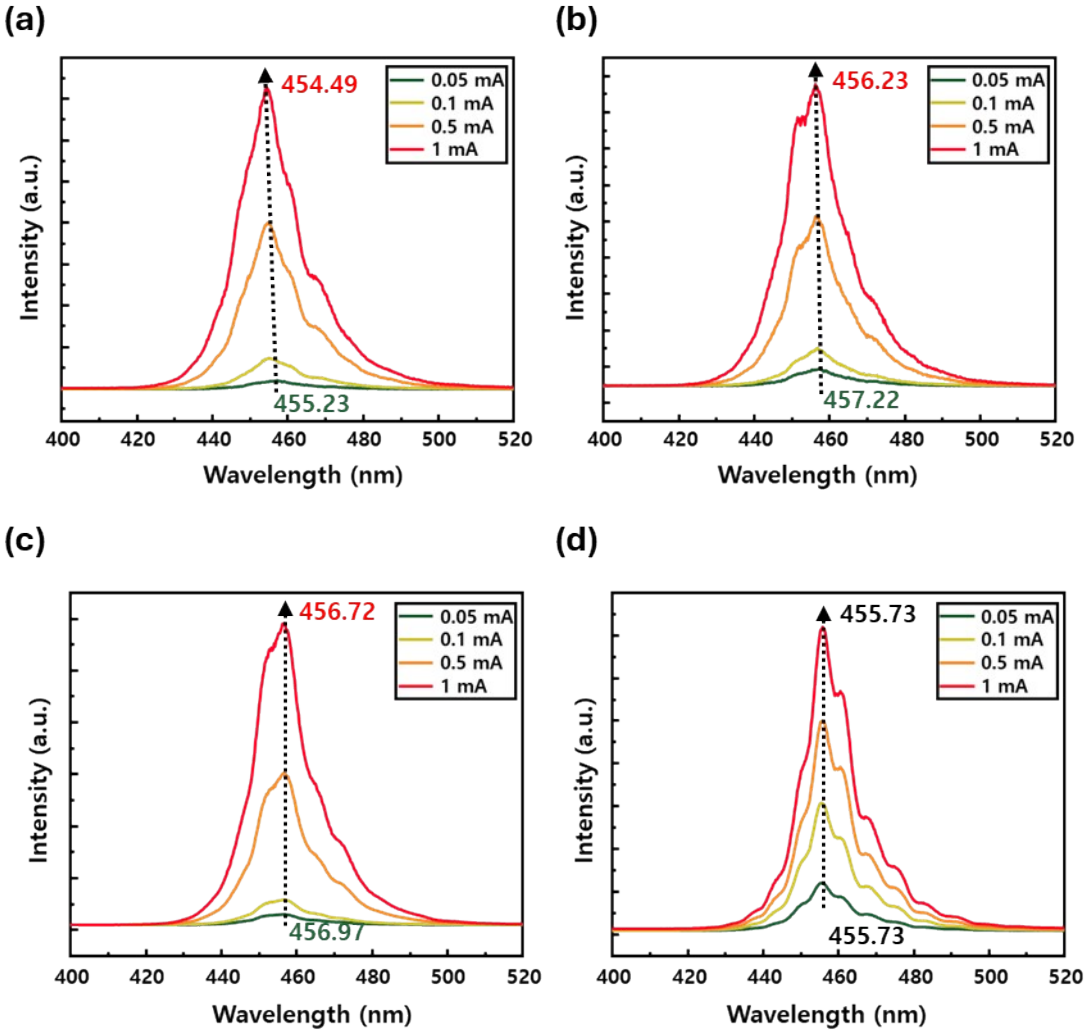


Fig. S5 EL spectrum of the micro-LEDs with dimensions of (a) 20 × 20 μm^2, (b) 30 × 30 μm^2, (c) 70 × 70 μm^2, and (d) 150 × 150 μm^2.

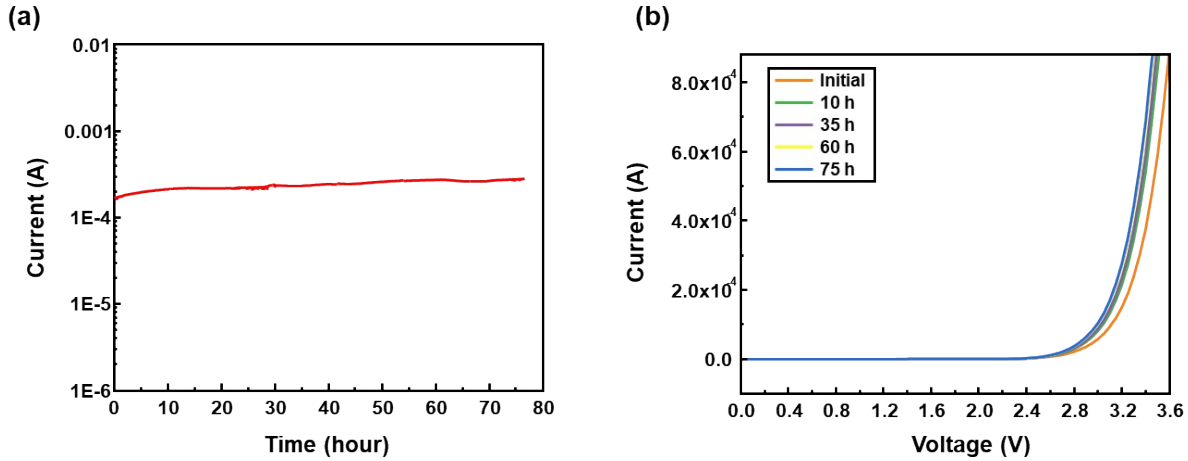


Fig. S6 Constant voltage stress (CVS) analysis of the bilayer ITO contact under 3.2 V for 76.5 h. (a) Time-dependent current evolution. (b) *I-V* curves measured after 10, 35, 60, 75 h.