

Suppression of electrical crosstalk in 6047 pixel-per-inch ultrahigh-resolution white tandem organic light-emitting diodes on silicon via a trench structure

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Abstract

Interpixel electrical crosstalk caused by lateral leakage current remains a key challenge in high-resolution organic light-emitting diodes (OLEDs) displays, leading to severe color distortion in full-color panels. In this study, a trench structure incorporated into a 6047 pixel-per-inch (PPI) stripe-based high-resolution pixel structure is demonstrated to effectively suppress electrical crosstalk in top-emitting white tandem OLEDs on silicon. The trench deeply etches the insulating layer between bottom electrodes, substantially increasing the effective path length of lateral leakage current. In addition, cross-sectional transmission electron microscopy revealed that the organic layer of tandem OLEDs on the trench sidewall was approximately seven times thinner than that on the pixel electrodes, increasing the sheet resistance; this was further supported by simulations. Consequently, the lateral leakage current was reduced by more than sevenfold in the 6047 PPI pixel structure with tandem OLEDs. Furthermore, two-dimensional spectroradiometer measurements show that light leakage into adjacent off-state pixels was reduced from approximately 13–15% to approximately 2% relative to the active pixel luminance, in excellent agreement with the reduction in lateral leakage current. These results demonstrate that the trench structure provides an effective strategy for suppressing lateral leakage current and improving color fidelity in high-resolution OLED displays.

Keywords OLED · Tandem · Crosstalk · Lateral leakage · OLEDoS · Trench

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Introduction

Following the growing interest in augmented reality (AR) and virtual reality (VR) devices^{1–3}, active research and development efforts have been expended on high-resolution display technologies that are essential for their realization. Extremely high luminance and resolution are required to enhance the immersion in AR/VR applications^{4–7}. Furthermore, self-emissive displays, such as organic light-emitting diodes (OLEDs), are advantageous over non-emissive displays, such as liquid crystal displays, for achieving superior image quality⁸.

To realize high-resolution OLED displays, silicon (Si) substrates with complementary metal–oxide–semiconductor backplanes are typically used instead of traditional glass substrates with thin-film transistor backplanes^{9–11}. Owing to the opacity of Si substrates, a top-emission structure is employed instead of a bottom-emission structure, and this structure can maximize the aperture ratio^{12,13}. As OLEDs are primarily composed of organic materials, tandem structures have recently been adopted to ensure high luminance and operational stability^{14–18}. A tandem structure consists of vertically stacked OLED units separated by a charge generation layer (CGL) that supplies holes and electrons to the adjacent units¹⁹. This CGL typically comprises a bilayer structure of p- and n-type doped layers and exhibits considerably higher conductivity than other general organic layers^{20–23}.

As the pixel density of high-resolution display panels increases, the pixel dimensions decrease, and the inter-pixel spacing narrows continuously. This results in pixel-to-pixel crosstalk issues that are not commonly observed in conventional display panels^{24,25}. This crosstalk causes color distortion and a reduction in the color gamut^{26,27}. Pixel-to-pixel crosstalk can be considered as both optical and electrical crosstalk. Electrical crosstalk arises when the lateral leakage current flows despite the application of a vertical electric field; this phenomenon becomes more probable as the interpixel spacing decreases^{28–30}. This issue is particularly exacerbated in tandem structures owing to the high conductivity of the CGL³¹.

Addressing the electrical crosstalk in tandem structures is critical yet challenging. Recent studies have indicated that the conductivity of the organic layers is a dominant factor influencing electrical crosstalk²⁷. Based on this, methods such as adjusting the doping concentration or thickness of the p- or n-type doped layers in the CGL have been attempted to mitigate the lateral leakage current. However, these approaches often suffer from poor reproducibility and can degrade the overall performance of the tandem device.

In this study, we propose the application of a trench structure within the pixel architecture to resolve these issues. We fabricated a substrate capable of analyzing electrical crosstalk based on a red (R), green (G), and blue (B) stripe configuration with a pixel density of 6047 pixel-per-inch (PPI) that—to the best of our knowledge—represents the highest density reported to date. By inserting a trench structure with deep valleys between the pixel electrodes, we realized tandem OLEDs without altering the CGL properties. Tandem OLEDs with a trench structure exhibit a drastic reduction in lateral leakage current compared with those on planar substrates. We analyzed the reduction in light leakage caused by current leakage using a two-dimensional (2D) spectroradiometer to measure the luminance relative to the distance from the emitting-pixel. Furthermore, the structural impact of the trench on the device thin films was verified using focused ion beam transmission electron microscopy (FIB-TEM) and simulations.

Results and discussion

To investigate electrical crosstalk, we designed and fabricated a test element group on a Si wafer, as shown in Fig. 1a. Each element consisted of pixel arrays, and the bottom electrode was designed as a multifinger-type structure to examine the lateral leakage between adjacent pixels, as shown in Fig. 1b. One type of pixel size was $1.4\ \mu\text{m} \times 4.2\ \mu\text{m}$ for RGB stripe structure, and another was $2.1\ \mu\text{m} \times 2.1\ \mu\text{m}$ for pentile structure, as shown in Fig. 1c, d, respectively. For the RGB stripe structure, the active emission area, inter-pixel gap, and fence width surrounding the bottom electrode were $3.5\ \mu\text{m} \times 0.7\ \mu\text{m}$, $0.7\ \mu\text{m}$, and $0.1\ \mu\text{m}$, respectively, whereas for the pentile

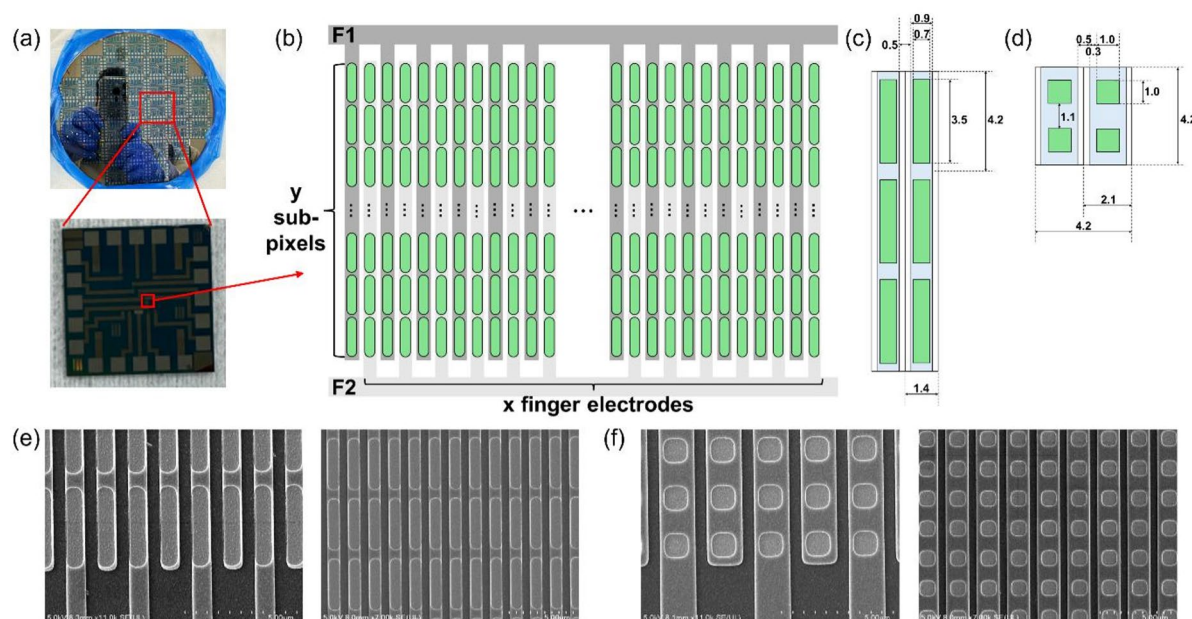


Fig. 1 Fabricated test element group. **(a)** Fabricated Si wafer and die with pixel circuit image used for the investigation of the electrical crosstalk, **(b)** schematic circuit structure with finger electrodes, dimension (μm scale) of **(c)** stripe and **(d)** pentile structures, SEM images of finger electrode with **(e)** stripe and **(f)** pentile structures.

structure, these dimensions were $1.0\ \mu\text{m} \times 1.0\ \mu\text{m}$, $1.1\ \mu\text{m}$, and $0.3\ \mu\text{m}$, respectively. The fill factor of the stripe and pentile structure were 41.6% and 22.7%, respectively, and the pixel density of these dimensions was 6047 PPI. Because the RGB stripe structure exhibits a higher fill factor at an equivalent pixel density, it is more advantageous than the pentile structure regarding luminance and aperture ratio. Figure 1e, f show scanning electron microscope (SEM) images of the finger electrodes fabricated on a Si wafer with stripe and pentile structures, respectively. The dimensions of the fabricated pixel electrodes were almost identical to those of the designed specifications. Minor patterning deviations are typically inevitable owing to the alignment tolerance of the i-line stepper and the process tolerance of the etching step.

Three driving conditions were used, as illustrated in Fig. 2a. In the “OLED (O)” driving condition, the driving voltage was applied to the F1 electrodes while the F2 electrodes were in the floating state, and the top cathode was in the ground state. In the “Lateral (L)” driving condition, the driving voltage was applied to the F1 electrodes while the F2 electrodes were in the ground state, and the top cathode was in the floating state. In the “OLED+Lateral (O+L)” driving condition, the driving voltage was applied to F1 while the F2 electrodes and top cathode were in the ground state. Five different pixel arrays, namely E1, E2, E3, E4, and E5, were designed and used for electrical crosstalk analysis. E1, E3, E4, and E5 were stripe structure, whereas E2 was a pentile structure. As the pixel array scales up, the number of constituent pixels increases, thereby multiplying the potential pathways for the lateral leakage currents. To elucidate how these factors influence electrical crosstalk, we analyzed the device characteristics as a function of the pixel array size. The number of pixel arrays of E1, E2, E3, E4, and E5 were 90×30 , 120×60 , 180×60 , 270×90 , and 360×120 , respectively. Blue fluorescent OLEDs were fabricated on these pixel arrays. The device structure is shown in Fig. S1 in the supplementary information. Three different driving conditions were applied to the pixel array. Figure 2b shows the current density–voltage (J – V) characteristics of the devices under O driving condition. All devices exhibited a low current density below 2.5 V and the current density increased rapidly thereafter; these constitute characteristic features of a typical OLED J – V curve. The E2 array, with a pentile structure, exhibited the lowest current density. For pixel arrays with the same stripe structure, the current density typically exhibited an increasing tendency as the number of pixel arrays increased. For example, the current density of the pixel arrays E1, E2, E3, E4, and E5 are $17.40\ \text{mA}/\text{cm}^2$, $10.74\ \text{mA}/\text{cm}^2$,

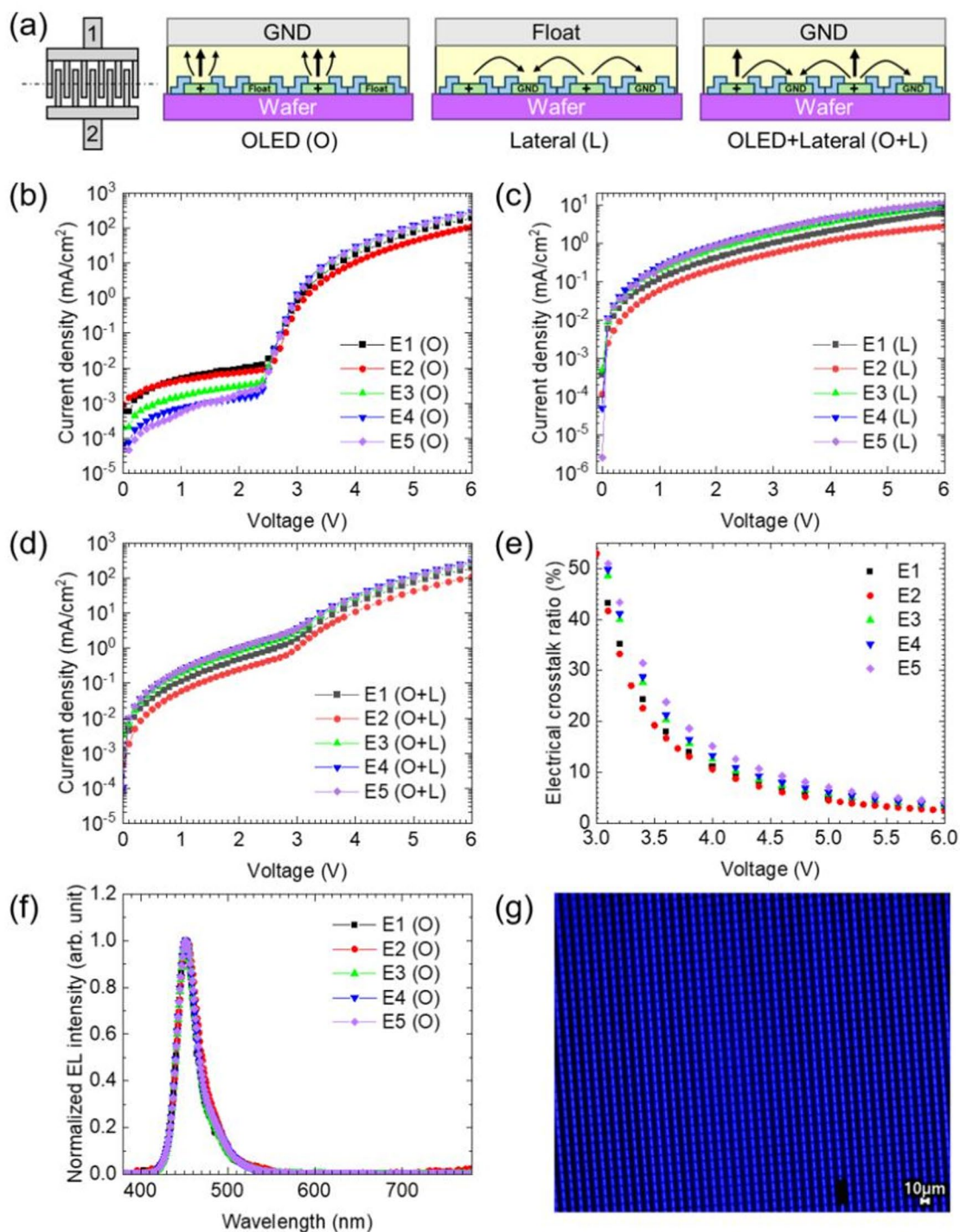


Fig. 2 Device characteristics of blue OLEDs with different pixel dimensions and array numbers. **(a)** Schematic cross-sectional structure of finger electrodes with different driving conditions, $J-V$ characteristics of **(b)** O driving condition, **(c)** L driving condition, **(d)** O+L driving condition, **(e)** electrical crosstalk ratios, **(f)** EL spectra, and **(g)** optical microscope image of 6047 PPI stripe structure pixels of blue OLEDs.

26.11 mA/cm², 30.40 mA/cm², and 26.64 mA/cm² at 4 V, respectively. Under the L driving condition, the current density increases as the driving voltage increases, as shown in Fig. 2c, implying the existence of a lateral current. The current densities of E1, E2, E3, E4, and E5 were 2.06 mA/cm², 1.17 mA/cm², 3.52 mA/cm², 4.35 mA/cm², and 4.48 mA/cm² at 4 V, respectively. E2 exhibited the lowest lateral current among them because the distance between the bottom electrodes was 1.1 μm, which was longer compared with that of the device with a stripe pixel structure which had a distance between the bottom electrodes equal to 0.7 μm. The current density increased as the number of pixel arrays increased in devices E1, E3, E4, and E5, which had the same stripe structure. In the O+L driving condition, all devices yielded a higher current density than that of the O driving condition in the low driving voltage region, which was below 2.5 V, as shown in Fig. 2d. In addition, the sum of the current densities under the O and L driving conditions was similar to that under the O+L driving condition. For instance, the current densities of E1, E2, E3, E4, and E5 were 18.51 mA/cm², 10.99 mA/cm², 28.06 mA/cm², 32.78 mA/cm², and 29.61 mA/cm² at 4 V, respectively. Electrical crosstalk ratios were calculated from the measured current densities, as shown in Fig. 2e²⁷. The E2 device exhibited the lowest electrical crosstalk ratio, and the electrical crosstalk ratio increased as the number of pixel arrays increased. Moreover, the electrical crosstalk ratio decreased considerably as the driving voltage increased. Consequently, the distance between the bottom electrodes and the number of pixel arrays are significant factors in determining electrical crosstalk in high-resolution OLED displays. Figure 2f shows the electroluminescence (EL) spectra of devices under the O driving conditions. All devices exhibited the same typical blue EL spectra with a 451 nm main emission peak and 27 nm full-width-half-maximum, regardless of the pixel type and the number of pixel arrays. Blue pixels with 6047 PPI stripe structure emitted blue light, as shown in Fig. 2g. This result indicates that finger-type test element group structure is an effective platform for analyzing electrical crosstalk without color distortion.

These results indicate that the electrical crosstalk can be a critical issue in high resolution pixel structure with typical single OLEDs. RGB stripe pixel structures with tandem OLED can impose extremely stringent conditions on high-resolution displays under which electrical crosstalk is practically unavoidable. To resolve this issue, a trench structure was employed for the 6047 PPI pixel structure, as shown in Fig. 3a. In conventional pixel structures, the gaps between the bottom electrodes are filled with insulating materials such as SiO₂ as shown in Fig. S2a, b in the supplementary information, which allows lateral leakage currents to flow relatively easily. In contrast, the trench structure etches deeply into the SiO₂ layer between the bottom electrodes, thereby increasing the effective path length for lateral current flow. Furthermore, the trench structure can affect the thicknesses of various functional layers in OLEDs. The fabrication process for the 6047 PPI stripe pixel structures with trenches and OLEDs is shown in Fig. S3 in the supplementary information. Compared with the fabrication process of the pixel structure without trenches, only one additional step—SiO₂ etching—is incorporated into the entire sequence for trench formation. In other words, the trench-structure process proposed in this work is highly compatible with the existing fabrication process without requiring additional photomasks, despite a slight increase in fabrication cost and processing time. Top-emitting white tandem OLEDs with blue fluorescent emitting layer (EML), green and red phosphorescent EMLs, and CGLs composed of p- and n-type doping layers were employed in the trench pixel structure, as shown in Fig. 3b. To investigate the multilayered trench structure, cross-sectional FIB-TEM images were obtained, as shown in Fig. 3b. Narrow trench architectures were successfully patterned, and multilayers, which were organic layers, Mg:Ag top electrodes, a capping layer (CPL), and thin film encapsulation (TFE) layers are deposited as designed. The depth of trench is 472.99 nm, as shown in Fig. 3b. In the gaps between the bottom electrodes, the thicknesses of the organic layers were considerably reduced compared with those on molybdenum (Mo) bottom electrodes. For instance, the total organic layer thickness on Mo electrodes was 239.58 nm, whereas that on the sidewall of the trench structure was just 34.06 nm, which was approximately 7.03 times lower. This thin organic layer and the increased lateral current path can increase the resistance for the lateral current. In contrast, the top metal electrode and Al₂O₃ TFE layer maintained their thicknesses regardless of the structure. Uniform top electrode and TFE layer thicknesses are important for uniform display panel driving and for protecting OLEDs from moisture and oxygen, respectively.

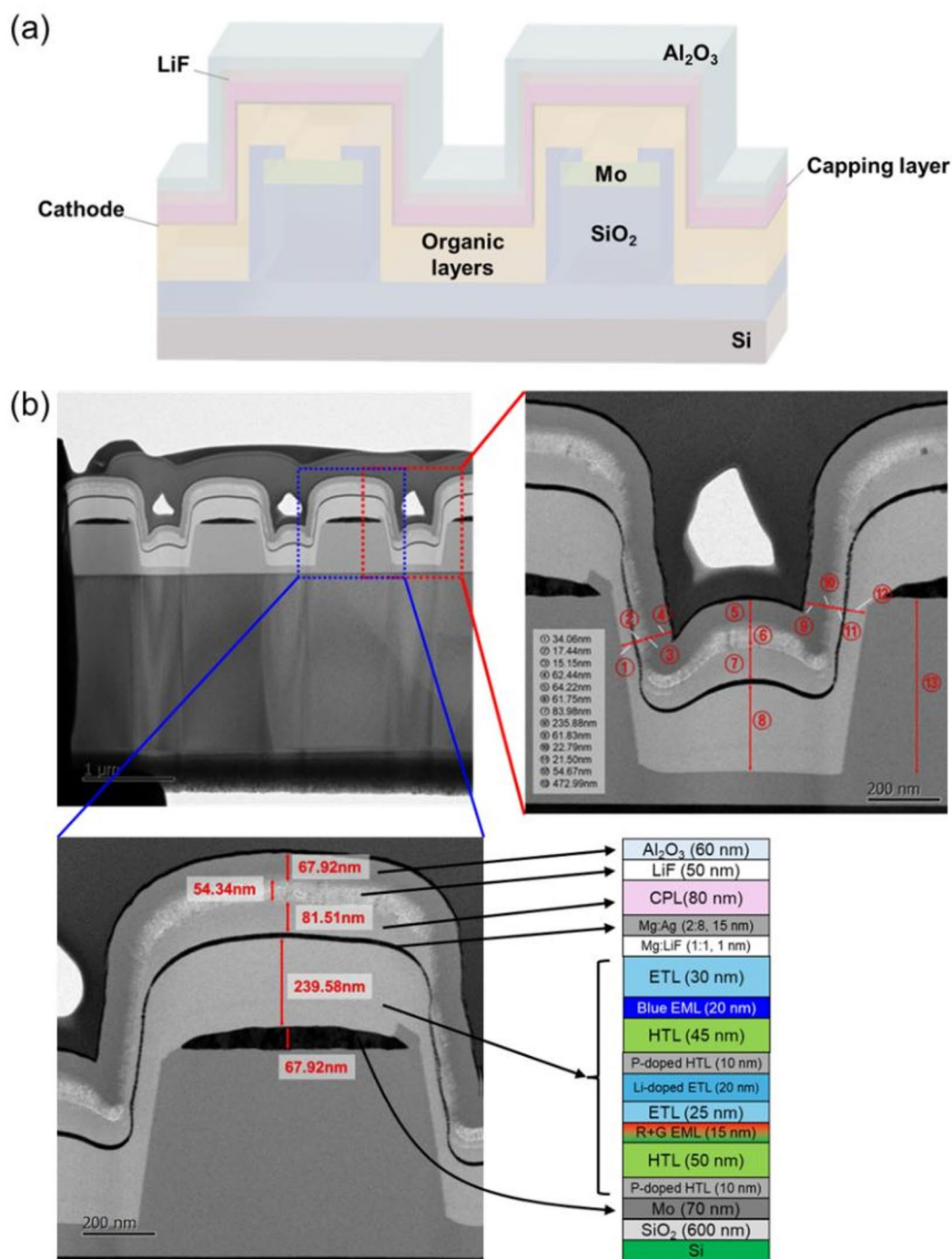


Fig. 3 6047 PPI pixel structure with trench. (a) Schematic of pixel structure with trench, and (b) cross-sectional FIB-TEM images of finger electrodes; indicated are the trench structures and thickness values of all the layers with white tandem OLED structures.

Figure 4a, b show the J - V characteristics of the top-emitting white tandem OLEDs on the E1 pixel arrays without and with trench structure, respectively, depending on the driving conditions. Since the pixel adopts a multifinger-type geometry, the effective emitting area was taken as half of the product of the unit E1 pixel area and the number of pixels in the array, i.e., approximately $3.3 \times 10^{-5} \text{ cm}^2$; the current density was then obtained by dividing the measured current by this value. In the absence of a trench structure, the device under the O driving

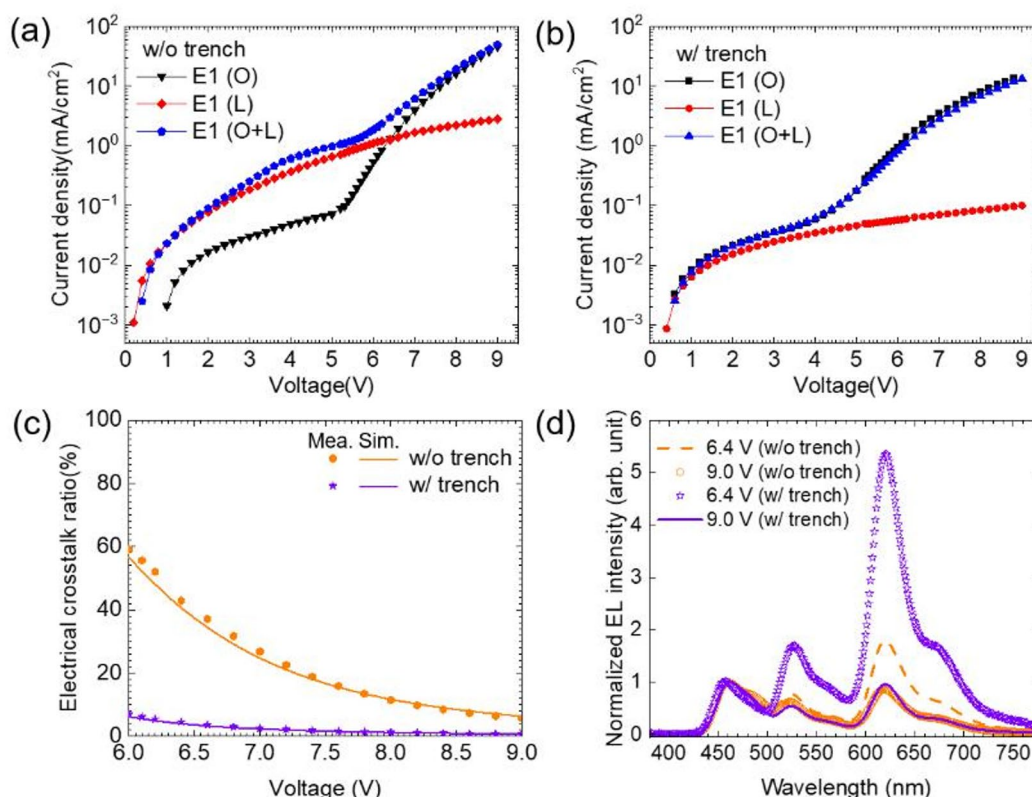


Fig. 4 Characteristics of pixel arrays depending on trench structures. J – V characteristics of top-emitting white tandem OLEDs on E1 pixel arrays (a) without (w/o) trench, (b) with (w/) trench structures depending on driving conditions, (c) measured (Mea.) and simulated (Sim.) electrical crosstalk ratios as a function of driving voltages, simulated using LAOSS (Fluxim) ver. 4.3.2; Software URL: <https://www.fluxim.com/laoss>, and (d) normalized EL spectra of devices w/o and w/ trench structures at 6.4 V and 9.0 V (normalized at blue peaks).

condition exhibits typical OLED J – V characteristics, showing low current values in the voltage regime below 5 V followed by a steep increase, as shown in Fig. 4a. However, under the O+L driving condition, a rapid increase in the current was observed, even in the low-voltage region below 5 V. This is attributed to the substantial lateral leakage current in the low-voltage regime, as exhibited by the L driving condition. For instance, at 3 V, the current density under the O+L driving condition was 0.256 mA/cm², which is similar to the sum of the current densities under the L (0.186 mA/cm²) and O (0.030 mA/cm²) driving conditions. At driving voltages greater than 8 V, the currents under the O and O+L driving conditions converged to similar values. These results indicate that in a pixel structure without a trench structure, the lateral leakage current occurs predominantly in the low-voltage regime. By contrast, when the trench structure was incorporated, the current density under the O+L driving condition was nearly identical to that under the O driving condition, as shown in Fig. 4b. This is because the lateral leakage current, as shown under the L driving condition, is considerably lower at the same voltage compared with the pixel structure without a trench. For example, at 3 V, the current densities under the L and O+L driving conditions are 0.025 mA/cm² and 0.036 mA/cm², respectively, which were reduced by factors of 7.44 and 7.11 compared with the structure without a trench. Figure S4a in the supplementary information shows luminance–voltage characteristics of the devices without and with trench structures under the O driving condition. Since the device consists of micro-pixels, a fill factor of 20.8% was applied to account for the effective emission area when calculating luminance. The device with the trench structure exhibited a turn-on voltage approximately 0.2 V lower than that of the device without the trench structure, while both devices show nearly identical luminance above 6.4 V. For current efficiency, the device with trenches has higher values than the device without trenches over

most of the luminance range as shown in Fig. S4b. This is attributed to the lower current density of the device with trenches despite offering comparable luminance at the same voltage. In other words, the device without the trench structure conducts higher current than what effectively contributes to light emission, owing to lateral leakage current. These results confirm that the trench structure drastically suppressed the lateral leakage current without degrading the intrinsic device characteristics. The electrical crosstalk ratio was calculated based on the measured results. The pixel structure employing the trench structure reduced the electrical crosstalk, maintaining an exceptionally low electrical crosstalk ratio across the entire voltage range, as shown in Fig. 4c. To analyze the reduced electrical crosstalk in the pixel structure with a trench structure, simulations were conducted using the commercial software (Large-Area Organic Semiconductor Simulation (LAOSS), Fluxim)²⁵. A 90×30 pixel array was designed; this array was identical to the E1 pixel structure, as shown in Fig. S5 in the supplementary information. When the sheet resistances of the organic layers without and with trench structures are $350 \text{ G}\Omega/\square$ and $20,000 \text{ G}\Omega/\square$, respectively, the simulation results correspond to the calculation results from the measurement data, as shown in Fig. 4c. Consequently, the experimental and simulation analyses demonstrate that introducing a trench structure effectively increases the resistance of the organic stack. This increased resistance profoundly suppressed the lateral leakage current, leading to a major reduction in the electrical crosstalk between adjacent pixels. Figure 4d shows the normalized EL spectra of devices without and with trench structures. At 9.0 V, the EL spectrum of the device with the trench structure was almost identical to that of the device without the trench structure. The main R, G, and B emission peaks of the devices with and without trench structures were 620, 524, and 462 nm and 619, 523, and 460 nm, respectively. The Commission Internationale de l'Eclairage (CIE) color coordinates of the devices with and without the trench structures were (0.3281, 0.2930) and (0.3163, 0.3020), respectively. Conversely, the device with the trench structure exhibited much higher G and R emissions compared with those of the device without trench structure at 6.4 V. For example, the CIE color coordinates of the devices with and without trench structures were (0.4859, 0.3730) and (0.3893, 0.3240), respectively. This result indicates that at 9.0 V, a low electrical crosstalk allows for similar current injection into both the top and bottom tandem units, irrespective of the trench structure, generating similar EL spectra. However, at 6.4 V, extensive electrical crosstalk drove distinct lateral leakage currents; thus, the current distributed to the bottom of the R–G and top B-emitting units became highly dependent on the trench structure, resulting in different emission characteristics.

To investigate the emission characteristics of the off-state pixels surrounding the driven pixel induced by electrical crosstalk, we fabricated a pixel array structure with a resolution of 6047 PPI, as illustrated in Fig. 5a. In this configuration, among the three pixels comprising a single RGB pixel (as that used in a practical display panel), only one pixel is connected to a power line to remain in the active (on) state. The other two pixels only possessed electrodes without power connections, thereby remaining permanently in an inactive (off) state. Under these conditions, a driving voltage was applied, and the luminance distribution across the pixel arrays was measured using a two-dimensional (2D) spectroradiometer. As shown in Fig. 5b, the pixel structure without a trench exhibits a strong luminance distribution even in the adjacent off-state pixels. However, the pixel structure employing the trench structure demonstrates negligible emission from the surrounding pixels. The position-dependent normalized luminance profiles of the active (on) and adjacent inactive (off) state pixels without and with the trench structure are plotted in Fig. 5c. For instance, in a pixel structure without a trench structure, when the luminance of the active pixel at position 1 reaches approximately 5148 cd/m^2 , the luminances at positions 3 and 5 (which contain only electrodes and are disconnected from the power supply) were 686 cd/m^2 and 760 cd/m^2 , respectively. These correspond to the exceptionally high values of 13.3% and 14.8% relative to the luminance of the active pixel, respectively. This indicates that substantial light leakage occurred in the unpowered pixels owing to the lateral leakage current. In contrast, for the pixel structure with the trench, when the active pixel at position 1 exhibits a normalized luminance of 100%, the relative luminances at positions 3 and 5 are dramatically suppressed to 2.3% and 2.1%, respectively. This represents an approximately seven-fold reduction in light leakage compared with the trenchless structure, which is in excellent agreement with the reduction ratio of the lateral leakage current caused by electrical crosstalk. The 2D spatial luminance distribution of five different regions in the 6047 PPI stripe pixel structure was investigated, as shown in Fig. S6 in the supplementary information. In all five different

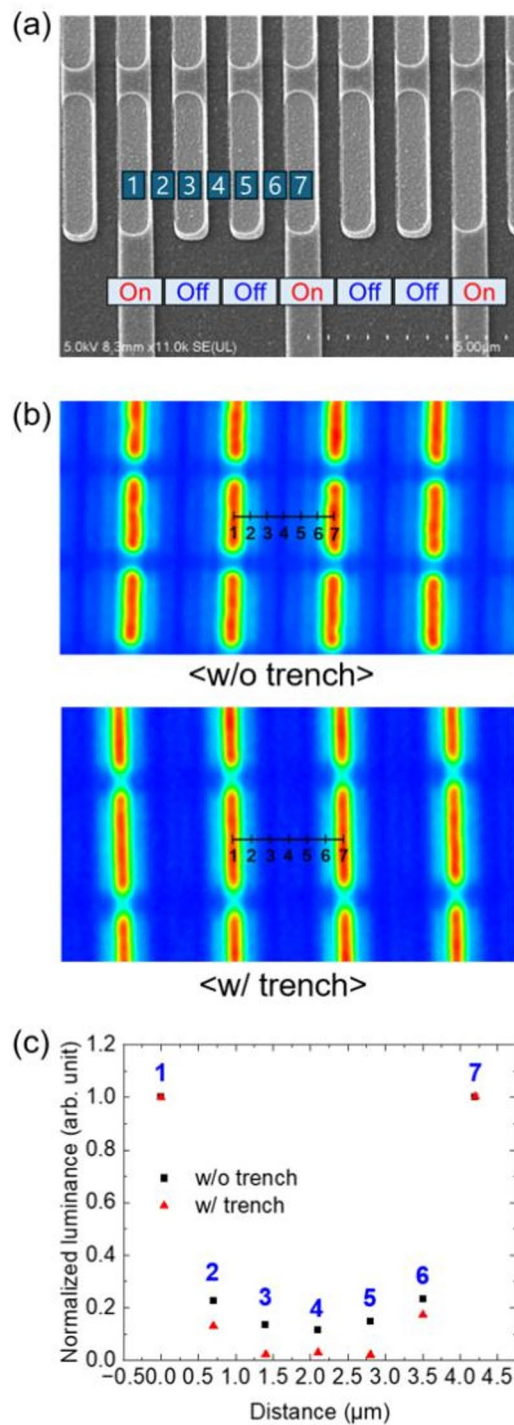


Fig. 5 Luminance distribution across the pixel arrays depending on trench structures. **(a)** SEM image of pixel array, **(b)** 2D spatial luminance distribution image of the pixel array without (w/o) and with (w/) trench structures, and **(c)** normalized luminance variations as functions of distance from on-pixels w/o and w/ trench structures.

pixel regions, the pixel structure with the trench exhibits substantially lower inactive (off) state pixel luminance than the structure without the trench. Consequently, these results suggest that the trench structure drastically suppresses the lateral leakage current, thereby effectively mitigating the light leakage to adjacent pixels.

Conclusion

In this study, we investigated electrical crosstalk in a 6047 PPI high resolution pixel structure employing white tandem OLEDs on Si and demonstrated that a trench structure can effectively suppress lateral leakage current. A multifinger-type test element group fabricated on Si substrates was used to systematically analyze the electrical crosstalk under three driving conditions. The results revealed that the lateral leakage current was strongly influenced by the interelectrode spacing and the number of pixel arrays, and that the electrical crosstalk became particularly pronounced at low driving voltages. To address this issue, a trench structure was introduced between the pixel electrodes. FIB-TEM cross-sectional analysis confirmed that the organic layers on the trench sidewalls are approximately seven times thinner than those on the Mo electrodes, thereby increasing their lateral resistance of the organic layers. The trench structure reduced the lateral leakage current by more than a factor of seven compared with a planar pixel structure, as consistently validated by both experimental measurements and electrical simulations. Consistent with the reduction in the lateral leakage current, 2D spectroradiometric characterization revealed substantial suppression of light leakage into adjacent inactive pixels, dropping from 13 to 15% to approximately 2% relative to the active pixel luminance. These results indicate that the trench structure provides an effective and reliable strategy for mitigating electrical crosstalk in high-resolution tandem OLED displays without degrading the intrinsic device performance, demonstrating its potential for next-generation ultrahigh-resolution AR/VR display applications.

Materials and methods

For device fabrication, 6 in Si substrates with plasma-enhanced chemical vapor deposition (P-5000 Mark II, AMAT)-processed SiO₂ (600 nm) were used. The Mo was deposited as the top metal on the Si substrate using a sputterer (3180, Varian). An I-line stepper (NSR-2205i12D), reticle, and dry etcher (P-5000 Mark II (MxP), AMAT) were used for photolithography patterning. After the patterning process, the wafer was diced to 2 cm × 2 cm, which matched the size of the substrate. The substrates were sequentially rinsed with acetone, methanol, and deionized water for 15 min each and dried in a vacuum oven at 80 °C. Subsequently, the organic and metal layers were deposited using a vacuum thermal evaporator to fabricate the OLEDs. A 60 nm thick Al₂O₃ layer was deposited onto the OLEDs using atomic layer deposition (ALD) to protect the OLEDs from moisture and oxygen. The ALD process temperature was maintained at 95 °C.

The J - V characteristics of the devices were measured in a dark room at room temperature using a source measurement unit (Keithley 2450). The luminance, EL spectra and CIE color coordinates were measured using a spectroradiometer (Konica Minolta CS-2000). Field-emission SEM (SU8230, Hitachi, Japan, and JSM-7600F, JEOL, Japan) was used to observe the patterned pixel structures. An FIB (Nova NanoLab 200, Thermo Fisher Scientific, Netherlands, and FB-2100, Hitachi High-Tech, Japan) and field-emission TEM (JEM-2100F HR, JEOL, Japan) were used to observe the cross-sections of the fabricated devices. An optical microscope (MIC-S39B, Chongqing MIC Technology, China) was used to obtain high-resolution emitting-pixel images. A 2D spectroradiometer (SR-5000HM, Topcon Technohouse Corporation, Japan) was used to determine the luminance distribution across the pixel arrays.

The commercial software LAOSS (Fluxim), which used a 2 + 1D finite-element model based on the conductivity of the common layer and current density–voltage–luminance characteristics of the fabricated OLEDs was used for electrical crosstalk simulation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1038/s41598-026-71264-0>.

Author contributions J.-W.S., and H.L. conceived the study. J.-W.S., and H.L. supervised the study. Y.Y., N.B., C.W.J., S.C., and H.L. experimented with OLED fabrication. J.-W.S., C.K., H.J., C.-W.B., and H.L. designed and fabricated 6047 PPI pixel structure on Si substrate. Y.Y., J.-W.S., N.B., S.S. and H.L. conducted the film and device characterization and analyzed the data. Y.Y., S.C., and H.L. conducted simulation. Y.Y., J.-W.S., and H.L. drafted the manuscript. All authors have contributed to the manuscript and approved the submitted version.

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Data availability The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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