nature portfolio

Peer Review File

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

Corresponding Author: Professor Young Rag Do

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
This is a careful study presenting two developments: 1) incorporating MQWs on the large facet of a several-micron long cuboid GaN structure (finLED). Authors show an 8 times larger active region relative to nanorodLEDs, leading to brighter fin LEDs. 2) Alignment of finLEDs which includes fin axial direction and rotation and placement of the desired facet on the underlying electrodes using dielectrophoretic (DEP) method. Authors also state "… our study attained a 91.3% vertical assembly percentage". This represents the fraction of the fins that face down correctly. The facet-controlled placement is introduced to enable a brighter pixel with 8640 cd/m2, while EQE stands at 9.1%. In a sense a better light extraction is obtained relative to other types of nanorod LEDs.

Authors, as far as I understand, do not disclose a distinct advantage in their DEP assembly method (which is the main point of this work) relative to what has been previously reported, for instance, in ref. 26. In other words, their contribution seems gradual and not in a stark difference relative to the prior methods. They don't show if their torque-induced rotation is different from the earlier reports or what are the new aspects! It should be noted that the manipulation and placement of micro-finLEDs, several microns long, seems to be a new aspect (relative to ref 26), however, as discussed in my comments below, there are some questions and ambiguities around that. As such this work is not suitable for publication in Nature Comm. Below are my questions and comments:

Line 223: "We define pixels with 15 or fewer fin-LEDs aligned in a 42x42 μm2 area as bad cells, and out of a total of 2940 pixels, only two defective subpixels were found." It appears that their method has no deterministic control over the number of finLEDs per pixel and process seems stochastic; is that true? Based on what criteria, value 15 is chosen as the threshold of normal or bad pixel? The 99.93% assembly accuracy is based on how many experimental runs? Also based on Figure 5f, there seems to be a noticeable variation in the emission intensity of different pixels with the large array. How is this variation contrasted with the # of finLEDs per pixel? Does the poor emission indicate poor contact with the metal electrodes?

Line 237 In sentence:"…, namely the triple-shell, SiO2-shell, and TiO2-shell, in terms of brightness", the "triple-shell" seems redundant.
Line 247-249: Figure 5e precedes Figure 5d.
Line 254: "Figures 5f-g illustrate the array cell containing 588 pixels...". Figure 5g in comparison with 5f, does not look like the right one as it shows a small pixel.

Line 43. "Upon transferring nanorod-LED display technology by our team, the Samsung Display Company (SDC) reported the successful fabrication of a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process, highlighting the various advantages of the DEP process". This sounds a causal sentence implying the SDC work was based on the work of this team. Rewording recommended. Perhaps replace "Upon" with "following".

Page 2. "These nanorod-LEDs autonomously align on subpixel electrodes using fluidic assembly". If they align autonomously, then what is the purpose of the fluidic assembly? Word "autonomously" should be reworded or omitted.

Line 96: What are the superior optical characteristics that author refer to on line 96. Do they mean a stronger light extraction efficiency? Please clarify.

Line 50: What is the goal of discussing nanorod LEDs in this work? It is understandable that finLEDs with a larger active region are better than nanorod LEDs. Perhaps authors should consider eliminating this section as it seems a distraction from the main point.

Figure 1c. Why the emissions related to the EBL and MQW layers are not apparent in the nanorod LEDs. In CL, at least, due to its high sensitivity, it should have some signature?

Page 4: line 110: how is the 20-fold CL enhancement calculated? Is it based on analysis of individual structures or their groups?

Lastly, fin LED design is not a new concept and several teams have reported them with aspect ratios that look like a fin (in contrast to the small aspect ratio cuboid objects of this study). It is recommended that authors site their work for a fair and accurate description of the field, for instance:
1.Selective-Area Growth of III-Nitride Core-Shell Nanowalls for Light-Emitting and Laser Diodes. In 2014 Conference on Lasers and Electro-Optics, IEEE: 2014; pp 1-2.
2.Molecular beam epitaxial growth and characterization of AlN nanowall deep UV light emitting diodes. Appl. Phys. Lett. 2017, 111.
3.High-brightness lasing at submicrometer enabled by droop-free fin light-emitting diodes (LEDs). Sci. Adv. 2020, 6, eaba4346.

Reviewer #2

(Remarks to the Author)
In this manuscript, fin-LEDs that overcome the weaknesses previously reported in nanorod-LEDs have been demonstrated. These fin-LEDs show marked improvements in transfer efficiency and pixel assembly yield compared to former nanorod-LEDs. The increased volume of the MQW (more than 8 times) and the thickening of the EBL (electron-blocking layer) contribute to the observation of strong blue light (as shown in PL, CL, and EL graphs). Additionally, a triple-shell fin-LED EL device was developed, which demonstrates superior performance in terms of passivation, brightness, and emission uniformity.

By enhancing the performance of fin-LEDs, significant contributions to the advancement of next-generation inorganic displays are anticipated. Please refer to the following comments.

1.The size distribution of fin-LEDs should be provided. The authors used millions of chips for these experiments. However, it seems that the size of the fin-LEDs is not uniform, as shown in Figures 1b and 2f. The size distribution of fin-LEDs might change the EL distribution. All these effects should be addressed.

2.In addition, each fin-LED contains a large number of defects at the edges, as shown in Figure 2f. It is questionable whether the large number of defects in each fin-LED might affect the uniformity of brightness and, consequently, the uniformity of the pixel. This effect should also be addressed.

3.In the electric field simulation part, FDEP and TDEP are calculated as functions of θx, as shown in Figures 3b and 3d. However, further explanation is required for Figures 3b and 3d in conjunction with Figures 4a to 4h. It is not clear how such a high yield is achieved from the DEP force or DEP torque differences.

4.The bad pixels and good pixels were defined. If a bad pixel is defined as a pixel with 15 or fewer fin-LEDs, it is anticipated that using a large number of chips for alignment will lead to fewer bad pixels. Is it possible to quantitatively explain the relationship between the number of bad pixels and the number of input chips?

5.The production yield of 99.93% is unclear. Please explain the calculation method of the production yield.

6.In Figure 5d, the threshold voltage of the triple-shell LED shifts positively with a steep increase in current density as the driving voltage increases. However, the mechanism of the increasing EQE is unclear in the manuscript. This should be further addressed.

7.In the conclusion, it is mentioned that the EQE is slightly lower than in prior results. However, the method for improving the EQE was not properly addressed. This should also be further addressed.

Reviewer #3

(Remarks to the Author)
The authors presented a novel, FIN-based approach for micro-LEDs. This is a very timely, important topic, and the results are interesting and of significance. I recommend publication pending the following revisions.

1. The Comparison of different transfer methods

From the introduction part, the idea of this Fin-LEDs with DEP is to reduce the cost and increase the yield. In table S1, DEP method is compared with other transfer methods. But the transfer yield of LASER and Stamp is higher than DEP. LASER also has a small chip size. In the main text, it is mentioned that LASER method may generate more damages and has high requirement of parameters thus increasing cost. However, the analysis of damages is very limited in the following part. For the comparison cost, the parameter requirement is also not very low from your following discussions, so it is a bit confusing about the cost comparison and how did the authors lower the cost by DEP. In addition, the assembly speed is lower in your method.

2. The introduction of DEP method and its advantages is limited. The authors only mentioned that it has several advantages in the line 44 of the page 2, but the advantages are not listed clearly. It is a bit unclear about the motivation of choosing DEP as the method. Did someone else use this method for transfer? Some more literature reviews in this part may be helpful to depict the picture of your idea and let readers know this method.

3. As table S2 shows, the face selective alignment ratio of this work is higher than other nanorod LEDs. But the comparison with other transfer methods is lacked from here. What is the alignment performance of other methods?

4. The authors mentioned that the EQE of DEP Fin-LED is 9.1%, which is a bit lower than nanorod LEDs. Because it is short-wavelength LED, the 9.1% EQE performance is not dominant in the current industry. It seems that there is a trade-off between efficiency and other factors.

5. In figure S1(a), there is a typo. It should be “emission” instead of “emmision”.

6. From the section “Properties of vertically oriented Fin-LEDs vs Horizontally Oriented Nanorod-LEDs”, the comparison focuses on the Fin-LED and nanorod-LED. The authors mentioned that the MQW volume is an advantage of Fin-LED compared to nanorod LED, but how about the comparison with other structures or methods? Is the MQW and front emission still an advantage?

7. In the Line 103 of page 3, the authors mentioned the decreased surface-defect density and its reason. But it is better if the authors can add some references here to support this conclusion, and the decreased surface-defect density can be reflected by analyzing the EL or PL spectra such as the full-width at half-maximum. The analysis of EL and PL spectra is a bit over-simplified.

8. From the line 111-112, the authors attribute the increasing of emission intensity of Fin-LED to the increased MQW and the decreased defect density. But in the following paragraph, only the influence of MQW on the emission intensity is discussed, the defect density is not mentioned any more. Maybe the explanation of defect or damage is required since this is one of the key factors showing DEP is better than LASER transfer method as the authors discussed in the previous par

9. The Maxwell stress tensor and the finite element method are used to simulate the force and torque. The authors list a reference to verify the dipole approximation method is not suitable, but there is no reference to support the suitability of MST+FEM. Did anyone use these methods to simulate before?

10. In line 176-183 at page 6, the authors summarized the limitation of this simulation, and the observation is observed in the experiments. However, it seems that it is not mentioned any more in the following discussions.

11. In the “Face-Selective Assembly of Fin-LEDs” section, the very detailed comparison among different structures, different shell materials and solvents are conducted. But it looks like this method has a very high demanding of materials used, and different materials have very different performance which may limit the potential wide application. Hence, how do the authors control the cost of this method if there is a high requirement of parameters and materials, and how do the authors show its universality? As the introduction part, the authors attributed the high-cost problem of LASER to the high requirement of the laser parameters and bonding methods, but the authors also need a relatively high demanding in you method. In addition, how do the authors keep the stability of this method if the performance varies so much among different parameters or materials.

12. In line 238-239, the high performance of triple-shell LED is attributed to the effective passivation from face-selective effect, how do the authors prove this conclusion?

13. The optical performance of Fin-LED is only compared with nanorod-LEDs, but the comparison with other structures and methods is also important to show the advantage of the reported method.

14. The luminance of 8640 cd/m2 is one advantage of Fin-LED compared to nanorod-LED, but what about this value in other structures or methods?

15. There are some recent developments of nanowire (or nanorod) LEDs by other growth methods, e.g., MBE, showing significantly improved efficiency for device sizes in the sub-micron regime. These studies should be referenced to provide a

more comprehensive overview of the micro-LED fields.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
The response prepared by authors answers the question and concerns to a reasonable extent. The advantages of the reported approach and the scope of the fabricated devices and results reported makes this work appropriate for consideration in this journal.

One minor comment is on lines 57-58. "Following the transfer of nanorod-LED display
58 technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated...". What do authors mean by "transfer". Is this a technology transfer. The relevance of this sentence is not clear.

Reviewer #2

(Remarks to the Author)
The manuscript has been revised according to the reviewer's comments. I would like to recommend this manuscript for publication in Nature Communications as is.

REVIEWER COMMENTS

August 26, 2024

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Dear Reviewer,

In response to the reviewers' comments, we have revised the introduction as follows. We would appreciate it if you could refer to our responses.

Revised introduction

Micro-LEDs have emerged as a star player in next-generation display technology due to their efficient performance, extended lifespan, wide color gamut, modular capabilities, and stability.[1-8] Notably, several companies have introduced TVs featuring micro-LED technology.[9-10] Apple meanwhile planned to incorporate micro-LED displays in its smartwatch scheduled for release in the future.[11-12] Micro-LEDs are positioned as a possible platform technology for a wide range of applications, from compact screens to giant displays. However, critical challenges remain in micro-LED display production. A significant concern is the need to improve the yield of the pixel manufacturing process while addressing the substantial fabrication costs associated with micro-LED chip production.[13-16]

The production cost of micro-LEDs depends on the chip size, assembly speed, and transfer yield. The smaller the chip size is, the faster the assembly speed is, and the higher the transfer yield is, the lower the unit cost is. **Table S1** provides an overview of chip size, assembly speed, and transfer yield for various micro-LED transfer methods. It is crucial to note that the transfer yield depends on precise positioning of micro-LEDs within pixel grooves. Fluidic self-assembly (FSA) exhibits lower selective transfer rates and requires larger micro-LED chips.[10]

In contrast, stamp transfer printing offers the advantages of smaller chip sizes and faster transfer speeds than FSA, albeit with lower repeatability.[10] Despite presenting small chip sizes, rapid transfer speeds, and high accuracy, LASER-based transfer is susceptible to LED chip damage when the chip size becomes smaller.[17] Additionally, it relies on specific laser parameters and bonding methods, with the significant drawback of higher initial costs.[7-10] Conventional FSA, laser transfer, and stamp transfer have respective strengths and weaknesses, but each method has critical issues that must be solved prior to commercializing low-cost micro-LEDs.

One of the micro-LED transfer methods with various sizes, ranging from nano to micrometer, reported to date combines the FSA and dielectrophoretic (DEP) methods. DEP is a method of moving materials by controlling the movement of particles under a non-uniform electric field. This is promising for effectively aligning under 10 micron micro-LEDs as it can quickly move particles to a selective location depending on the strength of the electric field.[28] LG Electronics (LGE) recently expanded the FSA-DEP approach by aligning ~40μm micro-LEDs into subpixel grooves and assembling them using DEP force within the groove through a positive DEP field and secondary magnetic field to improve the site and face-selectivity of micro-LEDs, which cannot be achieved in conventional FSA with high production yield. In contrast, our team introduced an innovative display device and manufacturing process using nanorod-LEDs to effectively address the high material cost of micro-LEDs and the low assembly speed of conventional FSA processes.[19-20] Following the transfer of nanorod-LED display technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated the practical possibility of the DEP process by fabricating a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process and inkjet printing process. These reports demonstrates the various advantages of inkjet-DEP process, such as low-cost nanorod materials, fast assembly speed matched with commercial inkjet speed, and high possibility of transfer yield, promising a bright future for micro-LED manufacturing.[26-27] However, the horizontal orientation of nanorod-LEDs leads to lateral light emission spread, causing limited MQW volume and diminished forward-directed light emission [19-20], as depicted in **Figure 1a**.

This study suggests adopting fin-LEDs to overcome the challenges presented by nanorod-LEDs and the high costs associated with micro-LED displays. Fin-LEDs are similar in size to nanorod-LEDs and are distinguished by the orientation of the p-GaN/MQW/n-GaN

structure, aligned parallel to the long axis of fin-LEDs. Featuring a vertical LED device structure, the fin-LED shows a substantial ~eight-fold increase in MQW volume compared to nanorod-LEDs, leading to enhanced forward-directed light emission (**Figure 1a**). This effect intensifies when fin-LEDs are face-selectively arranged on lower assembly electrodes, concentrating light emission primarily on the front side. The vertical structure of fin-LEDs demands precise alignment for the p-GaN or n-GaN side with the lower assembly electrode to ensure their optical functionality. The DEP field induces motion in fin-LEDs through positive-DEP (p-DEP) movement, attracting them perpendicularly between interdigitated electrodes.[20,25,28-30] Achieving the desired face-selective assemblies involves critical rotation around the long axis and optimizing DEP assembly parameters, such as shell and electrode material, solvent type, applied frequency, and voltage, for precise placement on bottom electrodes within subpixels. As indicated in prior reports (**Table S2**), the alignment yield for nanorod-LEDs reached a maximum of 74.4% using DEP assembly.[20] In contrast, our study attained a 91.3% vertical assembly percentage with face-selective DEP, enabling the creation of brighter, vertically structured fin-LED devices and displays. Therefore, the DEP method of nanorod-LEDs was enhanced by a combined approach involving rotation around the short axis by the asymmetric field for horizontal alignment and inkjet printing for site-selective assembly. In the case of larger micro-LEDs, the DEP approach was improved by using chip-shaped grooves for site selectivity and additional magnetic fields for face-selective vertical alignment. Here, the DEP of fin-LEDs is enhanced by rotating around a long axis with specific design adjustments for face-selective vertical alignment without secondary force. This technique appears complex but has been successfully demonstrated in this study and remains unreported.

As shown in **Table S2**, much higher brightness can be achieved when fin-LEDs are aligned vertically while having a high assembly percentage, whereas horizontally aligned nanorod-LEDs have either low brightness or are not mentioned. As previously reported, employing DEP assembly techniques featuring double or triple-shelled nanorod-LEDs with dimensions measuring 600 nm in diameter and 4~5 μm in length, they fabricated electroluminescent (EL) test devices that achieved external quantum efficiency (EQE) levels ranging from 20.2% to 22.2%.[26,27] Previous papers claiming the highest EQE seldom report brightness data. On the other hand, our fin-LED, emitting blue light at a wavelength of 448nm, achieved a reasonable EQE of 9.1% and a peak luminance of 8640 cd/m^2 at 5V. This EQE is comparable to the best EQE of nanorod-LEDs reported without using a high indium doped wafer, especially at wavelengths below 455nm.[27] In addition, the brightness of fin-LEDs is

much higher than that of other reported nanorod data.[19,20,26,27,28]

Fin-LEDs and nanorod-LEDs, due to their similar shapes and sizes, are well-suited for a color-by-blue approach using quantum dots (QDs). The integration of inkjet and DEP techniques allows us to achieve a full-color display with fin-LEDs, as depicted in **Figure S1**.[31-34] Additionally, we can use inkjet technology to apply a QD-based color conversion layer onto red (R) and green (G) subpixels, achieving a wide-gamut RGB color spectrum. The inkjet-DEP process for fin-LEDs can effectively overcome transfer challenges typically encountered with micro-LEDs, even though the conventional FSA method used in this paper allows the assembly of fin-LEDs with somewhat high assembly speed and transfer yield. Similar to the nanorod-LEDs, the tiny fin-LED can use inkjet printing to improve site selectivity, transfer yield, and speed and reduce material cost.[26,35] This face-selective DEP-based fin-LED assembly process offers notable advantages, including preventing chip damage, achieving rapid assembly speed, and attaining a high pixelation fabrication yield exceeding 99.93%. Our results position this process as a promising technology for creating next-generation inorganic displays.

Reviewer #1 (Remarks to the Author):

This is a careful study presenting two developments: 1) incorporating MQWs on the large facet of a several-micron long cuboid GaN structure (finLED). Authors show an 8 times larger active region relative to nanorodLEDs, leading to brighter fin LEDs. 2) Alignment of finLEDs which includes fin axial direction and rotation and placement of the desired facet on the underlying electrodes using dielectrophoretic (DEP) method. Authors also state "… our study attained a 91.3% vertical assembly percentage". This represents the fraction of the fins that face down correctly. The facet-controlled placement is introduced to enable a brighter pixel with 8640 cd/m2, while EQE stands at 9.1%. In a sense a better light extraction is obtained relative to other types of nanorod LEDs.

Authors, as far as I understand, do not disclose a distinct advantage in their DEP assembly method (which is the main point of this work) relative to what has been previously reported, for instance, in ref. 26. In other words, their contribution seems gradual and not in a stark difference relative to the prior methods. They don't show if their torque-induced rotation is different from the earlier reports or what are the new aspects! It should be noted that the manipulation and placement of micro-finLEDs, several microns long, seems to be a new aspect (relative to ref 26), however, as discussed in my comments below, there are some questions and ambiguities around that. As such this work is not suitable for publication in Nature Comm. Below are my questions and comments:

Previous research has explored methods for aligning nanorod LEDs horizontally using DEP force that attracts across two-assembled electrodes and torque that rotates around an axis perpendicular to the long axis (a short axis) of the nanorod.[1-6] However, our research takes a novel approach to aligning fin-LEDs vertically using only DEP force and specific torque that rotates around a long axis of the fin-LED, a method not previously reported. Other researchers have reported approaches for aligning micro-LEDs vertically by combining DEP with additional forces, focusing on selectively aligning the p-GaN or n-GaN faces in specific directions.[7] Notably, this approach recently used a magnetic field in combination with DEP force to achieve face-selective vertical alignment of micro-LEDs, ensuring that the p-GaN faces align in the same direction.[7] However, the challenge we address is the high cost and complexity of fabricating vertically aligned micro-LED devices. This complexity arises from the need to control DEP and additional forces while fabricating micro-LEDs responsive to these

forces.

In response to the challenges faced in previous methods, our paper introduces a simple and viable method for aligning ultra-small and ultra-thin devices, such as fin-LEDs, vertically in a face-selective manner using only DEP force and torque. Our approach eliminates the need for additional complex forces and control systems, making the alignment process more straightforward. We also demonstrate that fin-LEDs with a structure sensitive to DEP force and torque can be fabricated by adjusting the shell material on the sides and the electrode material on the top. This enables face-selective vertical alignment with DEP alone, confirming the advantage of simplicity of our method and facilitating the creation of vertically structured fin-LED light-emitting devices and displays.

Our approach is significant because it simplifies the vertical alignment process, reducing the need for complex external adjustments. This concept makes precise vertical alignment feasible and contributes to the advancement of vertical micro/nano-LED devices. By paving the way for more cost-effective and efficient micro/nano-LED displays in the future, our research holds potential for a significant impact in micro/nano-LED display technology.

Please refer to the attached revised introduction based on the reviewers' comments.

1. Line 223: “We define pixels with 15 or fewer fin-LEDs aligned in a 42x42 μm^2 area as bad cells, and out of a total of 2940 pixels, only two defective subpixels were found.” It appears that their method has no deterministic control over the number of finLEDs per pixel and process seems stochastic; is that true? Based on what criteria, value 15 is chosen as the threshold of normal or bad pixel? The 99.93% assembly accuracy is based on how many experimental runs? Also based on Figure 5f, there seems to be a noticeable variation in the emission intensity of different pixels with the large array. How is this variation contrasted with the # of finLEDs per pixel? Does the poor emission indicate poor contact with the metal electrodes?

Our response: Thank you for your valuable comments.

We fabricated and evaluated five fin-LED devices, each containing 588 subpixels, and found only two bad subpixels. On average, with one ink drop, approximately 30 fin-LEDs are aligned in the 42 × 42 μm^2 area, which we have defined as the optimal LED count for a pixel. This suggests that deterministic control over the number of aligned fin-LEDs is achievable. The threshold of 15 fin-LEDs was chosen as it represents half of the average number of aligned fin-

LEDs, providing a margin for non-operational fin-LEDs while maintaining uniform emission intensity within the 42 × 42 μm² area. However, if more than 60 fin-LEDs are aligned within a pixel, this not only increases the cost but also risks inducing leakage current during device manufacturing, and we define such pixels as defective. To compensate for LEDs that do not turn on due to contact failures, maintaining the number of fin-LEDs between 15 and 60 is critical to avoid performance degradation and manufacturing defects. The 99.93% assembly accuracy is derived from five experimental runs, each evaluating 588 pixels, resulting in a total evaluation of 2940 pixels. The variation in emission intensity observed in **Figure 6f** is closely related to the number of fin-LEDs per pixel; as the number of fin-LEDs in a pixel increases, the emission intensity also increases. While poor contact with metal electrodes can indeed cause lower emission intensity, other factors, such as a particle issue from using a classroom for a clean room and a misalignment issue of the manual fabrication process, which can cause leakage in pixel lines and affect micro-scale patterns, must also be considered.

This paper presents a method for area-selective alignment of vertically structured fin-LEDs that entails dropping a fin-LED solution and using DEP assembly. This verifies that fin-LEDs can be vertically aligned within subpixel areas and somewhat evenly distributed across each subpixel. Looking ahead, we plan to utilize inkjet technology to deposit a consistent number of fin-LEDs into the subpixels. Unlike traditional pipette-based dropping methods, the inkjet technique is expected to enhance the distribution of fin-LED uniformity. As previously reported, inkjet printing is already recognized for its ability to precisely place a uniform number of horizontally aligned nanorod LEDs in each pixel.[3]

Based on the comments, the text has been modified as follows.

Before) Page 7, Line 13

Figures 4i-k illustrate images of bad pixels and normal pixels. We define pixels with 15 or fewer fin-LEDs aligned in a 42x42 μm^2 area as bad cells, and out of a total of 2940 pixels, only two defective subpixels were found. Based on this assessment, the assembly accuracy reached 99.93%. Furthermore, the aligned fin-LEDs also show a ~91% face-selective alignment ratio, primarily with the p-GaN side facing over the bottom electrode.

After) Page 8, line 19

Figure 5a-b shows images of bad and good pixels. We defined a bad cell as a pixel with 15 or less but 60 or more fin-LEDs aligned in an area of 42×42 μm^2. This is because fin-LEDs with less than 15 fin-LEDs produce uniform light intensity within the pixel, and fin-LEDs with over 60 fin-LEDs will act as dead pixels due to overlapped alignment of the fin-LEDs. This overlapped alignment can cause leakage current during device processing. The fin-LEDs produced five cells with a total of 588 pixels, and only two defective sub-pixels were found out of a total of 2940 pixels.

Before) Figure 4 To reduce confusion, we divided it into two figures.

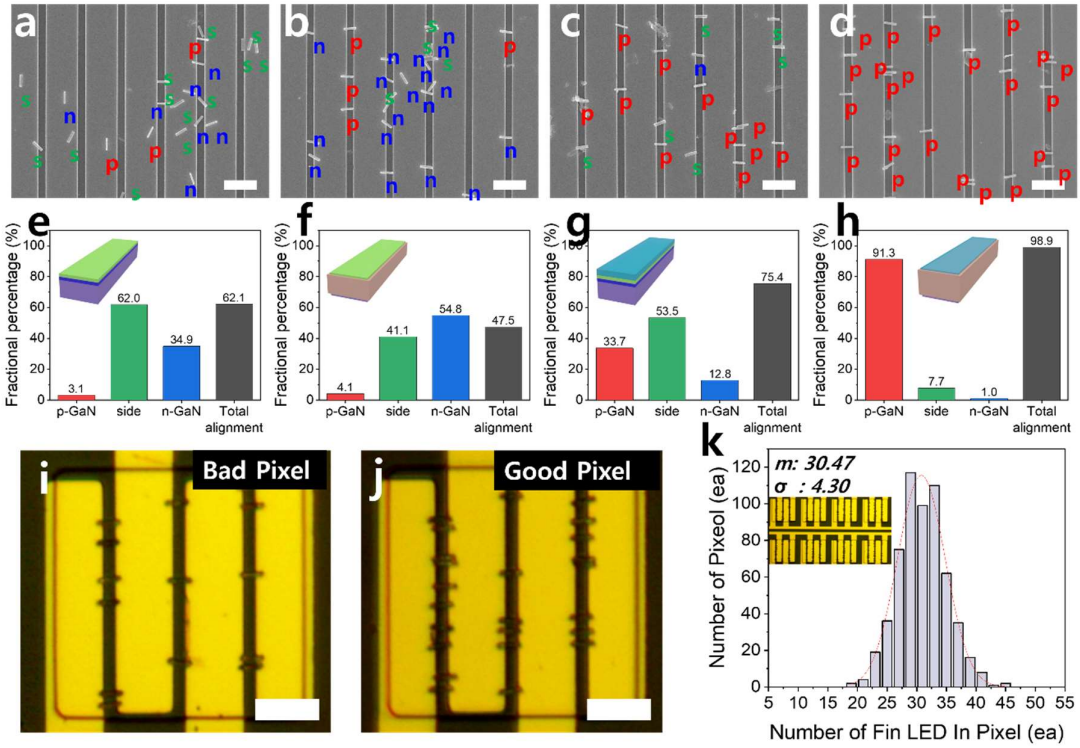
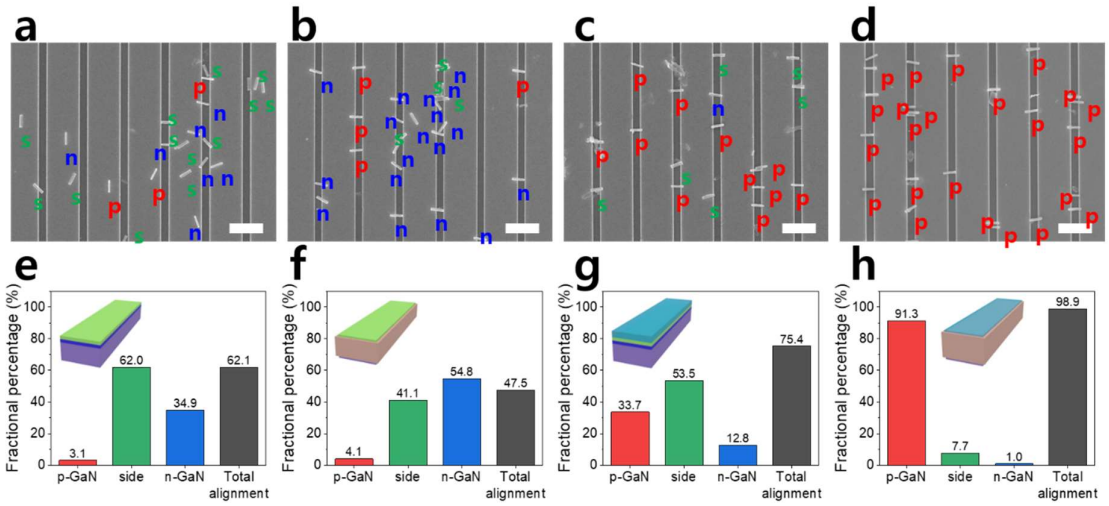


Figure 4. Self-assembly results of differently structured fin-LEDs by DEP force. **a–d,** SEM image of fin-LED, fin-LED@SiO_2, ITO/fin-LED, and ITO/fin-LED@SiO_2 structures. To align the fin-LEDs of all structures, a sinusoidal function with a voltage of 20 V_{pp} and a frequency of 10 kHz was applied 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. **e–h,** Fractional ratios of different contacts of fin-LED, fin-LED@SiO_2, ITO/fin-LED, and ITO/fin-LED@SiO_2 structures. **i–k,** Optical

microscope (OM) image of Fin LED Array Cell assembled using DEP method **i.** Bad pixel : fin LED assembled in pixel (number of fin LEDs : 14 ea) **j.** Good pixel : fin LED asembled in pixle (number of fin LEDs : 25 ea) **k.** Distribution of fin LED count per pixel , Insect image : Fin LED pixel array image (pixel size: 40 x 40 μm^2). All scale bars represent 10 μm.

After) Figure 4 and figure 5



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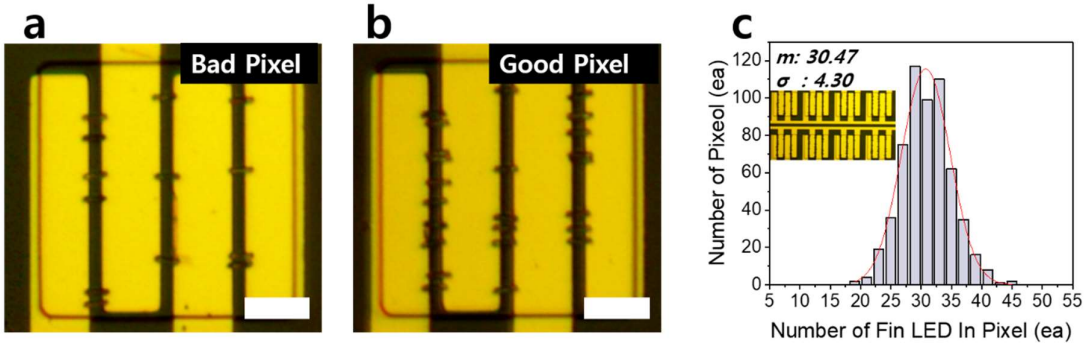
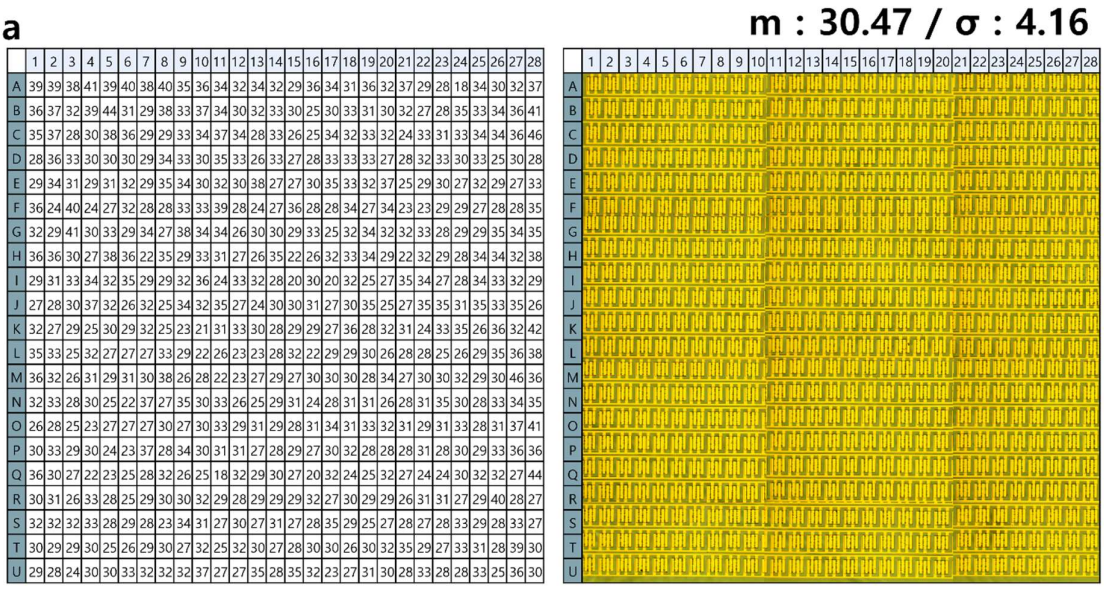


Figure 5. DEP alignment of fin-LEDs in the pixel **a–b,** Optical microscope (OM) image of Fin LED Array Cell assembled using DEP method **a.** Bad pixel: fin LED assembled in pixel (number of fin LEDs: 14 ea) **b.** Good pixel: fin LED asembled in pixle (number of fin LEDs: 25 ea) **c.** Distribution of fin LED count per pixel , Insect image : Fin LED pixel array image (pixel size: 42 x 42 μm^2). All scale bars represent 10 μm.

After: Supporting Figure 9, data for five devices with 588 pixels has been added.



b **m : 31.06 / σ : 6.40**

	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	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
E	35	28	28	27	37	32	31	32	25	31	30	30	32	24	30	32	22	30	30	30	32	30	28	41	37	26	26	31
F	41	33	27	29	28	30	28	24	20	31	28	27	25	20	32	27	42	30	35	24	32	39	37	25	22	15	33	41
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
L	39	39	37	33	32	39	36	35	28	28	25	25	25	33	30	42	34	39	37	30	39	33	31	34	35	38	26	37
M	39	40	24	23	32	34	30	34	34	29	30	28	31	35	29	43	25	26	35	31	22	33	26	33	19	21	20	36
N	45	27	25	29	34	23	16	27	29	34	34	23	27	27	32	30	33	33	36	28	34	33	36	32	20	26	37	40
O	51	23	27	23	23	21	31	28	31	28	24	34	29	31	28	35	41	31	31	26	40	42	33	44	38	27	18	35
P	35	44	38	32	24	29	33	27	31	25	32	40	39	26	29	28	25	35	35	38	34	40	22	38	25	27	27	38
Q	48	30	25	19	28	31	35	35	23	23	31	34	37	34	48	38	35	25	42	40	40	27	31	26	31	23	21	33
R	41	37	35	22	30	29	23	28	36	43	41	34	36	29	36	34	26	37	49	32	28	29	32	22	33	35	19	37
S	37	29	36	38	27	27	28	45	36	26	41	34	24	41	34	35	33	48	28	17	25	23	24	33	38	32	35	38
T	35	35	37	29	34	30	32	36	41	39	31	39	37	47	59	32	16	23	23	30	35	22	27	15	28	30	34	44
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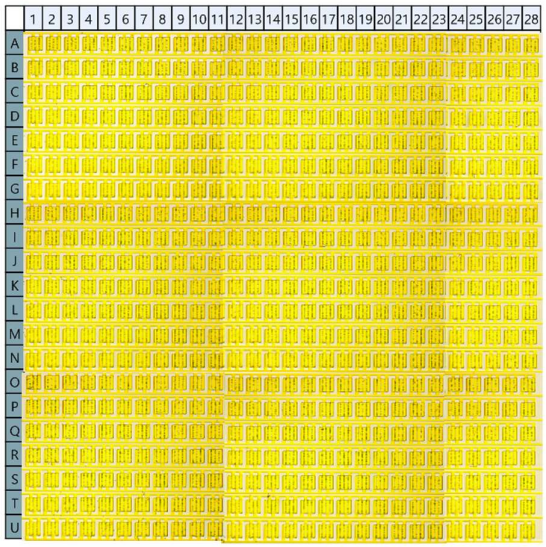

1

c **m : 31.27 / σ : 5.35**

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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
D	35	31	35	43	42	37	33	39	36	40	32	32	35	33	35	32	38	41	37	33	31	36	32	28	34	37	37	34
E	38	29	22	29	31	31	33	30	31	36	29	31	33	34	35	37	32	36	32	35	29	31	32	31	30	36	33	33
F	35	23	29	31	28	29	34	36	34	35	25	28	30	30	33	29	31	33	32	28	37	38	39	36	31	41	34	33
G	35	32	29	30	31	33	32	33	32	32	37	28	31	28	41	32	31	31	35	34	29	30	30	32	29	39	38	33
H	43	26	28	23	33	34	32	31	31	40	30	33	30	36	32	42	37	30	36	34	34	35	32	34	32	33	30	25
I	41	28	33	43	35	32	35	30	37	35	37	32	29	36	34	33	39	28	38	30	32	29	39	36	31	33	35	35
J	31	35	29	27	31	25	41	26	31	29	32	23	32	24	22	31	30	37	36	28	22	35	34	36	38	32	30	31
K	32	23	26	28	23	32	29	27	27	27	25	29	30	22	27	33	26	33	30	28	31	32	36	35	35	33	31	26
L	29	27	31	27	33	19	27	24	28	23	26	25	30	29	30	28	29	32	33	29	34	30	30	36	40	38	28	31
M	32	27	30	30	30	28	26	30	34	27	31	30	28	29	29	24	32	27	27	32	32	37	31	34	37	28	31	37
N	34	26	15	30	25	30	23	30	30	33	31	34	29	31	29	36	32	35	33	34	32	33	35	37	35	45	26	36
O	29	24	21	19	23	29	27	28	22	22	32	29	26	25	31	33	27	26	34	31	36	30	33	36	36	37	40	27
P	22	20	21	28	19	26	25	24	17	28	26	31	22	24	33	32	31	25	27	22	37	29	38	32	35	36	29	25
Q	30	19	21	17	20	23	21	22	28	29	26	21	22	23	22	22	25	30	30	26	26	27	31	29	31	27	33	22
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
S	33	29	27	36	33	22	27	33	27	30	25	26	32	28	32	35	36	29	23	31	31	28	32	34	30	33	30	34
T	32	28	26	29	24	28	29	18	27	28	32	28	25	30	30	25	30	33	31	32	30	31	30	26	27	35	36	36
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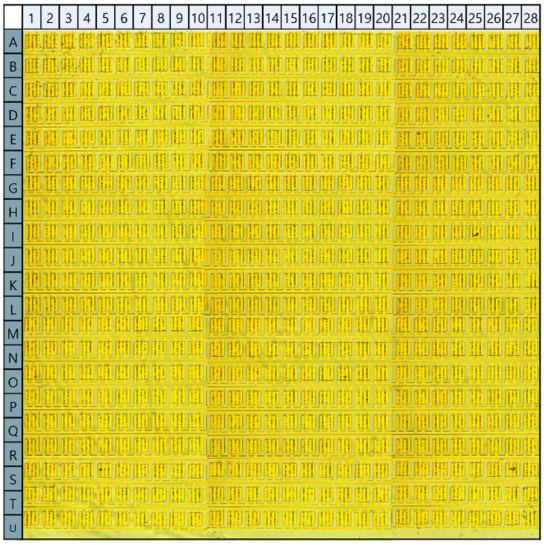

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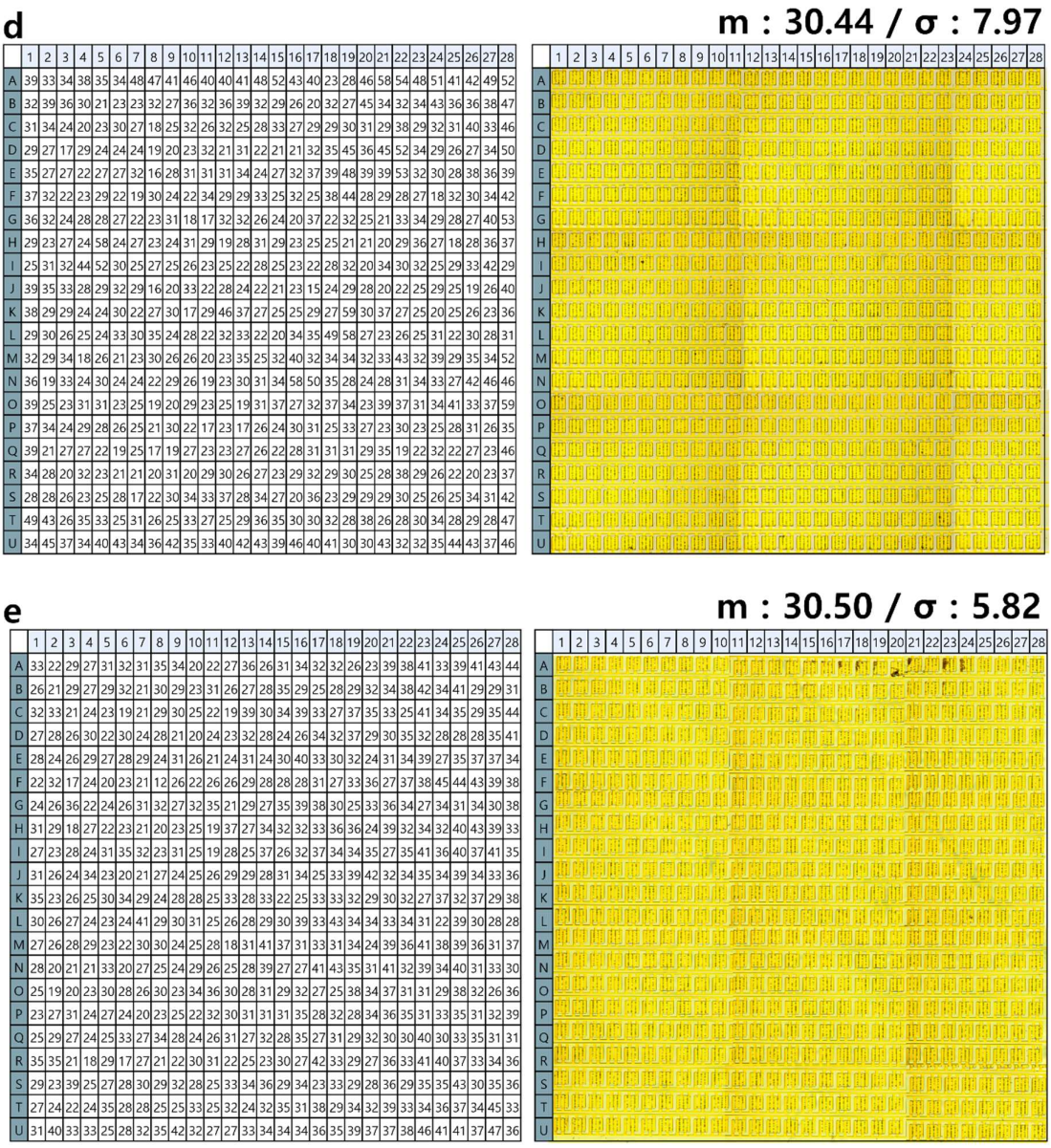

Figure S9. Optical microscope (OM) image of Fin LED Array Cell assembled using DEP method (Left) The number of fin-LEDs that fit into one pixel in the 588 Array Cell. (Right) Full OM image of 21*28 array cell

2. Line 237 In sentence:"…, namely the triple-shell, SiO2-shell, and TiO2-shell, in terms of brightness", the "triple-shell" **seems redundant.**

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The explanation of line 237 has been modified.

Before) Page 7 Line 27

Figures 5a and 5b confirm that the triple-shell fin-LED EL device outperforms its counterparts, namely the ~~triple~~ SiO_2-shell and TiO_2-shell, in terms of brightness and uniformity of light emission.

After) Page 9, Line 4

Figures 6a and 6b confirm that the triple-shell fin-LED EL device outperforms its counterparts, namely the SiO_2-shell and TiO_2-shell, in terms of brightness and uniformity of light emission

3. Line 247-249: Figure 5e precedes Figure 5d.

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The explanation of line s247-249 has been modified. (The order has been changed.)

Before) Page 8, Line 2

Figure 5e shows that, compared to micro-LEDs, the fin-LED displays a relatively modest blue shift with increasing applied voltage. This behavior is attributed to the smaller dimensions of fin-LEDs, which mitigate the MQW polarization effect. Figure 5d shows the current density-voltage (J-V) curve of the fin-LEDs. The turn-on voltages for SiO_2, TiO_2, and triple-shelled fin-LEDs are 2.6 V, 2.7 V, and 2.6 V, respectively, with brightness at the turn-on voltage of 10.78 cd/m², 5.1171 cd/m², and 47.495 cd/m², respectively. Among these, the triple-shelled fin-LED exhibits the lowest leakage current density. This substantial reduction in leakage current is thus achieved through improved passivation and face-selective alignment.

After) Page 9, Line 16

Figure 6d shows the current density-voltage (J-V) curve of the fin-LEDs. The turn-on voltages for SiO_2, TiO_2, and triple-shelled fin-LEDs are 2.6 V, 2.7 V, and 2.6 V, respectively, with brightness at the turn-on voltage of 10.78 cd/m², 5.1171 cd/m², and 47.495 cd/m², respectively.

Among these, the triple-shelled fin-LED exhibits the lowest leakage current density. This substantial reduction in leakage current is thus achieved through improved passivation and face-selective alignment. Figure 6e shows that, compared to micro-LEDs, the fin-LED displays a relatively modest blue shift with increasing applied voltage. This behavior is attributed to the smaller dimensions of the fin-LEDs, which mitigate the MQW polarization effect.

4. Line 254: “Figures 5f-g illustrate the array cell containing 588 pixels...”. Figure 5g in comparison with 5f, does not look like the right one as it shows a small pixel.

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The image in figure 5f image has been modified.

Before) Figure 5

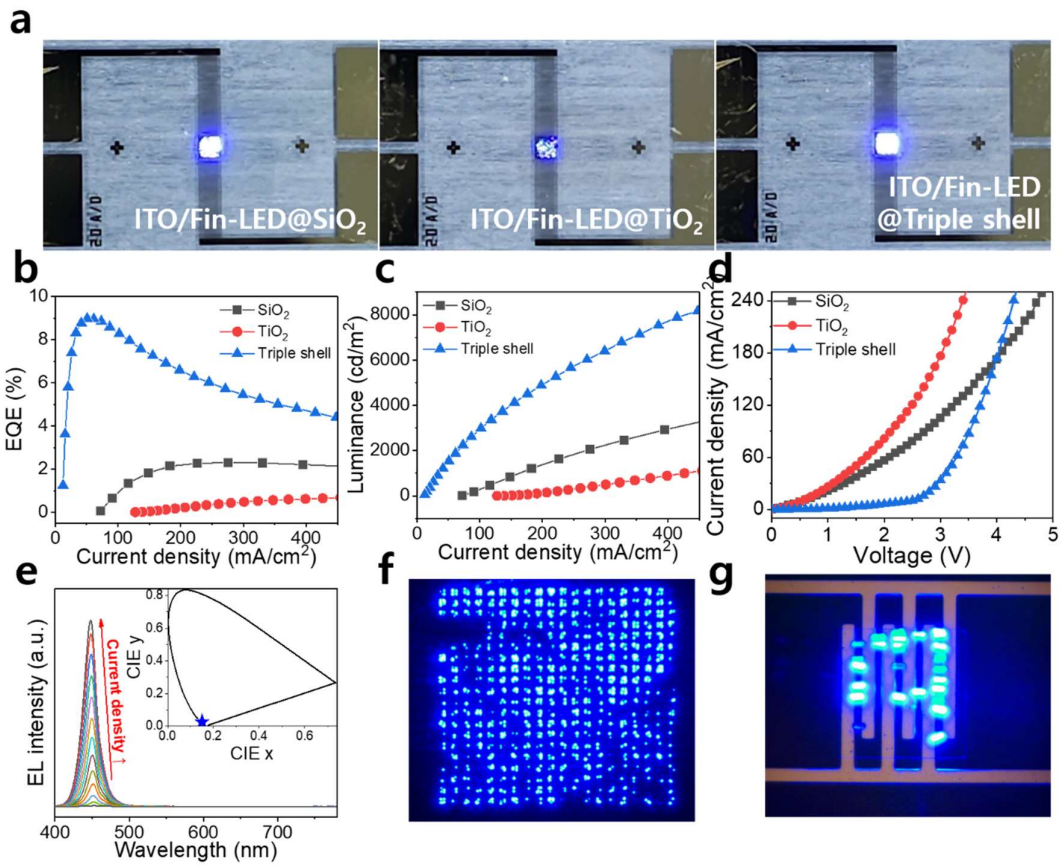

Figure 5. EL characteristics of fin-LED devices according to fin-LED shell materials. **a,** Photographs of EL emission images. A voltage of 3.5 V was applied to all devices and the light

emitting area was 1 × 1 mm^2. **b,** External quantum efficiency (EQE)-current density curve. **c,** Luminance-current density (L-J) curve. **d,** Current-voltage (I-V) curve in 0 to +5 V range. **e,** EL spectra and CIE color coordinates according to current density. **f,** Fin-LED array cell emission images of fin-LED array. **g,** Magnified optical microscope image of fin-LED pixel (fin-LED array : 21x28 array /total 588 pixels, pixel size: 40 x 40 μm^2)

After: Figure 6

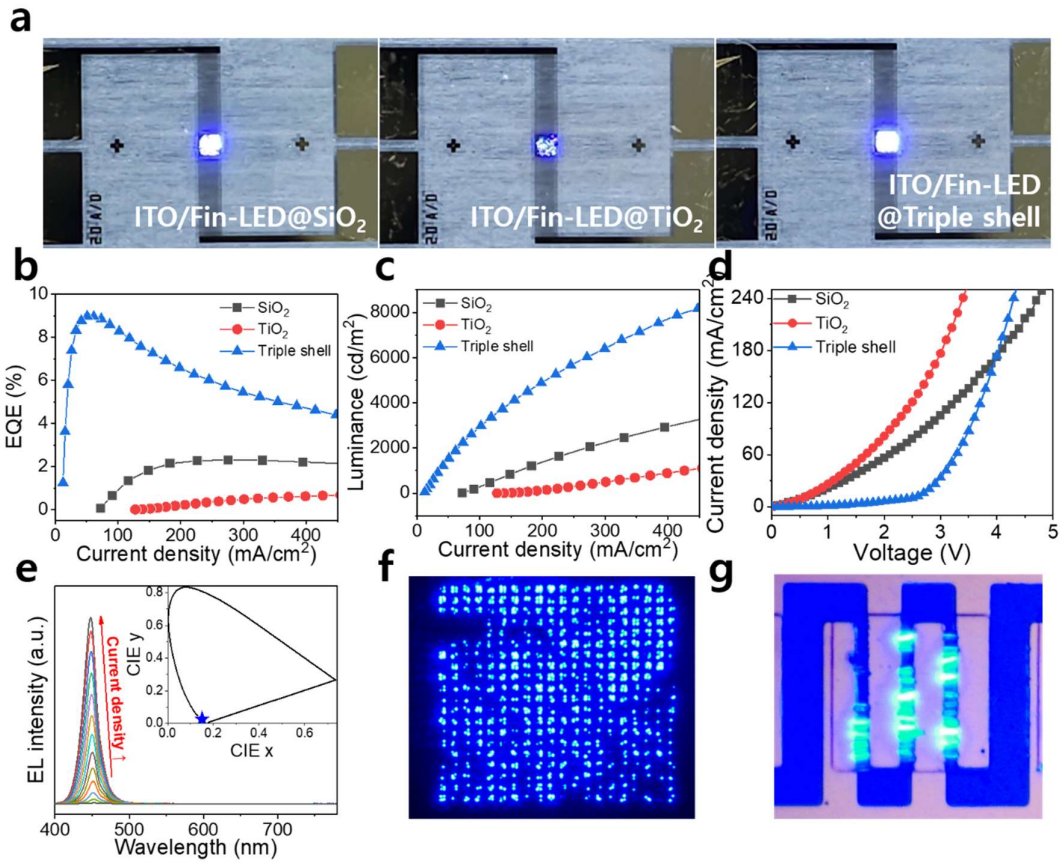

Figure 6. EL characteristics of fin-LED devices according to fin-LED shell materials. **a,** Photographs of EL emission images. A voltage of 3.5 V was applied to all devices and the light emitting area was 1 × 1 mm^2. **b,** External quantum efficiency (EQE)-current density curve. **c,** Luminance-current density (L-J) curve. **d,** Current-voltage (I-V) curve in 0 to +5 V range. **e,** EL spectra, and CIE color coordinates according to current density. **f,** Fin-LED array cell emission images of fin-LED array. **g,** Magnified optical microscope image of fin-LED pixel (fin-LED array: 21 × 28 array / total 588 pixels, pixel size: 42 × 42 μm^2)

5. Line 43. “Upon transferring nanorod-LED display technology by our team, the Samsung Display Company (SDC) reported the successful fabrication of a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process, highlighting the various advantages of the DEP process”. This sounds a causal sentence implying the SDC work was based on the work of this team. Rewording recommended. Perhaps replace “Upon” with “following”.

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The explanation in line 43 has been modified.

Before) Page 2, Line 8

Upon transferring nanorod-LED display technology by our team,[21-25] the Samsung Display Company (SDC) reported the successful fabrication of a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process, highlighting the various advantages of the DEP process.[26-27]

After) Page 2, Line 22

Following the transfer of nanorod-LED display technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated the practical possibility of the DEP process by the fabrication of a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process and inkjet printing process. These reports suggested the various advantages of the inkjet-DEP process, such as low-cost nanorod materials, fast assembly speed matching commercial inkjet speed, and high possibility of transfer yield, promising a bright future for micro-LED manufacturing.[26-27]

6. Page 2. “These nanorod-LEDs autonomously align on subpixel electrodes using fluidic assembly”. If they align autonomously, then what is the purpose of the fluidic assembly? Word “autonomously” should be reworded or omitted.

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The overall introduction has changed. Please refer to the revised introduction provided on the page with Reviewer comment 1.

7. Line 96: What are the superior optical characteristics that author refer to on line 96. Do they mean a stronger light extraction efficiency? Please clarify.

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The explanation of line 96 has been modified.

Before) Page 3, Line 23

Figure 1b presents SEM images that compare the fabricated fin-LEDs with nanorod-LEDs. The fin-LEDs exhibit a volume and surface area similar to those of nanorod-LEDs but show superior optical characteristics.

After) Page 4, Line 12

Figure 1b shows an SEM image comparing the fabricated fin-LED and nanorod LED. Fin-LEDs have similar volumes and surface areas as nanorod LEDs, but exhibit superior optical properties due to their vertical emission and large MQW area. Vertical emission corresponds to the direction perceived by the eye.

8. Line 50: What is the goal of discussing nanorod LEDs in this work? It is understandable that finLEDs with a larger active region are better than nanorod LEDs. Perhaps authors should consider eliminating this section as it seems a distraction from the main point.

Our response: Thank you for your valuable comments.

The discussion of nanorod LEDs in line 50 provides a clear context for the advantages of fin-LEDs in our study. By comparing nanorod LEDs and fin-LEDs, we aim to highlight that fin LEDs offer superior emission efficiency and overall performance due to their larger active MQW areas.

We understand that this discussion may diverge from the main point of the study. However, since most sub-micron LEDs currently being developed are nanorod LEDs, this comparison is

essential to emphasize the advantages of fin-LEDs, thereby strengthening the importance and impact of our work.

9. Figure 1c. Why the emissions related to the EBL and MQW layers are not apparent in the nanorod LEDs. In CL, at least, due to its high sensitivity, it should have some signature?

Our response: Thank you for your valuable comments.

Table R1 compares the volumes of MQW, EBL, and n-GaN between nanorod LEDs and fin-LEDs. In the case of fin-LEDs, the CL spectrum shows a high intensity of the MQW and EBL layers located at the top, similar to an EL device with the P-GaN surface at the top. However, the sensitivity of the n-GaN layer located at the bottom is relatively low. On the contrary, in nanorod LEDs, the CL spectrum, detected from a smaller surface area, shows lower emission from the EBL and MQW layers. In contrast, the n-GaN layer, which occupies a larger area, shows higher intensity. Additionally, nanorod LEDs are exposed to plasma for extended periods during the fabrication process. This can cause damage to the MQW and AlGaN layers, resulting in lower intensity. The same trend is observed in micro PL measurements (**Figure 2b**).

	MQW (μm^3)	EBL (μm^3)	GaN (μm^3)
Nanorod LED	0.04	0.01	0.90
Fin LED	0.42	0.14	10.64

Table R1. Volume comparison of nanorod and fin-LEDs for MQW, EBL, and GaN

10. Page 4: line 110: how is the 20-fold CL enhancement calculated? Is it based on analysis of individual structures or their groups?

1.Selective-Area Growth of III-Nitride Core-Shell Nanowalls for Light-Emitting and Laser Diodes. In 2014 Conference on Lasers and Electro-Optics, IEEE: 2014; pp 1-2.

2.Molecular beam epitaxial growth and characterization of AlN nanowall deep UV light emitting diodes. Appl. Phys. Lett. 2017, 111.

3.High-brightness lasing at submicrometer enabled by droop-free fin light-emitting diodes (LEDs). Sci. Adv. 2020, 6, eaba4346.

Our response: Thank you for your valuable comments.

We calculated the 20-fold CL enhancement based on the values extracted from the CL spectra of nanorod LEDs and fin-LEDs separated from the substrate. This calculation was based on the analysis of individual structures. The papers attached by the reviewer discuss structures similar to fin-LEDs, but they were fabricated using different methods and analyzed in different contexts. Our method specifically focuses on a comparison of individual nanorod and fin-LED structures to accurately determine the CL enhancement.

Reviewer #2 (Remarks to the Author):

In this manuscript, fin-LEDs that overcome the weaknesses previously reported in nanorod-LEDs have been demonstrated. These fin-LEDs show marked improvements in transfer efficiency and pixel assembly yield compared to former nanorod-LEDs. The increased volume of the MQW (more than 8 times) and the thickening of the EBL (electron-blocking layer) contribute to the observation of strong blue light (as shown in PL, CL, and EL graphs). Additionally, a triple-shell fin-LED EL device was developed, which demonstrates superior performance in terms of passivation, brightness, and emission uniformity. By enhancing the performance of fin-LEDs, significant contributions to the advancement of next-generation inorganic displays are anticipated. Please refer to the following comments.

1.The size distribution of fin-LEDs should be provided. The authors used millions of chips for these experiments. However, it seems that the size of the fin-LEDs is not uniform, as shown in Figures 1b and 2f. The size distribution of fin-LEDs might change the EL distribution. All these effects should be addressed.

Our response: Thank you for your valuable comments.

Figure 2(f) shows that the average size of the fin-LEDs is 4.0 × 0.7 × 1.1 μm, with slight variations in length, width, and height within the error range. It has the following aspect ratio structure to ensure the stability of the EL device. Figure 1b shows fin-LEDs randomly distributed on a silicon wafer. Since fin-LEDs have no orientation without an external electric field, they appear to be oriented differently. Because of this, they appear to be of different sizes. **Figure R1** provides the size distribution data of fin-LEDs produced on a 4-inch wafer. Since the fin-LED size and MQW do not vary significantly within micrometers (±7.98%), the EL emission wavelength does not differ depending on the size and MQW variation. Additionally, since multiple LEDs are mixed within one pixel, the impact of size and MQW variations on the overall EL distribution is minimized.

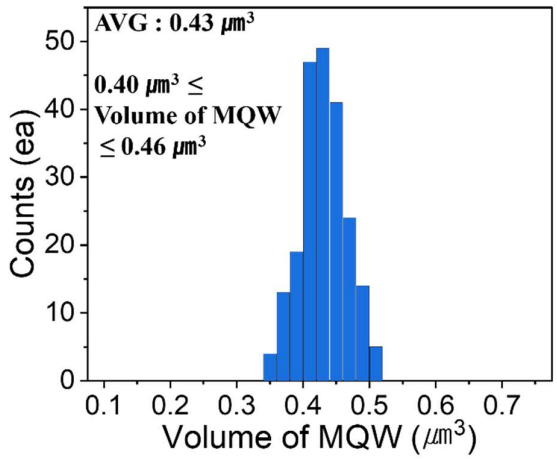

Figure R1. volume of MQW distributions of fin-LEDs fabricated on 4-inch wafer

2. In addition, each fin-LED contains a large number of defects at the edges, as shown in **Figure 2f**. It is questionable whether the large number of defects in each fin-LED might affect the uniformity of brightness and, consequently, the uniformity of the pixel. This effect should also be addressed.

Our response: Thank you for your valuable comments.

The pores on the n-GaN surface that may appear to be as defects are actually a result of the precise electrochemical etching (ECE) method used to separate the fin LED from the substrate. This method, employed in the manufacturing of thin LEDs, creates tiny pores that can increase the internal quantum efficiency (IQE) by relieving the stress of the n-GaN layer and enhancing light extraction. While these pores may seem to affect the uniformity of brightness, our results show that the benefits of reduced stress and improved light extraction outweigh any potential negative impact. Furthermore, we have optimized the pore size and distribution to ensure uniformity of the pixel brightness.[8]

3.In the electric field simulation part, FDEP and TDEP are calculated as functions of θx, as shown in Figures 3b and 3d. However, further explanation is required for Figures 3b and 3d in conjunction with Figures 4a to 4h. **It is not clear how such a high yield is achieved from the DEP force or DEP torque differences.**

Our response: Thank you for your valuable comments.

To supplement the answer to the comment, the text has been modified.

Before) Page6, Line 14

We fabricated two groups of fin-LED configurations featuring different fin structures (fin-LED, fin-LED@SiO_2, ITO/fin-LED, and ITO/fin-LED@SiO_2) and different shell materials (ITO/fin-LED@TiO_2, ITO/fin-LED@SiN_x, ITO/fin-LED@SiO_2/Al_2O_3/SiO_2) to compare face-selective assembly (SEM images in **Figure S6**). We conducted DEP assembly tests on four distinct fin-LED structures, visually represented in **Figure 4** and elaborated further in **Figure S7**. Baseline conditions were established at a frequency of 10 kHz and a voltage of 20 V_{pp}. As seen in **Figure 4**, various fin-LEDs dispersed in acetone underwent self-assembly on the electrode surface. Observations of the fin-LED structure indicated a substantial presence of non-assembled fin-LEDs, with random placement predominantly on the shell face and at the n-GaN face contacts. In contrast, the ITO/fin-LED structures yielded consistent simulation results, demonstrating an enhanced tendency for p-GaN face contact. Further substantiating these findings, SEM images of the ITO/fin-LED@SiO_2 structure revealed that approximately 91.3% of fin-LEDs exhibited selective assembly with a downward orientation, establishing contact between the ITO layer of p-GaN and the bottom electrodes. It was also noted that most ITO/fin-LED@SiO_2 displayed alignment tendencies spanning two interdigitated electrodes.

We conducted additional assembly experiments based on the ITO/fin-LED@Shell structure with various shell materials (**Figure S7**) under different conditions. Face-selective assembly was only possible using low dielectric constant SiN_x and SiO_2-shelling ITO/fin-LEDs. In contrast, the high dielectric constant shell of the ITO/fin-LED@TiO_2 structure did not lead to face-selective alignment, as shown in **Figure S7**. These results suggest that face-selective assembly is achievable when the dielectric constant of the shelling material surrounding the fin-LED is low.

We also compared alignment based on the ITO/fin-LED@SiO_2 structure as a function of the solvent and determined the optimal face-selective alignment. We performed experiments by comparing their dielectric constants for each medium (hexane, acetone, and IPA). **Figure S8a** illustrates the results of face-selective alignment as a function of applied voltage when the medium is hexane. In addition to the lack of p-GaN or n-GaN face-selective

alignment, many fin-LEDs remained unaligned between the electrodes. However, **Figures S8a,c** demonstrate that acetone and IPA enable face-selective alignment of over 90% between 20 ~ 40 sin(ωt) voltage as the dielectric constant of the medium increases. These figures indicate that face-selective alignment is more achievable when the medium solvent has a higher dielectric constant (e.g., acetone and IPA). Figure S8d confirms that face-selective alignment achieves the highest values at applied frequencies between 10^1 and 10^2 kHz under an acetone medium using a 20 sin(ωt) voltage. The decrease in fin-LED rotation at a high frequency of 10^3 kHz can be attributed to the relatively lower T_{DEPx} values of the fin-LED.

Video S1 demonstrates the rapid and precise alignment of fin-LEDs under an electric field, moving precisely toward the positions of the pixels. LEDs that do not align correctly with the pixels remain in the solvent during assembly. After completion, any misaligned fin-LEDs can be recovered, leaving no LEDs outside the designated pixel areas. **Figures 4i-k** illustrate images of bad pixels and normal pixels. We define pixels with 15 or fewer fin-LEDs aligned in a 42x42 μm^2 area as bad cells, and out of a total of 2940 pixels, only two defective subpixels were found. Based on this assessment, the assembly accuracy reached 99.93%. Furthermore, the aligned fin-LEDs also show a ~91% face-selective alignment ratio, primarily with the p-GaN side facing over the bottom electrode. **Figure S9** illustrates the numbers of assembled fin-LEDs on each pixel using DEP and ink-dropping processes within an array cell of 588 sub-pixels. On average, approximately 26 fin-LEDs are assembled on the designated electrodes and aligned within each subpixel, with a standard deviation of 4.07.

After) Page 7, Line 4

We fabricated a group of fin-LED configurations featuring different fin structures (fin-LED**,** fin-LED@SiO_2**,** ITO/fin-LED, and ITO/fin-LED@SiO_2) to compare face-selective assembly (SEM images in **Figures S6a–S6d**). We conducted DEP assembly tests on four distinct fin-LED structures, visually represented in **Figure 4**. Baseline conditions were established at a frequency of 10 kHz and a voltage of 20 V_{pp}. Various fin-LEDs dispersed in acetone underwent self-assembly on the electrode surface. Self-assembly results for the basic fin-LED structure revealed that a significant number of LEDs were not assembled, and the assembled LEDs were mainly randomly assembled on the side and n-GaN face contacts (**Figures 4a and 4e**). Adding a SiO_2 shell to the side of the fin-LED (fin-LED@SiO_2) reduced

the total alignment of the LEDs compared to the assembled result of the basic fin-LED, but increased the fraction of LEDs aligned to the n-GaN side (**Figures 4b and 4f**). These differences occurred because the electrical conductivity of SiO_2 used as the shell material was lower than that of the medium. As simple examples, spherical particles composed of SiO_2 experience negative-DEP (n-DEP) in a similar low-frequency range as used for self-assembly of fin-LEDs, while spherical particles composed of GaN experience p-GaN in that frequency range.[39,40] Therefore, it is intuitively clear that when the fin-LED@SiO_2 with coexisting p- and n-GaN and SiO_2 experiences DEP, the face on which the LED is aligned on the electrodes is determined by the exposed material. Because the magnitude of the electric field increases closer to the electrode, the n-GaN side, which has the highest electrical conductivity among the constituent materials of the fin-LED@SiO_2, tends to face the electrode. For this reason, it is obvious that ITO/fin-LED in which an ITO layer having much higher electrical conductivity than n-GaN is added on p-GaN has a greater proportion of LEDs aligned with the p-GaN side than the n-GaN side on electrodes (**Figures 4c and 4g**). Similar to the basic fin-LED alignment results, the high proportion of ITO/fin-LED aligned on the side is due to the exposure of the side (GaN epi- and ITO layers) of the LED. Ultimately, further substantiating these findings, the SEM image of the ITO/fin-LED@SiO_2 structure revealed that approximately 91.3% of fin-LEDs exhibited selective assembly with a downward orientation, establishing contact between the ITO layer of p-GaN and the bottom electrodes (**Figure 4d**). It was also noted that most ITO/fin-LED@SiO_2 displayed alignment tendencies spanning two interdigitated electrodes (**Figure 4h**).

We conducted additional assembly experiments based on the ITO/fin-LED@shell structure with various shell materials (ITO/fin-LED@SiO_2, ITO/fin-LED@TiO_2, ITO/fin-LED@SiN_x, and ITO/fin-LED@SiO_2/Al_2O_3/SiO_2) under identical conditions (**Figures S6d–S6g**). Face-selective assembly was only possible using low dielectric constant SiN_x and SiO_2-shelling ITO/fin-LEDs. In contrast, the high dielectric constant shell of the ITO/fin-LED@TiO_2 structure did not lead to face-selective alignment, as shown in **Figure S7**. These results suggest that face-selective assembly is achievable when the dielectric constant of the shelling material surrounding the fin-LED is lower than that of the medium.

4.The bad pixels and good pixels were defined. If a bad pixel is defined as a pixel with 15 or fewer fin-LEDs, it is anticipated that using a large number of chips for alignment will lead to

fewer bad pixels. Is it possible to quantitatively explain the relationship between the number of bad pixels and the number of input chips?

Our response: Thank you for your valuable comments.

The definition of a defective pixel is contingent upon pixel size. Assuming 6 to 14 LEDs per row, we have defined the optimal LED count for a 42x42μm² pixel as an average of 30. To compensate for LEDs that do not turn on due to contact failures, we have established a threshold: if the average LED count is less than 15, applying current to more LEDs can negatively impact performance. Additionally, using high-concentration ink limits the number of fin-LEDs per pixel, often resulting in discarded LEDs. Arranging more than 60 fin-LEDs within a pixel not only increases the cost but also induces leakage current during device manufacturing, thus defining such pixels as defective. Therefore, the number of fin-LEDs must be appropriately maintained between 15 and 60 to avoid performance degradation and manufacturing defects. This research focuses on utilizing DEP to selectively align fin-LEDs on a surface by controlling the surrounding solvent and fin-LED shell. We have identified the potential for pixelation.

Please refer to the revised text attached to reviewer 1's question 1.

5.The production yield of 99.93% is unclear. Please explain the calculation method of the production yield.

Our response: Thank you for your valuable comments.

We fabricated and evaluated five fin-LED array devices containing 588 pixels to determine the production yield. On average, about 30 fin LEDs (ranging from 27 to 33) are aligned into a pixel measuring 42x42 μm² with one ink drop. As noted in the above answer regarding a threshold, we established a bad pixel: the average LED count is less than 15. In evaluating the five fin-LED array devices, only two pixels had fewer than 15 fin-LEDs aligned. Thus, out of 2940 pixels, 2938 pixels had more than 15 fin-LEDs aligned, resulting in a production yield of 99.93%.

Please refer to revised **figure S9** attached to reviewer 1's question 1.

6. In Figure 5d, the threshold voltage of the triple-shell LED shifts positively with a steep increase in current density as the driving voltage increases. However, the mechanism of the increasing EQE is unclear in the manuscript. This should be further addressed.

Our response: Thank you for your valuable comments.

The increase in EQE can be attributed to two main factors. First, the triple shell passivates defects on the fin-LED surface, as reported in previous studies. Second, the outermost shell of the triple shell is SiO_2, which significantly increases the face-selective alignment of fin-LEDs when aligned, similar to the single SiO_2 shells. This minimizes electrical leakage and improves EQE. As a result, despite potential causes of leakage current, such as dust and low-grade lithography facilities, the overall EQE is enhanced by the improved face-selective alignment and passivation provided by triple shelling.

We have added an additional explanation to the text as follows.

Before) Page7, Line 23

We fabricated three fin-LED electroluminescent (EL) devices using TiO_2, SiO_2, and a triple-shell $SiO_2/Al_2O_3/SiO_2$ configuration. These differently aligned EL devices were manufactured using fin-LEDs, employing $SiO_2/Al_2O_3/SiO_2$ triple-shells to reduce surface defects and maintain a high face-selective ratio. **Figure 5a** visually compares emission images captured from the three types of fin-LED EL devices operated at 5 V. **Figures 5a and 5b** confirm that the triple-shell fin-LED EL device outperforms its counterparts, namely the triple-shell, SiO_2-shell, and TiO_2-shell, in terms of brightness and uniformity of light emission. The exceptional performance within the triple-shell configuration is attributed to the effective passivation that results from the face-selective effect.

After) Page 8 Line 34

We fabricated three fin-LED electroluminescent (EL) devices using TiO_2, SiO_2, and a triple-shell $SiO_2/Al_2O_3/SiO_2$ configuration. These differently aligned EL devices were manufactured using fin-LEDs, employing $SiO_2/Al_2O_3/SiO_2$ triple-shells to reduce surface defects and maintain a high face-selective ratio. Additionally, Al_2O_3 also serves as an etch block layer during device fabrication, and the passivation further complements the E-beam deposition passivation, providing more effective overall passivation.[26-27] **Figure 6a** visually compares

emission images captured from the three types of fin-LED EL devices operated at 5 V. **Figures 6a and 6b** confirm that the triple-shell fin-LED EL device outperforms its counterparts, namely the SiO_2-shell and TiO_2-shell, in terms of brightness and uniformity of light emission. The difference between the SiO_2-shell and the TiO_2-shell appears to be due to face-selective alignment. In addition, since the triple shell shows alignment similar to that of the SiO_2 shell, the difference can be attributed to the passivation effect as well as the superiority of surface-selective alignment.

7.In the conclusion, it is mentioned that the EQE is slightly lower than in prior results. However, the method for improving the EQE was not properly addressed. This should also be further addressed.

Our response: Thank you for your valuable comments.

Several methods with great potential have been proposed to enhance the maximum EQE of ultra-small LEDs. These include growth techniques that significantly reduce defects by controlling indium (In) levels during nano LED fabrication, etching methods that greatly minimize defects of 3.5 μm-LED (EQE = ~ 28.5%) through neutral beam etching[9], and shell coating technologies of nanorod LEDs that perfectly passivate surface defects (EQE = 20.2 ~ 22.2%) using sol-gel SiO_2 coating method.[3]

In this paper, we achieved an EQE of ~9.1% or more, not by using the highest reported EQE methods but by employing conventional dry etching and passivation techniques. We use passivation technology with a $SiO_2/Al_2O_3/SiO_2$ triple-shell coating through conventional PECVD and ALD coatings to passivate the surface defects. Face-selective DEP alignment technology is mainly applied to decrease the electrical leakage of misaligned fin-LEDs and increase EQE. While not matching the best previously reported EQEs, our approaches achieve a reasonably high EQE despite triple-shell passivation and low leakage by the face-selective assembly. These challenges include defects and leakage caused by low cleanliness and lower-grade lithography equipment typical of academic fabrication facilities.

In future, we can realize a significantly high EQE by obtaining the best-qualified wafer and high indium wafer, reducing etched defects, improving the process environment, and achieving optimal passivation in harmony. This potential for improvement instills hope that, even in the face of challenges, we can enhance the overall performance of DEP fin-LEDs.

Reviewer #3 (Remarks to the Author):

The authors presented a novel, FIN-based approach for micro-LEDs. This is a very timely, important topic, and the results are interesting and of significance. I recommend publication pending the following revisions.

1. The Comparison of different transfer methods from the introduction part, the idea of this Fin-LEDs with DEP is to reduce the cost and increase the yield. In table S1, DEP method is compared with other transfer methods. But the transfer yield of LASER and Stamp is higher than DEP. LASER also has a small chip size. In the main text, it is mentioned that LASER method may generate more damages and has high requirement of parameters thus increasing cost. However, the analysis of damages is very limited in the following part. For **the comparison cost, the parameter requirement is also not very low from your following discussions**, so it is a bit confusing about the cost comparison and how did the authors lower the cost by DEP. In addition, the assembly speed is lower in your method.

Our response: Thank you for your valuable comments.

For a 55" 4K TV, the required micro-LED chip size is 9 micrometers, while for a 5.8" QHD display, it must be 3 micrometers, with a minimum internal quantum efficiency (IQE) of 25%.[10,11] The largest cost contributor in micro-LED production is the epitaxy process (chip fabrication). Additionally, transferring micro-LEDs using an interposer (groove) increases the overall cost. Therefore, aligning fin-LEDs via FSA and DEP without the use of an interposer and directly transferring the LEDs to achieve a high transfer yield represents a promising technology for the commercialization of micro-LEDs.

Considering these factors, we have revised the introduction and Table S1 accordingly, representing chip costs relative to chip size. In the case of LLO (Laser Lift-Off), the chip cost increases as a buffer layer is required to reduce damage to the chip.[12-14] Although many sources suggest that LLO incurs high costs, specific figures are rarely mentioned.

Before) Table S1

	Ours	**Fluid assembly**	**LASER Transfer**	**Stamp transfer**

	(Dielectricphoresis)			
Chip size (μm^2)	0.196 ~ 2.28	> 400	> 1	> 100
Assembly speed	≈1 million per hour	≈50 million per hour	≈100 million per hour	≈1 million per hour
Transfer yield (%)	99.93	65.00	99.99	99.99

Table S1. Comparison for micro-LED transfer method.

1. Lin, Y.-C., Chen, L.-Y. & Chiu, F.-C. Lossy Mode Resonance-Based Glucose Sensor with High-κ Dielectric Film. *Crystals* **9**, 450 (2019).

2. Zhou, X. et al. Growth, transfer printing and colour conversion techniques towards full-colour micro-LED display. Progress in *Quantum Electronics* **71**, 100263 (2020).

3. Ryu, J. E., Park, S., Park, Y., Ryu, S., Hwang, K., Jang, H. W. , *Advanced Materials* 2023, 2204947 (2023).

4. Anwar, A.R., Lepkowski, S. P., *Laser photoics Rev*. **16**, 2100427 (2022).

5. Gong, Y. Gong, Z., *Advanced materials technologie*. **8**, 202200949 (2023).

After) Table S1

Assembly	Transfer method	Chip size (μm^2)	Chip cost	Transfer Cost	Transfer speed	Transfer yield	Ref
Pick up	Elastomer stamp	~1256	Middle	High	1M/hr	99.50	[1,2]
	LASER	~1	Low~Middle	Middle~High	100M/Hr	99.80	[1,2]
Fluidic assembly	Wave energy	~1256.00	Middle	Middle	NR	97.00	[3]
	Gravity and capillary force	~1256.00	Middle	Middle	1M/hr	99.90	[4]
	Vander walls force	1256.00	Middle	Middle	54K/hr	99.99	[5]

Molten solder	706.50	Middle	Middle	1M/hr	99.88	[6]
magnetic-force-assisted dielectrophoretic self-assembly technology	~980.20	Middle	Middle	NR	99.50	[7]
Dielectricphoresis	~0.193	Low	Low	NR	99.98	[8~13]
	2.80	Low	Low	1M/hr	99.93	**Our works**

Table S1. Comparison for micro-LED mass transfer method.

1. Anwar, A.R., Lepkowski, S. P., *Laser photoics Rev*. **16**, 2100427 (2022).

2. Chen, D., Chen, Y.-C., Zeng, G., Zhang, D. W. & Lu, H.-L. Integration Technology of Micro-LED for Next-Generation Display. *Research* **6**, 0047 (2023).

3. Ryu, J. J. *et al.* Wave energy-assisted fluidic self-assembly of LED chips for display applications. *Journal of Information Display* **23**, 267–272 (2022).

4. Paul J. et al. Display with surface mount emissive elements US patent US009825202B2 (2017)

5. Hwang, J. *et al.* Wafer-scale alignment and integration of micro-light-emitting diodes using engineered van der Waals forces. *Nat Electron* **6**, 216–224 (2023).

6. Lee, D. *et al.* Fluidic self-assembly for MicroLED displays by controlled viscosity. *Nature* **619**, 755–760 (2023).

7. Chang, W. et al. Concurrent self-assembly of RGB microLEDs for next-generation displays. *Nature* **617**, 287–291 (2023).

8. Park, H. K. et al. Horizontally assembled green InGaN nanorod LEDs: scalable polarized surface emitting LEDs using electric-field assisted assembly. *Sci. Rep.* **6**, 28312 (2016)

9. Eo, Y. J. et al. Enhanced DC-Operated Electroluminescence of Forwardly Aligned p/MQW/n InGaN Nanorod LEDs via DC Offset-AC Dielectrophoresis. *ACS Appl. Mater. Interfaces* **9**, 37912–37920 (2017).

10. Sheen, M. et al. Highly efficient blue InGaN nanoscale light-emitting diodes. *Nature* **608**, 56–61 (2022).

11. Cho, H., Kim, D., Lee, S., Yoo, C. & Sim, Y. Efficiency enhancement of submicron-size light-emitting diodes by triple dielectric layers. *J. Soc. Inf. Disp*. **31**, 289–297 (2023).

12. Kim, S. *et al.* Self-array of one-dimensional GaN nanorods using the electric field on dielectrophoresis for the photonic emitters of display pixel. *Nanoscale Adv.* **5**, 1079–1085 (2023).

13. Kim, T., Uthirakumar, P., Cho, Y.-H., Nam, K. H. & Lee, I.-H. Enhanced quantum efficiency of horizontally aligned individual InGaN/GaN nanorod LEDs by self-assembled Ag nanoparticles. *Applied Surface Science* **656**, 159706 (2024).

Before) Page 1, Line 31

Table S1 provides an overview of chip size, assembly speed, and transfer yield for various micro-LED transfer methods. It is crucial to note that the transfer yield depends on the precise positioning of micro-LEDs within pixel grooves. Fluidic self-assembly (FSA) exhibits lower selective transfer rates and requires larger micro-LED chips.[10] In contrast, stamp transfer printing offers the advantages of smaller chip sizes and faster transfer speeds than FSA, albeit with lower repeatability.[10] Despite presenting small chip sizes, rapid transfer speeds, and high accuracy, LASER-based transfer is susceptible to LED chip damage.[17] Additionally, it relies on specific laser parameters and bonding methods, with the significant drawback of higher initial costs.[7-10]

After) Page 1, Line 34

The production cost of micro-LED depends on the chip size, assembly speed, and transfer yield. The smaller the chip size is, the faster the assembly speed is, and the higher the transfer yield is, the lower the unit cost is. **Table S1** provides an overview of chip size, assembly speed, and transfer yield for various micro-LED transfer methods. It is crucial to note that the transfer yield depends on the precise positioning of micro-LEDs within pixel grooves. Fluidic self-assembly (FSA) exhibits lower selective transfer rates and requires larger micro-LED chips.[10]

In contrast, stamp transfer printing offers the advantages of smaller chip sizes and faster transfer speeds than FSA, albeit with lower repeatability.[10] Despite presenting small chip sizes, rapid transfer speeds, and high accuracy, LASER-based transfer is susceptible to LED chip damage when the chip size becomes smaller.[17] Additionally, it relies on specific laser parameters and bonding methods, with the significant drawback of higher initial costs.[7-10] Conventional FSA, laser transfer, and stamp transfer have respective strengths and weaknesses, but each method has critical issues that must be solved prior to commercializing low-cost micro-LEDs.

2. The introduction of DEP method and its advantages is limited. The authors only mentioned that it has several advantages in the **line 44 of the page 2,** but the advantages are not listed clearly. It is a bit unclear about the motivation of choosing DEP as the method. Did someone else use this method for transfer? Some more literature reviews in this part may be helpful to depict the picture of your idea and let readers know this method.
More superiors Luminance properties

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. The explanations of page 1 line 35 to page 2 line 3 have been modified.

Before) Page 2, Line 4

LG Electronics (LGE) recently expanded the FSA-DEP approach, aligning ~40 μm micro-LEDs to subpixel grooves, achieving high assembly production yields with a positive DEP field and a secondary magnetic field.[18] In contrast, to effectively address the challenges of micro-LEDs and FSA processes, our team introduced an innovative display device and manufacturing process using nanorod-LEDs.[19-20] Upon transferring nanorod-LED display technology by our team,[21-25] the Samsung Display Company (SDC) reported the successful fabrication of a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process, highlighting the various advantages of the DEP process.[26-27] These nanorod-LEDs autonomously align on subpixel electrodes using fluidic assembly, including inkjet printing and DEP assembly processes, although no reported transfer yield data are available.[26-28] However, the horizontal orientation of nanorod-LEDs leads to lateral light emission spread, causing limited MQW volume and diminished forward-directed light emission[19-20], as depicted in

Figure 1a.

After) Page 2, Line 12

The micro-LED transfer method under 10 micrometers reported to date is a method that combines the FSA and DEP method. DEP is a method of moving materials by controlling the movement of particles under a non-uniform electric field. This is promising for effectively aligning under 10 micron micro-LEDs as it can quickly move particles to a selective location depending on the strength of the electric field.[28] LG Electronics (LGE) recently expanded the FSA-DEP approach by aligning ~40μm micro-LEDs into subpixel grooves and assembling them using DEP force within the groove through a positive DEP field and secondary magnetic field to improve the site and face-selectivity of micro-LEDs, which cannot be achieved in conventional FSA with high production yield. In contrast, our team introduced an innovative display device and manufacturing process using nanorod-LEDs to effectively address the high material cost of micro-LEDs and the low assembly speed of conventional FSA processes.[19-20] Following the transfer of nanorod-LED display technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated the practical possibility of the DEP process by fabricating a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process and inkjet printing process. These reports demonstrates the various advantages of inkjet-DEP process, such as low-cost nanorod materials, fast assembly speed matched with commercial inkjet speed, and high possibility of transfer yield, promising a bright future for micro-LED manufacturing.[26-27]

3. As table S2 shows, the face selective alignment ratio of this work is higher than other nanorod LEDs. But the comparison with other transfer methods is lacked from here. What is the alignment performance of other methods?

Our response: Thank you for your valuable comments.

Only one transfer method, excluding DEP, has been reported for chip sizes of 10 μm^2 or less. This method involves separating nanorod LEDs from the wafer using laser lift-off (LLO). The transfer yield for this method is reported to be 99.5%. However, while LLO shows promise for separating nano-LEDs, the performance of the devices after the transfer was not reported.[15] In contrast, the reported DEP transfer of nanorod LEDs shows promise for high transfer yields

and device performance in sub-micron scale LEDs. On this basis, fin-LEDs with face-selective alignment show significant potential.

4. The authors mentioned that the EQE of DEP Fin-LED is 9.1%, which is a bit lower than nanorod LEDs. Because it is short-wavelength LED, the 9.1% EQE performance is not dominant in the current industry. It seems that there is a trade-off between efficiency and other factors.

Our response: Thank you for your valuable comments.

In the case of the reported nanorod LED, a wafer with a high indium content was used.[4] As the indium content increases, non-radiative recombination due to defects occurring during dry etching decreases. Additionally, the relatively low EQE of our DEP fin-LEDs can be attributed to the research being conducted in a school-level clean room environment, where particle contamination (index of particles larger than 0.1㎛ in 1㎥ air) can cause leakage sources. Furthermore, passivation using the sol-gel method involves the formation of nanoparticles, which can generate particles that affect the performance evaluation when applied to actual fin-LEDs.[3] We can realize a significantly high EQE by obtaining the best-qualified wafer and high indium wafer, reducing etched defects, improving the process environment, and achieving optimal passivation in harmony. This potential for improvement instills hope that, even in the face of challenges, we can enhance the overall performance of DEP fin-LEDs.

5. In figure S1(a), there is a typo. It should be “emission” instead of “emission”.

Our response: Thank you for your valuable comments.

We sincerely apologize for any confusion. Figure S1 (a) has been modified.

Before)

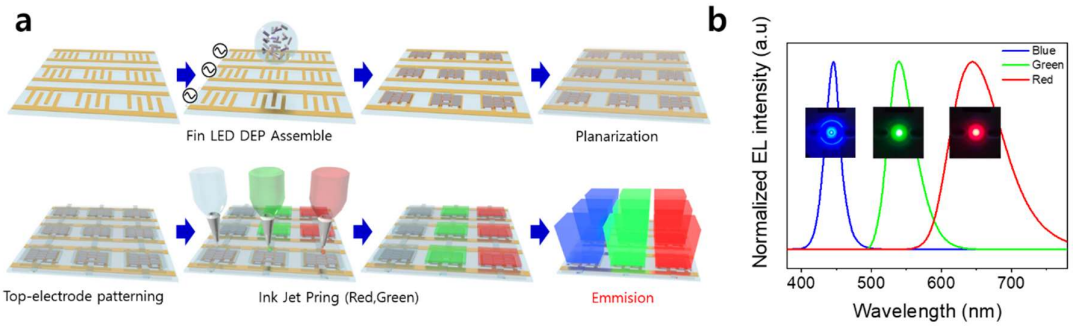

Figure S1. (a) Schematic of Implementing a Full-Color Fin LED Display. (b) Fin LED Color Conversion RGB EL Spectrum (Blue: Fin LED, Green: Fin LED@InP QDs Color Film, Red: Fin LED@R6832 Phosphor Color Film.

After)

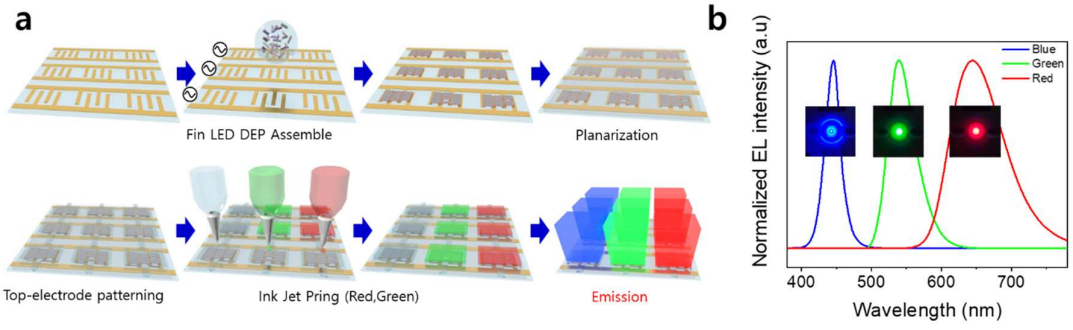

Figure S1. (a) Schematic of Implementing a Full-Color Fin LED Display. (b) Fin LED Color Conversion RGB EL Spectrum (Blue: Fin LED, Green: Fin LED@InP QDs Color Film, Red: Fin LED@R6832 Phosphor Color Film.

6. From the section "Properties of vertically oriented Fin-LEDs vs Horizontally Oriented Nanorod-LEDs", the comparison focuses on the Fin-LED and nanorod-LED. The authors mentioned that the MQW volume is an advantage of Fin-LED compared to nanorod LED, but how about the comparison with other structures or methods? Is the MQW and front emission still an advantage?

Our response: Thank you for your valuable comments.

As summarized in Table R2, most sub-micron-scale LEDs, excluding nanorod LEDs, currently adopt a front emission structure. Compared to the side emission in nanorod LEDs, front emission does not require additional reflective processes within the device to enhance light extraction efficiency. Additionally, it can be confirmed that the light is emitted in the direction recognized. This makes front emission particularly advantageous in sub-micron LEDs. Furthermore, the slightly larger MQW volume in fin-LEDs remains an advantage compared to other structures or methods. The increased active region in fin-LEDs can contribute to higher emission efficiency and overall performance.

Process	**Transfer**	**Emission direction**	**Size (μm^2)**	**Luminance (cd/m^2)**	**EQE (%)**	**Ref**
Top down	Mesa	Front	12.25	Non-reported	26	[9]
Top down	SAMs	Front	0.44	1070	6.21	[8]
Top down	LLO	Front	0.785	Non-reported	Non-reported	[15]
Bottom up	MBE	Front	16	~10^6	0.2	[14]
Top down	DEP	Front	2.8	8640	9.1	Our works

Table R2. Sub-micron LED transfer method and luminance properties.

7. In the Line 103 of page 3, the authors mentioned the decreased surface-defect density and its reason. But it is better if the authors can add some references here to support this conclusion, and the decreased surface-defect density can be reflected by analyzing the EL or PL spectra such as the full-width at half-maximum. The analysis of EL and PL spectra is a bit over-simplified.

Our response: Thank you for your valuable comments.

In the case of LEDs fabricated from InGaN/GaN MQW wafers grown on the c-plane using a

top-down approach, surface dangling bonds generated during the dry etching process act as non-radiative recombination centers. Due to their long length, nanorod LEDs require a longer etching time. This prolonged etching time results in extensive exposure to plasma, generating a large amount of Ga-O vacancies.[3,9] In contrast, fin-LEDs have a lower height, resulting in a shorter etching time than nanorod LEDs. This can be confirmed through a XPS analysis, which shows that the Ga-O bond ratio for nanorod LEDs is 21.62%, whereas for fin-LEDs, it is 15.46%, indicating fewer defects.

Additionally, these defects can be further understood through the internal quantum efficiency (IQE). Nanorod LEDs have an IQE of 20.2 0%, while fin-LEDs have a higher IQE of 36.44%, indicating fewer defects in fin-LEDs.

Regarding EL characteristics, horizontal methods face challenges in achieving contact at the laboratory stage, as 2–3 micrometer scale is challenging to achieve without external factors such as dust. Reported nanorods efficiencies, such as those using SDC, show high efficiency but are produced in highly controlled environments and do not mention luminance.[3,4] Moreover, nanorod LEDs reported by *Kims,s et al.* show a low EL efficiency of 2%.[5] Therefore, it can be concluded that fin-LEDs have fewer defects compared to nanorod LEDs during the manufacturing process.

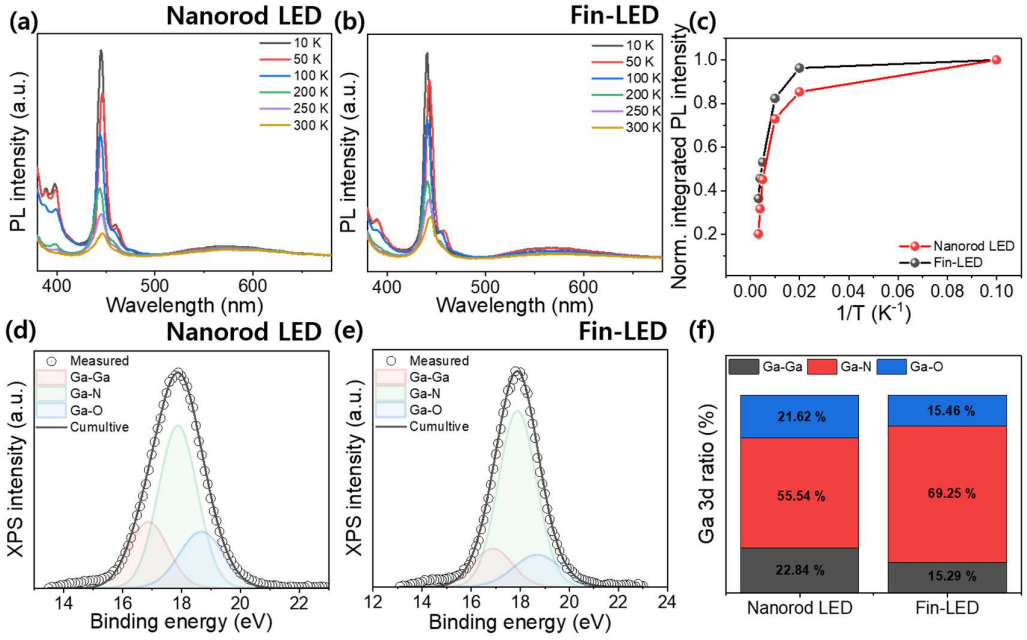

Figure R2. (a-c) Temperature dependence photoluminescence (TDPL) spectra of nanorod LED and fin-LED (d-e) Ga 3d X-ray photoelectron spectroscopy (XPS) spectra of nanorod LED and fin-LED (f) Ga 3d ratio of nanorod LED and fin-LED obtained XPS spectra

8. From the line 111-112, the authors attribute the increasing of emission intensity of Fin-LED to the increased MQW and the decreased defect density. But in the following paragraph, only the influence of MQW on the emission intensity is discussed, the defect density is not mentioned any more. Maybe the explanation of defect or damage is required since this is one of the key factors showing DEP is better than LASER transfer method as the authors discussed in the previous par

Our response: Thank you for your valuable comments.

In the case of LASER translocation, defects occur in the MQW due to screw dislocation in GaN from the LASER.[12] To reduce this damage, an additional buffer layer is added, increasing the thickness of the chip.[13,14] This buffer layer incurs additional costs. However, in the case of DEP, there is no damage because the LED is separated from the wafer using ECE. In addition, when measuring the micro PL of LEDs aligned using DEP, there is no significant difference in the excitation intensity, and thus it can be stated that the DEP method causes less damage.

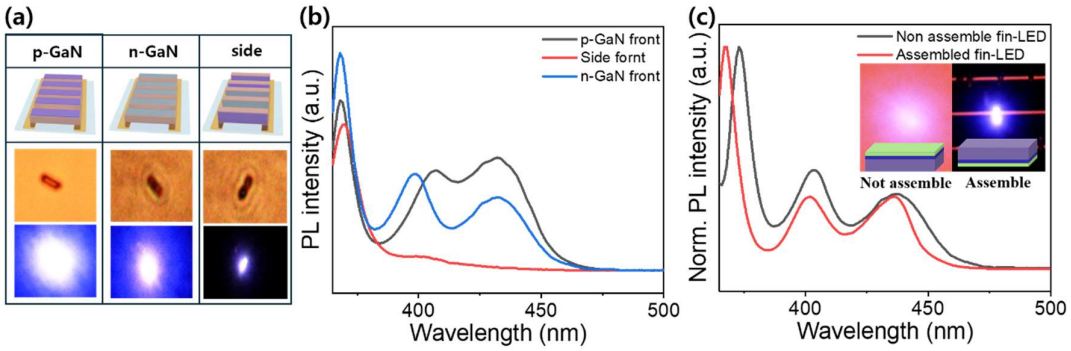

Figure R3. (a) Excitation image and micro PL spectra of fin-LED direction (c) micro PL spectra before and after alignment

9. The Maxwell stress tensor and the finite element method are used to simulate the force and torque. The authors list a reference to verify the dipole approximation method is not suitable, but there is no reference to support the suitability of MST+FEM. Did anyone use these methods to simulate before?

Our response: Thank you for your valuable comments.

We revised the text as follows and added references.

Before) Page 6 Line 14

We fabricated two groups of fin-LED configurations featuring different fin structures (fin-LED, fin-LED@SiO_2, ITO/fin-LED, and ITO/fin-LED@SiO_2) and different shell materials (ITO/fin-LED@TiO_2, ITO/fin-LED@SiN_x, ITO/fin-LED@SiO_2/Al_2O_3/SiO_2) to compare face-selective assembly (SEM images in **Figure S6**). We conducted DEP assembly tests on four distinct fin-LED structures, visually represented in **Figure 4** and elaborated further in **Figure S7**. Baseline conditions were established at a frequency of 10 kHz and a voltage of 20 V_{pp}. As seen in **Figure 4**, various fin-LEDs dispersed in acetone underwent self-assembly on the electrode surface. Observations of the fin-LED structure indicated a substantial presence of non-assembled fin-LEDs, with random placement predominantly on the shell face and at the n-GaN face contacts. In contrast, the ITO/fin-LED structures yielded consistent simulation results, demonstrating an enhanced tendency for p-GaN face contact. Further substantiating these findings, SEM images of the ITO/fin-LED@SiO_2 structure revealed that approximately 91.3% of fin-LEDs exhibited selective assembly with a downward orientation, establishing contact between the ITO layer of p-GaN and the bottom electrodes. It was also noted that most ITO/fin-LED@SiO_2 displayed alignment tendencies spanning two interdigitated electrodes.

We conducted additional assembly experiments based on the ITO/fin-LED@Shell structure with various shell materials (**Figure S7**) under different conditions. Face-selective assembly was only possible using low dielectric constant SiN_x and SiO_2-shelling ITO/fin-LEDs. In contrast, the high dielectric constant shell of the ITO/fin-LED@TiO_2 structure did not lead to face-selective alignment, as shown in **Figure S7**. These results suggest that face-selective assembly is achievable when the dielectric constant of the shelling material surrounding the fin-LED is low.

After) Page 7, Line 4

We fabricated a group of fin-LED configurations featuring different fin structures (fin-LED, fin-LED@SiO_2, ITO/fin-LED, and ITO/fin-LED@SiO_2) to compare face-selective assembly (SEM images in **Figures S6a–S6d**). We conducted DEP assembly tests on four

distinct fin-LED structures, visually represented in **Figure 4**. Baseline conditions were established at a frequency of 10 kHz and a voltage of 20 V_{pp}. Various fin-LEDs dispersed in acetone underwent self-assembly on the electrode surface. Self-assembly results for the basic fin-LED structure revealed that a significant number of LEDs were not assembled, and the assembled LEDs were mainly randomly assembled on the side and n-GaN face contacts (**Figures 4a and 4e**). Adding a SiO_2 shell to the side of the fin-LED (fin-LED@SiO_2) reduced the total alignment of the LED compared to the assembled result of the basic fin-LED, but increased the fraction of LEDs aligned to the n-GaN side (**Figures 4b and 4f**). These differences occurred because the electrical conductivity of SiO_2 used as the shell material was lower than that of the medium. As simple examples, spherical particles composed of SiO_2 experience negative-DEP (n-DEP) in a similar low-frequency range as used for self-assembly of fin-LEDs, while spherical particles composed of GaN experience p-GaN in that frequency range.[38,39] Therefore, it is intuitively clear that when the fin-LED@SiO_2 with coexisting p- and n-GaN and SiO_2 experiences DEP, the face on which the LED is aligned on the electrodes is determined by the exposed material. Because the magnitude of the electric field increases closer to the electrode, the n-GaN side, which has the highest electrical conductivity among the constituent materials of the fin-LED@SiO_2, tends to face the electrode. For this reason, it is obvious that ITO/fin-LED in which an ITO layer having much higher electrical conductivity than n-GaN is added on p-GaN has a greater proportion of LEDs aligned with the p-GaN side than the n-GaN side on electrodes (**Figures 4c and 4g**). Similar to the basic fin-LED alignment results, the high proportion of ITO/fin-LED aligned on the side is due to the exposure of the side (GaN epi- and ITO layers) of the LED. Ultimately, further substantiating these findings, the SEM image of the ITO/fin-LED@SiO_2 structure revealed that approximately 91.3% of fin-LEDs exhibited selective assembly with a downward orientation, establishing contact between the ITO layer of p-GaN and the bottom electrodes (**Figure 4d**). It was also noted that most ITO/fin-LED@SiO_2 displayed alignment tendencies spanning two interdigitated electrodes (**Figure 4h**).

We conducted additional assembly experiments based on the ITO/fin-LED@shell structure with various shell materials (ITO/fin-LED@SiO_2, ITO/fin-LED@TiO_2, ITO/fin-LED@SiN_x, and ITO/fin-LED@SiO_2/Al_2O_3/SiO_2) under identical conditions (**Figures S6d–S6g**). Face-selective assembly was only possible using low dielectric constant SiN_x and SiO_2-shelling ITO/fin-LEDs. In contrast, the high dielectric constant shell of the ITO/fin-LED@TiO_2 structure did not lead to face-selective alignment, as shown in **Figure S7**. These results suggest

that face-selective assembly is achievable when the dielectric constant of the shelling material surrounding the fin-LED is lower than that of the medium.

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10. In line 176-183 at page 6, the authors summarized the limitation of this simulation, and the observation is observed in the experiments. However, it seems that it is not mentioned any more in the following discussions.

Our response: Thank you for your valuable comments.

To address this, we would like to clarify and expand on the implications of these limitations in our study. The limitations mentioned specifically—the simplified geometric assumptions made during the simulation, such as modeling the fin-LED as a straight cuboid shape and not accounting for potential deformations of the n-GaN layer caused by the electrochemical etching (ECE) process—were crucial considerations in our analysis. These simplifications were necessary to manage the complexity of the simulation but inevitably introduced some discrepancies between the simulated and observed behaviors.

Despite these limitations, our experimental results were largely consistent with the simulation predictions. For example, the periodic variations in DEP torque observed in the simulation could not fully explain the selective alignment of the fin-LEDs. However, in the experiments, we observed that the actual alignment was influenced by additional factors, such as the physical properties of the n-GaN layer, which may have been altered by the ECE process, leading to lower electrical conductivity and affecting the DEP behavior.

While we briefly mentioned these points in the manuscript, we realize that further discussion would have strengthened the interpretation of our results. Therefore, we will ensure that the final manuscript includes a more detailed discussion on how these limitations impacted our findings and how they were addressed in our experimental procedures. This will help provide a more comprehensive understanding of the relationship between our simulations and

experimental outcomes.

11. In the “Face-Selective Assembly of Fin-LEDs” section, the very detailed comparison among different structures, different shell materials and solvents are conducted. But it looks like this method has a very high demanding of materials used, and different materials have very different performance which may limit the potential wide application. Hence, how do the authors control the cost of this method if there is a high requirement of parameters and materials, and how do the authors show its universality? As the introduction part, the authors attributed the high-cost problem of LASER to the high requirement of the laser parameters and bonding methods, but the authors also need a relatively high demanding in you method. In addition, how do the authors keep the stability of this method if the performance varies so much among different parameters or materials.

Our response: Thank you for your valuable comments.

The employed materials are currently used in submicron LEDs. Referring to Table R3, most micro-LEDs below 10 micrometers incorporate SiO_2 passivation. Additionally, PEG is a suitable solvent for inkjet, and its properties allow for face-selective alignment of fin-LEDs. Laser-assisted transfer technology successfully transfers numerous micro-LEDs by selectively irradiating a UV laser. However, it is not easy to apply in mass production due to precise laser power and resolution control, consideration of complex material absorption coefficient, and strict requirements.[14] Although the requirements for materials may be relatively high, the materials used are those used for micro LEDs of 10 micrometers or less.

Utilizing the SiO_2 shell commonly used for LEDs below 10 micrometers, the process for shelling fin-LEDs is remarkably simple. Unlike other LEDs, they do not require additional shelling for DEP alignment and only require shelling for device stability. This simplicity in fabrication adds to the appeal of fin-LEDs, although many different materials appear to be needed in different stages when making fin-LEDs. Additionally, inkjet-based patterning using PEG solvent allows for control of the dielectric constant and viscosity without additional high cost. As the optimum number of LEDs within a pixel decreases, alignment speeds can increase, making inkjet-based transfer faster.[3,16]

Chip size (μm)		Assemble	Passivation		Properties			Ref
Chip size (μm)	Chip size(μm 2)		Passivation	Materials	EQE (%)	Brightness (cd/m^2)	Wavelength (nm)	
3.5*3.5	12.25	Mesa	PECVD	SiO_2 150 nm	38	NR	NR	[9]
3.5*3.5	12.25	Mesa	PECVD	SiO_2 150 nm	28.50	NR	NR	[9]
0.53	0.22	DEP	Solgel	SiO_2 20nm Al_2O_3 40 nm	20.2	NR	450	[3]
0.53	0.22	DEP	PEALD	SiO_2 20nm Al_2O_3 40 nm	8.9	NR	450	[3]
0.58	0.26	DEP	PEALD/Thermal ALD	SiO_2 20nm Al_2O_3 40 nm	19.6	NR	464	[4]
0.58	0.26	DEP	Thermal ALD/PEALD/Thermal ALD	HfO_2 2 nm SiO_2 20nm Al_2O_3 40 nm	22.2	NR	464	[4]
0.58	0.26	DEP	Thermal ALD/PEALD/Thermal ALD	SiO_2 2 nm SiO_2 20nm Al_2O_3 40 nm	18.8	NR	464	[4]

Table R3. Table of sub-micron LED passivation

12. In line 238-239, the high performance of triple-shell LED is attributed to the effective passivation from face-selective effect, how do the authors prove this conclusion?

Our response: Thank you for your valuable comments.

In Figure 4d, there is no significant difference in alignment between the SiO_2 single shell and the triple shell. This suggests that surface-selective alignment is achieved due to the presence of SiO_2 on the outermost layer of the triple shell. The middle layer, Al_2O_3, acts as an etching block layer during device fabrication, enhancing device efficiency by preventing etching damage. Additionally, Al_2O_3 passivation further complements the E-beam-deposited passivation, providing more effective overall passivation. A fin-LED with a SiO_2 single shell was etched and failed during device manufacturing, and thus a single-shell and a triple-shell fin-LED device cannot be compared. A previous paper already reported that the SiO_2/Al_2O_3 double shell has a better passivation effect than the SiO_2 single shell to obtain maximum efficiency in nanorods.[3,4] See also our response to Reviewer 2's question 6.

13. The optical performance of Fin-LED is only compared with nanorod-LEDs, but the comparison with other structures and methods is also important to show the advantage of the reported method.

Our response: Thank you for your valuable comments.

Referring to **Table R2**, most groups that report LED efficiencies below 10 micrometers

mention EQE but not luminance. Additionally, the mesa structure requires two electrodes in one plane, and thus the presence of the electrodes reduces the effective light extraction area. On the other hand, fin-LEDs with a top-down contact structure have a larger light extraction area, making this technology more advantageous.

14. The luminance of 8640 cd/m^2 is one advantage of Fin-LED compared to nanorod-LED, but what about this value in other structures or methods?

Our response: Thank you for your valuable comments.

Referring to **Table R2**, most groups reporting the efficiency of LEDs smaller than 10 micrometers mention EQE but do not provide information on luminance. The dot LED, which has a similar structure to fin-LEDs, exhibits a luminance of approximately 1070 cd/m². Additionally, LEDs with a mesa structure require an electrode on the top, which reduces the light-emitting area compared to the actual chip size, potentially resulting in lower luminance. Therefore, the competitive and relatively high luminance of 8640 cd/m² for fin-LEDs using a top-down contact is a testament to the contribution and possibility of our research.

15. There are some recent developments of nanowire (or nanorod) LEDs **by other growth methods**, e.g., MBE, showing significantly improved efficiency for device sizes in the sub-micron regime. These studies should be referenced to provide a more comprehensive overview of the micro-LED fields.

Our response: Thank you for your valuable comments.

Referring to **Table R2**, Most micro-LED mesa structures report efficiency but not luminance. Additionally, in the mesa structure, the luminance area is small compared to the chip size due to the electrode portion for contact, resulting in low luminance. LEDs grown using MBE have the advantage of high brightness but have the disadvantage of low efficiency. This means controlling growing conditions is difficult. Therefore, the methods of separating chips from a wafer using ECE and transferring the separated chips using DEP can still be considered promising technologies.

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Response letter to the first reviewer

Reviewer #1 (Remarks to the Author):

1. One minor comment is on lines 57-58. "Following the transfer of nanorod-LED display 58 technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated...". What do authors mean by "transfer". Is this a technology transfer. The relevance of this sentence is not clear.

Our response: Thank you for your valuable comments.

Before) Page 2, Line 20

Following the transfer of nanorod-LED display technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated the practical possibility of the DEP process by fabricating a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process and inkjet printing process.

After) Page 2, line 34

Following the license and technical assistance of nanorod-LED display technology from our team, the Samsung Display Corporation (SDC) has successfully demonstrated the practical possibility of the DEP process by fabricating a nanorod-LED-based electroluminescent (EL) device through the FSA-DEP process and inkjet printing process.

Reviewer #2 (Remarks to the Author):

The manuscript has been revised according to the reviewer's comments. I would like to recommend this manuscript for publication in Nature Communications as is.