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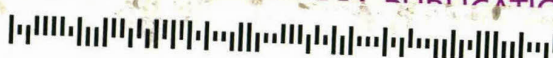
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SPECIAL ISSUE ON THREE-DIMENSIONAL DISPLAYS AND VISUALIZATION

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New Pixel Design on Emitting Area for High Resolution Active-Matrix Organic Light-Emitting Diode Displays

Soon-Kwang Hong, Jea-Ho Sim, In-Gyo Seo, Keun-Choul Kim, Sung-Il Bae, Hee-Young Lee, Nam-Yang Lee, and Jin Jang

Abstract—We propose new pixel design on emitting area and corresponding shadow mask design for high resolution active-matrix organic light-emitting diodes (AMOLEDs) to overcome the limitation of conventional shadow mask process. The proposed scheme has the extended emitting area into adjacent sub-pixel and gives flexibility for manufacturing shadow mask with quarter resolution compared with conventional requirement. The proposed scheme can use normal pixel driving circuit; however, anode electrode in each sub-pixel covers adjacent pixels to extend its own emitting aperture area for high resolution AMOLEDs. We have successfully implemented this scheme in a 4.3-in-sized WVGA ($854 \times \text{RGB} \times 480$) AMOLED using p-type advanced-solid phase crystallization (A-SPC) backplane technology and top emissive organic light-emitting diode (OLED) device structure and evaluated key performance characteristics.

Index Terms—A-SPC, active-matrix organic light-emitting diode (AMOLED), aperture area, patterning, resolution, shadow mask.

I. INTRODUCTION

AFTER lots of overcoming and preparation period, active-matrix organic light-emitting diode (AMOLEDs) displays have successfully commercialized in these days from mobile application market requiring small-sized displays, such as DMB (Digital Multimedia Broadcasting) and WiBro (Wireless Broadband Internet) because it has been considered to be realistic when compared with large-sized-display applications. However, AMOLEDs for mobile application still have several challenging issues to get competitiveness comparing with TFT-LCD in terms of performance and cost effectiveness.

As one of the key challenging issue, AMOLED display has difficulty caused by limitation on manufacturing R-G-B shadow metal mask in realizing a high resolution as compared with TFT-LCD even though the most common method for

patterning color primaries in the fabrication of small molecule light emitting devices is fine metal shadow mask method. The possible patterning accuracy of this method is around $\pm 15 \mu\text{m}$ and is marginal for high resolution above 200 ppi. [1], [2] As to the full-color OLED except R-G-B side-by-side evaporation process, various other technique have been studied, for instance, color conversion method (CCM), WOLED and Ink-Jet printing. [3]–[5] CCM has advantages in scalability and simplicity, there are still challenging issues in terms of lifetime, driving voltage and color performance, and so on. As another alternative approach, Ink-Jet printing method with organic soluble light-emitting materials have considered for full color OLED and has many advantages such as low material consumption, good scalability to large format mother glass. Nevertheless, this method has a serious limitation in OLED materials, because it requires soluble materials, such as polymers or soluble small molecules, which have relatively poor performance in efficiency and lifetime as of now. On the other way, laser thermal patterning methods can be applied to the patterning of electro-active OLED materials. There are several laser thermal transfer methods, such as laser ablative transfer (LAT), radiation-induced sublimation transfer (RIST), and LITI [6], [7].

Recently, some interesting approaches for high-resolution AMOLED in mobile application have been introduced. The first thing concerns pseudo-type display through using adjacent sub-pixel when the specific color will be displayed. The number of sub-pixels in the pseudo-type is less than then the required sub-pixel, so it can just intend to realize similar resolution. Because of that reason, when some text of a simple typestyle (for example, like the alphabets and like Chinese and Japanese characters currently used in Asia) is displayed on a portable information terminal, the pseudo-type display show fatally fake or unclear image [8]–[10].

In this paper, to overcome the resolution constraints and realize high performance AMOLED panel possessing the complicated pixel scheme, we have proposed innovative pixel arrangements scheme based on the conventional shadow mask process and ability. We have also implemented this scheme in a 4.3-in-sized WVGA ($854 \times \text{RGB} \times 480$) AMOLED. It shows that a 229 ppi display resolution can be achieved only by the quarter shadow mask resolution compared with the conventional shadow mask pixel density without any drops in image quality performance.

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S.-K. Hong, J.-H. Sim, I.-G. Seo, K.-C. Kim, S.-I. Bae, H.-Y. Lee and N.-Y. Lee are with the OLED Development Department, LG Display Company, Ltd., Gumi, Gyung-sangbuk-do, 730-030, Korea (e-mail: skhong@lgdisplay.com; tiger@lgdisplay.com; rgb@lgdisplay.com; rootiron@lgdisplay.com; sibae@lgdisplay.com; hyl@lgdisplay.com; nylee@lgdisplay.com).

J. Jang is with the Advanced Display Research Center, Kyung-Hee University, Seoul 130-701, Korea (e-mail: jjang@tftlcd.khu.ac.kr).

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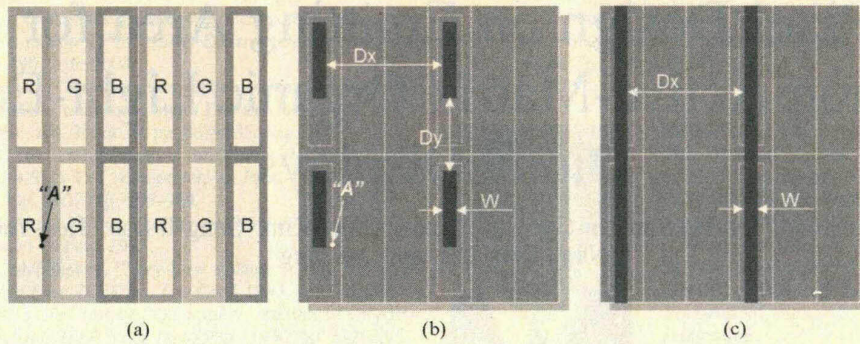


Fig. 1. Conventional shadow mask shape. (a) Pixel alignment. (b) Slot-type. (c) Grill-type.

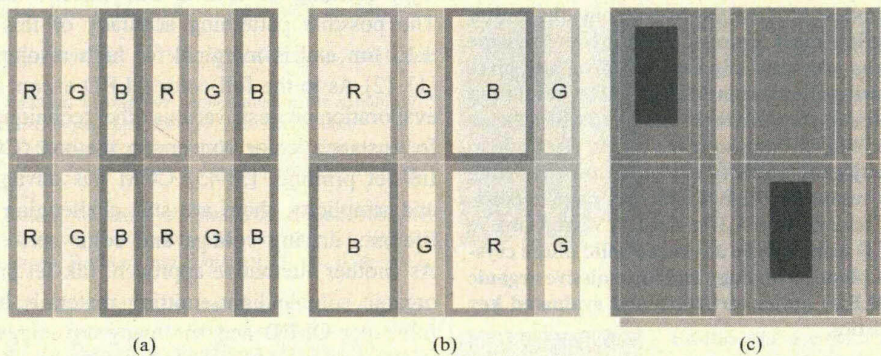


Fig. 2. Pixel alignment comparison. (a) Conventional design. (b) Pseudo-type design. (c) Emitting area in pseudo-type.

II. REVIEW OF SHADOW METAL MASK TECHNOLOGY AND ITS LIMITATION

For the manufacture of OLED displays, metal screens are used for the deposition of emitting layers onto the substrate of the panel. An OLED cell—corresponding to one pixel—contains all three colors (RGB). The mask openings are rectangular and at the end of the process a square containing the three colors is created. These masks are usually made from thin stainless steel or nickel/steel alloys. However, a high-precision shadow mask has a physical limitation in not being able to provide mask openings smaller than $20\ \mu\text{m}$ because the thickness of the sheet metal typically ranges from 30 to $50\ \mu\text{m}$. On the other hands, high resolution is a requirement for small-sized sub-pixel, which will be hampers in the use of shadow masks in the manufacture of high-resolution AMOLED displays. And also, there are two kinds of shadow mask in terms of existence of vertical/horizontal rib configured in Fig. 1. Slot-type has vertical and horizontal direction rib configured in Fig. 1(b), while grill-type has only one directional rib in metal mask for corresponding to pixel array in Fig. 1(c). “A” area in Fig. 1(a) and Fig. 1(b) is designated to anode electrode of OLED device and possible emitting area can be realized within “A” area. When adopting the shadow-mask process in the manufacture of full-color OLED displays, each opening in the mask corresponds to an emitting area of each sub-pixel. Thus, the panel resolution depends on the size of the mask opening and the density of these openings. In order to maintain the strength of a very-thin high-precision metal mask, the distance between the edges of adjacent openings (Dx, Dy) is normally in the range of a few tens of microns and, a min-

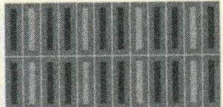
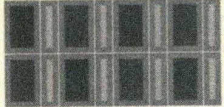
imum of $70\ \mu\text{m}$ is required. Furthermore, the size of the mask openings (W) has to be at least $20\ \mu\text{m}$ to ensure a higher aperture ratio, higher lifetime of OLED device and better yield for mask fabrication, the minimum opening can be attainable up to $7\ \mu\text{m}$, though. Therefore, the highest display resolution resulting from the use of a shadow mask is about 230 ppi, currently, due to the physical limitations of manufacturing precision shadow masks as above explained.

To cope with limitation in using shadow mask for high resolution display, pseudo-type pixel alignment and corresponding driving scheme proposed and successfully commercialized. Fig. 2 shows conventional pixel alignment and one of pseudo-type pixel alignment. Comparing with conventional pixel alignment in Fig. 2(a), pseudo-type pixel alignment just require the number of $2/3$ sub-pixel when the same resolution image displays shown in Fig. 2(b), while special driving algorithm is implemented in side of driver-IC. However, there is fatal problem in this scheme at the inclined or high-curvature area in displaying alphabet, character and sharp object. It means human eyes can recognize the difference between the real resolution display and pseudo-type display in terms of the perceived display quality and performance. In addition, Fig. 2(c) shows the realized emitting area in each sub-pixel based on Fig. 2(b) pixel alignment.

III. SHARED EMITTING-APERTURE OLED STRUCTURE WITHIN ADJACENT PIXELS

As a good approach for real high resolution AMOLEDs without yield-drop, higher aperture ratio and clear perception

TABLE I
COMPARISON OF PIXEL DESIGN IN TERMS OF PERFORMANCE AND PRODUCTIVITY

ITEM		Stripe	Pseudo	Proposed
Image	Format	Real	Visual	Real
	Quality	⊙	△	○
Aperture ratio		△	○	○
Lifetime		△	○	○
TFT Design		△	○	○
Shadow Mask	Type	Grill	Slot (R/B) & Grill (G)	Slot
	Yield	X	○	○
	Productivity	X	△	○
Pixel arrangement				

⊙: Excellent ○: Good △: Poor X: Unacceptable

image, a novel pixel alignment concept is proposed in Fig. 3. The proposed scheme has the shared emitting aperture area between horizontally adjacent 2 sub-pixel compared with normal sub-pixel design in Figs. 1 and 2. The horizontally extended anode electrodes for $R11'$ and $G11'$ make each OLED devices not be the vertically-designed emitting area within normal $R11$ and $G11$ area, but be the horizontally designed emitting area through the shared-design scheme between adjacent 2 sub-pixel, even though driving circuits for the newly defined sub-pixel ($R11'$ and $G11'$) which are composed of several thin-film transistors (TFTs) and capacitors are located in the original sub-pixel area ($R11$ and $G11$). This proposed scheme can give high resolution AMOLEDs the enlarged emitting aperture area, increment of OLED life-time and high yield by the enlarged area in shadow mask. The detailed drawing of the *sub-unit* from Fig. 3(a) is shown in Fig. 3(b). The emitting area of sub-pixel $R11$ is given body to $R11'$ based on the proposed pixel scheme. In the same tale with the proposed scheme, $G11'$, $R12'$ and $B11'$ can be designed. It means two sub-pixels of the same color ($R11'$, $R12'$) can be deposited through the same opening of the shadow mask. Thus, the size of the opening of the shadow mask can be doubled in lateral direction. Table I shows several important factors that we can expect when adopting the proposed scheme. The area of each opening can be over than two times that of the conventional shadow mask design. In other words, a 400 ppi display resolution can be achieved by using 100 ppi shadow mask resolution without any challenging point in manufacturing shadow metal mask and yield drop.

IV. SIMULATION RESULTS FOR NEW ALIGNMENT CONCEPT AND PANEL DESIGN

To further compare new sub-pixel arrangements with conventional sub-pixel arrangements, an ideal aperture ratio was calculated by considering only the limitations when using the mask. The bridge between mask openings is 70 μm , the mask alignment tolerance is 5 μm , and the border between two sub-pixel

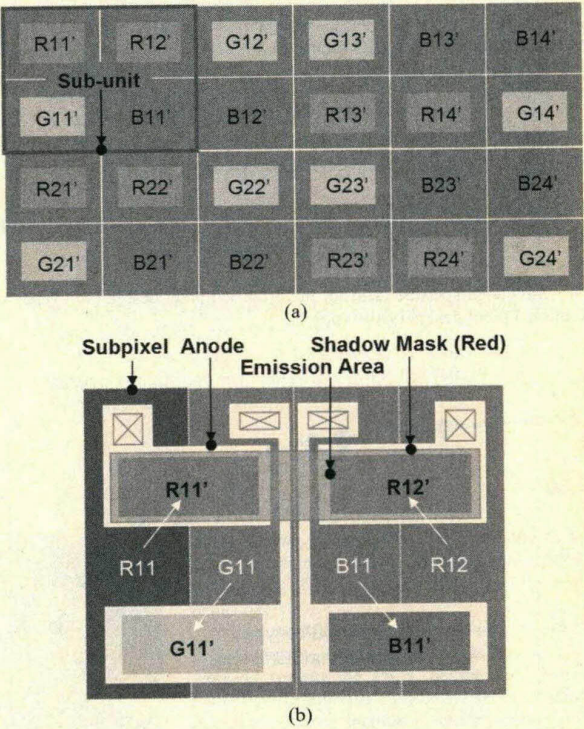


Fig. 3. Proposed novel pixel alignment. (a) Conceptual alignment. (b) Detail pixel design.

of the same color is 20 μm . Fig. 4 shows the possible aperture ratio in case of both the proposed slot-type pixel scheme shown in Fig. 3 and the conventional grill-type one shown in Fig. 1. Regardless of pixel resolution, if the required minimum aperture ratio should be considered over than 30%, it would be possible to realize around 280 ppi by the proposed slot-type pixel scheme because of the widening in bridge between mask openings, when conventional grill-type pixel scheme just give about 230 ppi resolutions. In case that the acceptable aperture ratio

TABLE II
PERFORMANCE OF THE FABRICATED PROTOTYPE WVGA PANELS

Item	Performance	Remark
Emission Type	Top Emission	
Display size (in.) / Resolution (mm ²)	4.3" / 854 × RGB × 480	Diagonal / WVGA
Pixel pitch / Density (ppi)	111 μm × 111 μm / 229	
Aspect ratio (%)	30 / 30 / 30	R / G / B
Number of colors	24 bit	16.7M
Surface brightness (nit)	300	with polarizer
Color gamut (%)	> 100	CIE 1976
Contrast ratio	> 100,000:1	Dark Condition

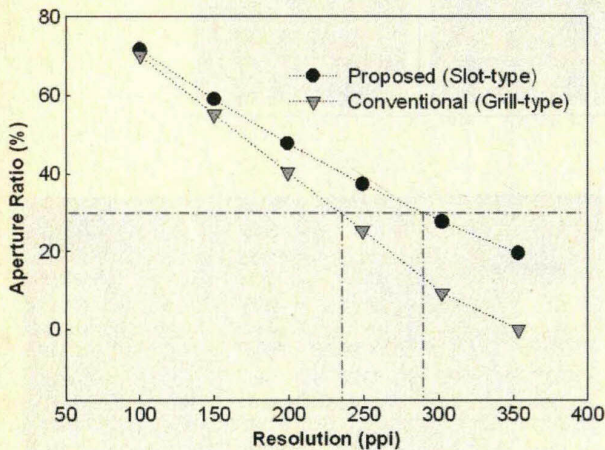


Fig. 4. Simulated aperture ratio for the proposed pixel design (slot-type) and conventional pixel design (grill-type).

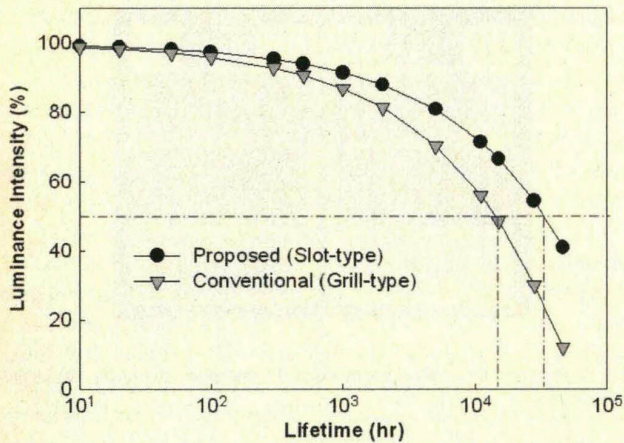


Fig. 5. Simulated lifetime of OLED for the proposed pixel design (slot-type) and conventional pixel design (grill-type).

might be 20% in terms of OLED lifetime and readability, the possible display pixel resolution based on the proposed slot-type pixel scheme can be up to 350 ppi. Fig. 5 shows that the simulated data of the proposed slot-type pixel scheme is significantly superior to that of the conventional one.

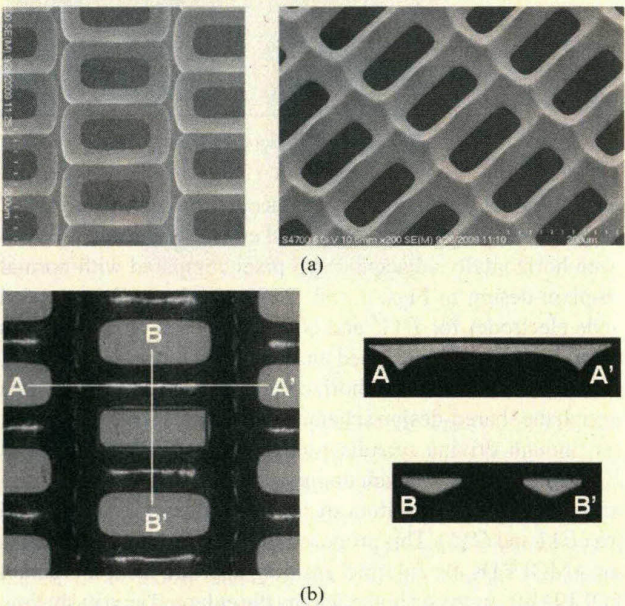


Fig. 6. Fabricated metal mask images. (a) Plane view. (b) Cross-sectional view.

V. PROTOTYPE FABRICATION AND ITS PERFORMANCES

We fabricated the shadow metal mask on the basis of the proposed pixel alignment schemes for 4.3-in. sized WVGA AMOLED. Fig. 6 shows the fabricated metal mask images. Fig. 6(a) is plane image of the fabricated shadow metal mask through current manufacturing technique and cross-sectional image of the same shadow metal mask shown in Fig. 6(b). This mask shows zigzag pixel opening alignment to deposit OLED material on the corresponding emitting pixel area in contrast to conventional strip-type pixel opening structure. The designated rectangular area with solid line in Fig. 6(b) means the same color area which are different data $R11'$ and $R21'$, however, this area is merged and extended into the unified large one for 4 sub-pixel stretch size shown in Fig. 3(b) from the viewpoint of shadow mask opening. The distance of $A-A'$ which is horizontally next opening area is eight sub-pixel range and vertically next opening area is just one sub-pixel range within $B-B'$ distance.

Fig. 7 shows the fabricated 4.3-in-sized WVGA AMOLED prototype by using the proposed pixel scheme and the corresponding shadow metal mask. The prototype shows almost the

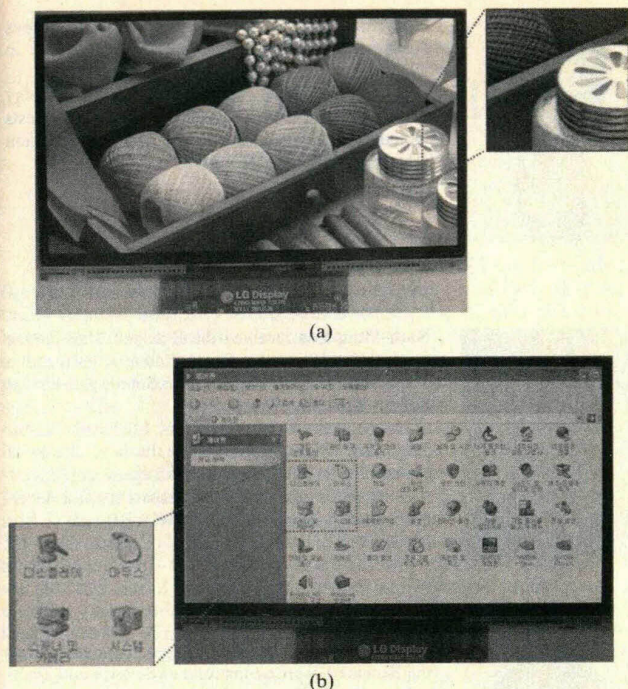


Fig. 7. Fabricated 4.3-in WVGA AMOLED prototype. (a) Displayed image. (b) Text readability.

same quality compared with the conventional 229 ppi display in terms of image and text readability in Fig. 7(b) by the naked eyes, even though its shadow mask resolution just has quarter of the conventional shadow mask technique. In Table II, the key performance characteristics of the fabricated prototype panels are shown. These are over 40% of aperture ratio and 300nit brightness, which indicate that it is possible to use high resolution AMOLEDs with the proposed pixel alignment schemes. This prototype shown in Fig. 7 was implemented by the p-type A-SPC backplane and have integrated scan driver, de-multiplex driver. As to the OLED device, top emissive structure was applied with small molecular materials [11], [12].

VI. CONCLUSION

To realize high resolution AMOLEDs through current manufacturing technique for in field of shadow mask, novel pixel design scheme, as low as quarter density than conventional concept, novel pixel design scheme has been proposed.

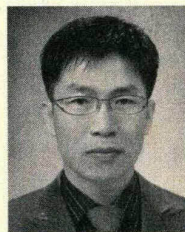
By applying the proposed novel pixel design, a 229-ppi 4.3-in-sized WVGA AMOLED has been successfully demonstrated. This convinced us that the proposed pixel alignment scheme can be supported up to at most 350 ppi high resolution AMOLED with higher production yields even by using low resolution shadow mask which is currently possible.

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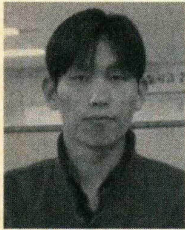
Soon-Kwang Hong received the B.S. and M.S. degrees in electrical and electronic engineering from Kyungpook National University in 1997 and 1999, respectively.

While working as a chief engineer at LG Display Company, Ltd., Gumi, Korea, he is currently working toward the Ph.D. degree in information display at Kyung Hee University, Seoul, Korea. His research interests include electrical circuit driving and compensation scheme in field of AMOLEDs.



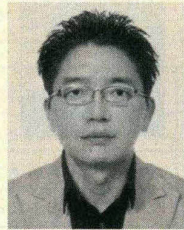
Jae-Ho Sim received the B.S. degrees from Kyungpook National University in 2002, in electrical and electronic engineering.

He is currently a junior engineer at LG Display Company, Ltd., Gumi, Korea. His research interests include panel design and compensation scheme in field of AMOLEDs.



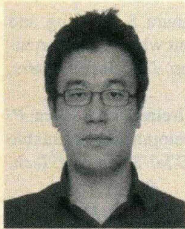
In-Gyo Seo received the B.S. degrees in electrical and electronic engineering from Kyungpook National University in 2002.

He is currently a research engineer at LG Display Company, Ltd., Gumi, Korea. He has worked in engineering and design of AMOLED Panel including driving and compensation scheme.



Hee-Young Lee received the B.S. and M.S. degrees in electrical engineering from Daegu University in 1993 and in 1995, respectively.

He is currently a chief engineer at LG Display Company, Ltd., Gumi, Korea. His research interests include electrical circuit design and compensation scheme in field of AMOLEDs.



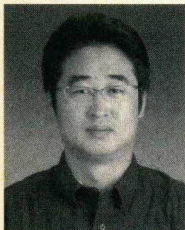
Guen-Cheol Kim received the B.S. degrees from the Department of Electronics, Electrical and Computer Engineering, Hanyang University, in 2006.

He is currently an associate engineer at LG Display Company, Ltd., Gumi, Korea. His research interests include electrical circuit design and compensation scheme in field of AMOLEDs.



Nam-Yang Lee received the B.S. and M.S. degree from Yonsei University, Seoul, Korea, in 1980 and in 1984, and the Ph.D degree from Sophia University, Tokyo, Japan, in 1994.

He is currently a Vice President, LG Display Company, Ltd., Gumi, Korea, where he is in charge of the head of OLED Development Department. His research interests include basic researches and development of product in field of AMOLEDs.



Sung-Il Bae received the B.S. and M.S. degrees from Ajou University in 2002 and in 2004, all in physics. He is currently a junior engineer at LG Display Company, Ltd., Gumi, Korea. His research interests include OLED process technology, especially, fine metal mask of AMOLEDs.



Jin Jang received the Ph. D. degree in physics from the Korean Advanced Institute of Science and Technology, Seoul, Korea, in 1982.

He is currently a Professor of Information Display with Kyung Hee University, Seoul, Korea, where he is in charge of the TFT-LCD National Laboratory and the Advanced Display Research Center. He has authored or coauthored over 300 technical publications in international journals. His current research interests include display devices, electronic devices using thin films, and solid-state physics.