Progress of display performances: AR, VR, QLED, OLED, and TFT

Ho Jin Jang, Jun Yeob Lee, Jeonghun Kwak, Dukho Lee, Jae-Hyeung Park, Byoungho Lee, and Yong Young Noh

ABSTRACT

In 2018, great progress in display performances was achieved in the field of virtual reality (VR), augmented reality (AR), quantum dot light-emitting diode (QLED), and organic light-emitting diode (OLED) displays, in addition to the thin-film transistor (TFT) for displays. In this work, the recent progress of the device performances in each display field was summarized, and the future direction of each technology was proposed.

1. Recent progress of AR and VR

The near-eye display (NED) and the head-mounted display (HMD) are among the key devices of the rapidly emerging augmented reality (AR) and virtual reality (VR) applications. Various researches are currently being conducted to enhance the performance factors of the AR and VR NEDs, including the field of view (FOV), resolution, eye box, form factor, and focal cue. Table 1 shows the features of the recently reported or commercialized NEDs. As shown in Table 1, commercialized wearable NED devices such as Google Glass, META2, Hololens, and Magic Leap are built in a relatively small form factor. They, however, adopt only binocular disparity for presenting 3D images, which does not generate a proper focal cue. Various researches have been conducted to apply 3D display techniques, which provide a correct focal cue, to NEDs because the focal cue is an essential factor for mitigating the user’s visual fatigue. To generate a proper focal cue in NEDs, 3D display techniques such as holography, light field, and varifocal methods have been studied, and additional techniques for eye tracking are also being applied. Besides the focal cue, there remain other challenging issues, such as the form factor, which is not yet sufficiently small, and the trade-off between the eye box size and the FOV. Research is actively being conducted to address those issues so as to enhance the NEDs’ performance to a level acceptable to the industry and the general users.

1.1. FOV

The FOV of a NED is the angular extent of the displayed virtual image. The maximum FOV of the human eye is about 120° for a static eye but can reach up to 160° if the eye rolling is considered [10]. Although a large FOV covering that of the human eye is desirable, the FOV of the currently commercialized NEDs is typically limited to 110° for VR [11] and to 30-40° for AR [3, 4]. The smaller FOV of the AR NEDs is caused by the design requirement of including a transparent image combiner for an optical see-through view. Generally speaking, an image combiner with a larger numerical aperture (NA) is desirable for a larger FOV. The transmission configuration is also advantageous over the reflection configuration as its smaller eye relief enables a larger FOV. Various types of image combiner are currently actively being researched on, including not only the traditional ones like the bird-bath type, freeform optics [12], holographic optical element (HOE), and diffractive optical element (DOE) but also newly emerging ones like the meta-based geometric-phase (GP) lens [13] and the liquid crystal (LC)-based GP lens [14]. Table 2 summarizes their features.

1.2. Eye box

The eye box is a spatial range where an eye can be located while seeing the entire FOV of a NED. Although a large eye box is desirable for a comfortable viewing experience,
Table 1. Features of the recently reported or commercialized AR and VR NEDs.

| Name                 | FOV (°) | Resolution (pixels) | Eye box (mm) | Form factor | Focal cue | Image combiner | Ref. |
|----------------------|---------|---------------------|--------------|-------------|-----------|----------------|------|
| Google Glass         | 13 × 7.3| 640 × 360           | Moderate     | Small       | X         | Beam splitter  | [1]  |
| META2                | 90 (diagonal) | 2550 × 1440     | Moderate     | Small       | X         | Curved half mirror | [2]  |
| Hololens             | 30 × 30 (diagonal) | 1366 × 768      | Moderate     | Small       | X         | DOE            | [3]  |
| Magic Leap           | 40 × 40 (45) | 1280 × 960        | Moderate     | Small       | Two layers | DOE            | [4]  |
| Holographic HMD (Yeom) | 80     | 1920 × 1080        | Narrow       | Large       | Holography | HOE            | [5]  |
| Holographic HMD (Maimone) | 55 × 40 | 960 × 540         | Moderate     | Moderate    | Light field | HOE            | [6]  |
| Retina 3D (Jang)     | 33 × 25 (40) | 1024 × 768       | Moderate     | Large       | Varifocal  | Freeform half mirror | [7]  |
| Multifocal (Hu)      | 55–63   | 1280 × 720         | Moderate     | Moderate    | Varifocal  | Diffuser-type HOE | [8]  |
| Varifocal (Aksit)    |         |                    |              |             |           |                |      |

*Eye box: narrow (< 10°), moderate (10–20°), wide (> 20°).

Table 2. Transparent image combiners for AR NEDs.

| Type         | FOV   | Transmission/reflection | Aberration | Exit pupil | Transparency | Thickness |
|--------------|-------|-------------------------|------------|------------|--------------|-----------|
| Birdbath type| Moderate | Both possible           | Good       | Moderate   | Good         | Large     |
| Freeform optic| Moderate | Reflection type         | Good       | Moderate   | Good         | Large     |
| Waveguide    | Narrow | Both possible           | Bad        | Large      | Moderate     | Small     |
| GP lens      | Meta   | Wide                    | Trans. type| Moderate   | Moderate     | Bad       |
|              | LC     | Wide                    | Trans. type| Moderate   | Moderate     | Small     |

Figure 1. Trade-off relation between the FOV and the eye box for different panels. (In this graph, the following parameters were used: lens F# = 1.67; pixel pitch of the display panel = 5 μm; imaging magnification = 10.)

the eye box of the AR and VR NEDs is limited by an etendue conservation law, which defines the trade-off relation between the eye box and the FOV, as shown in Figure 1 [10]. To obtain a large eye box and the FOV simultaneously, the etendue of the optical system should be increased either by increasing the display panel size or by increasing the NA of the optics. Since recently, however, novel techniques that overcome the etendue conservation law by using exit pupil expansion or eye tracking have been actively studied [7,15,16].

1.3. Angular resolution

The angular resolution of an AR or VR NED is defined by the number of pixels within a unit angle. The maximum angular resolution of the human eye is about 60 pixels/degree for central vision and 30 pixels/degree for peripheral vision [17]. The AR/VR NEDs should provide an angular resolution higher than the human eye limit to avoid a pixelated view. The optical design difficulty is mainly due to the trade-off relationship between the angular resolution and the FOV for a given display panel, as shown in Figure 2.

1.4. Focal cue

Focal cue is also an important aspect of a NED. As the AR and VR NEDs are usually binocular, it is trivial to give a depth sensation by presenting stereoscopic images with binocular parallax. Most commercialized AR and VR NEDs, however, provide only binocular parallax, without a corresponding focal cue for each eye. The absence of a correct focal cue causes a mismatch between the depth perceived by the brain and the depth focused on by the individual eye. This is called ‘vergence accommodation conflict (VAC)’ and is considered a major cause of eye fatigue in the extended AR and VR viewing experience.
In AR, this is a more important issue as a displayed image should give the same focal cue as the associated real object for realistic optical matching. To present a correct focal cue, various techniques are currently actively being researched on, including holographic, light field, multifocal, and varifocal displays. Such techniques can form images either in continuous depths giving true and exact focal cues or in a few discrete depth planes managing the focal cue error within the zone of comfort shown in Figure 3 [18]. Maxwellian NEDs, which partially alleviate the VAC by removing the focal cue completely, have also been attracting the attention of late.

2. Progress of QLEDs

2.1. Cd-based QLEDs

The synthesis methods of highly luminous Cd-based QDs have been widely investigated for a few decades now. So far, Cd-based QDs exhibit outstanding performances, such as narrow (less than 30 nm) emission spectra of full width at half maximum (FWHM) and high (over 90%) photoluminescence quantum yields for all visible colors. The external quantum efficiency (EQE) of QLEDs have been continuously increased, as shown in Figure 4, and thus, they show the highest EQE close to near-unity in terms of internal quantum efficiency. For example, the maximum EQEs of the red-, green-, and blue-emitting QLEDs are 20.5, 21.0, and 19.5%, respectively [20,24,32], but of course, more work needs to be done for their practical applications to display devices because the EQEs are the peak values at the low-current-density regions in general, and they decrease quite quickly when the current density increases (i.e. efficiency roll-off). Also, ultraviolet(UV)- and infrared(IR)-emitting QLEDs have been realized with the Cd- and Pb-based QDs, respectively. The UV and IR QLEDs can be used in display devices for the backlight source and touch screen, respectively. The device performances of the representative Cd-based QLEDs are summarized in Table 3.

2.2. Cd-free QLEDs

The commercial display devices using Cd-based QDs are limited in many countries due to their toxicity. The development of Cd-free QDs is therefore considered one of the most important factors in the industry. The performances of Cd-free QDs and QLEDs have been improved rapidly based on multilateral efforts on material synthesis and device fabrication. Recently, an EQE of over 6% was reported in red-emitting InP-based QLEDs, and the FWHM of the spectra has been decreasing continuously. On the contrary, blue-emitting QLEDs have not been achieved, and their overall performances should be further improved. The performances of the representative Cd-free QLEDs are summarized in Table 4.

3. Progress of OLEDs

3.1. Fluorescent OLEDs

The recent researches on red and green fluorescent OLEDs focused on developing singlet-exciton-harvesting fluorescent OLEDs rather than the traditional fluorescent OLEDs. The EQEs of the red and green fluorescent OLEDs reached about 20% when the singlet-exciton harvesting technology was used. The singlet-exciton-harvesting blue fluorescent OLED also achieved a high EQE of 26%. The lifetime of the singlet-exciton-harvesting fluorescent OLEDs, however, is still short compared to that of the conventional fluorescent OLEDs. Therefore, the blue-device development is centered on
the conventional OLED utilizing triplet-triplet fusion. The device performances of the fluorescent OLEDs achieved in 2018 are summarized in Table 5.

### 3.2. Thermally activated delayed fluorescent (TADF) OLEDs

The EQEs of the TADF OLEDs have been greatly improved and are now comparable to those of the phosphorescent OLEDs (PhOLEDs). The EQE of the red TADF OLEDs is 29.2%, which is much higher than the previous EQE of below 20%. As for the green and blue TADF OLEDs, their EQEs are 37.8 and 36.7%, respectively. The lifetime data of the TADF OLEDs are still short, and only several lifetime data were documented in 2018. The EQE and lifetime data of the TADF OLEDs are summarized in Table 6.

### 3.3. Phosphorescent OLEDs (PhOLEDs)

The EQE of the red and green PhOLEDs is almost saturated due to the high photoluminescence quantum yield and the high horizontal dipole orientation factor. There is still room, however, for the improvement of the blue-device performances. A remarkably high EQE of 24.8% with a deep-blue color coordinate of (0.13, 0.16) was reported in 2018, but the lifetime of the blue PhOLEDs has not been advanced in 2018. The EQE and lifetime data in 2018 are summarized in Table 7.

### 3.4. Soluble OLEDs

The EQE and lifetime of soluble OLEDs are continuously being improved year by year. In 2017 and 2018, the progress of the blue-device performances was dramatic.

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### Table 3. Device performances of Cd-based QLEDs.

| QD structure | Peak wavelength (nm) | FWHM (nm) | Max. luminance (cd/m²) | Max. EQE (%) | Max. CE (cd/A) | Ref. |
|--------------|----------------------|-----------|------------------------|-------------|--------------|------|
| Red          | CdSe/CdS             | 613       | 32                     | 34,500      | 18           | 19   | [19] |
| Green        | CdSe/CdS             | 640       | 28                     | 42,000      | 20.5         | -    | [20] |
| Red          | CdSe/CdS/ZnS         | 623       | 32                     | 6500        | 16.5         | 18.8 | [21] |
| Green        | CdSe/CdS/ZnS         | 632       | 38                     | 3800        | 16.8         | 19.0 | [22] |
| Blue         | CdZnS/ZnS            | 455       | 20                     | 7600        | 10.7         | 4.4  | [29] |
| Blue         | ZnCdS/ZnS            | 443       | 21.5                   | 4890        | 19.8         | 14.1 | [30] |
| Red          | CdZnS/ZnS            | 443       | 21.5                   | 4890        | 19.8         | 14.1 | [30] |
| Green        | CdSe/ZnS             | 515       | 38                     | 218,800     | 5.8          | 19.2 | [23] |
| Red          | CdSe/ZnS             | 526       | 27                     | 90,000      | 21           | 82   | [24] |
| Blue         | CdSe/ZnS             | 526       | 27                     | 90,000      | 21           | 82   | [24] |
| Blue         | CdSe/ZnS/ZnS         | 515       | 26                     | 460,000     | 6.4          | -    | [28] |
| Blue         | CdSe/ZnS/ZnS         | 515       | 26                     | 460,000     | 6.4          | -    | [28] |
| UV           | CdZnS/ZnS            | 390       | 23                     | 13.9 mW/cm² | 0.23         | -    | [33] |
| UV           | PbS                  | 1400      | 100                    | 9 W/sr m²   | 9.3          | -    | [34] |

*Current efficiency.*

*bEstimated from the graph.

### Table 4. Device performances of Cd-free QLEDs.

| QD structure | Peak wavelength (nm) | FWHM (nm) | Max. luminance (cd/m²) | Max. EQE (%) | Max. CE (cd/A) | Ref. |
|--------------|----------------------|-----------|------------------------|-------------|--------------|------|
| Red          | InP/ZnSeS/ZnS        | 619       | 63                     | 2849        | 2.5          | 4.2  | [35] |
| Green        | InP/ZnSeS/ZnS        | 607       | 48                     | 1600        | 6.6          | 13.6 | [36] |
| Yellow       | InP/ZnSeS/ZnS        | 545       | 56a                    | 10,490      | 1.5a         | 4.44 | [37] |
| Green        | InP/ZnSeS/ZnS        | 565       | 65                     | 1900        | 5.1          | 18   | [38] |
| Red          | InP/ZnSeS            | 518       | 64                     | 3900        | 3.46         | 10.9 | [39] |

*aEstimated from the graph.

### Table 5. Device performances of fluorescent OLEDs in 2018.

| EQE (%) | CE (cd/A) | Color coordinates | Lifetime (h) | Ref. |
|---------|-----------|-------------------|--------------|------|
| [1000 cd/m²] | [Max] | [1000 cd/m²] | [Max] | x | y | [1000 cd/m², LT50] | [1000 cd/m², LT50] | [1000 cd/m², LT95] | [40] |
| Reda     | –         | –                 | 28           | –   | 0.64 | 0.36 | 10,000 | – | 100 | [40] |
| Greenb   | 20.6      | –                 | –            | –   | 0.28 | 0.65 | 48,000 | – | – | [41] |
| Greenb   | 23.8      | 24.0              | –            | –   | 0.36 | 0.58 | – | – | [42] |
| Blueb    | 22        | 26                | –            | –   | –   | –   | 100 | – | – | [43] |
| Blueb    | –         | 10.7              | 9.5 ( @10 mA/cm²) | 0.138 | 0.100 | – | – | [43] |

*aSinglet-exciton-harvesting fluorescent OLEDs.*

*bConventional fluorescent OLEDs.*
The device structure of the soluble OLEDs was changed from a blue common layer structure to an all-inkjet-printed RGB pixel structure, which incited the development of blue soluble OLEDs. The device performances of the soluble OLEDs are gradually catching up with those of the vacuum-evaporated OLEDs. The EQE and lifetime data of the soluble OLEDs are summarized in Table 8.

### 3.5. TFT

The semiconducting materials currently being used as the active layer of the backplane TFTs for flat panel displays are polycrystalline silicon (PS) and metal oxides for OLEDs, amorphous silicon for the liquid crystal display (LCD), organic semiconductors for the e-paper display, and 2D semiconductors. Figure 5 shows the typical mobility of these materials at the current level.

To drive an OLED display, a charge carrier mobility of about 10–100 cm²/Vs is needed. Indium gallium zinc oxide (IGZO), a typical material of amorphous metal oxide TFTs, showed a mobility of about 10 cm²/Vs and was commercialized for OLED TVs by LG Display. For higher-resolution OLED display application, however, it is necessary to improve the mobility of metal oxide TFTs. Various metal oxide materials have been tried to obtain a mobility value higher than that of IGZO TFTs, but the stability has not yet reached the level of IGZO, so further studies are needed to commercialize such materials.

Low-temperature polycrystalline silicon (LTPS) has been successfully commercialized as a backplane for high-resolution mobile OLED displays due to its high mobility. It is difficult, however, to uniformly fabricate a backplane TFT for a large OLED TV with a high yield by applying the laser annealing process. Therefore, it is necessary to develop stable and high-mobility TFTs for application to a high-resolution large OLED TV. For this purpose, in addition to research on the performance improvement of the conventional materials, research is being conducted on new semiconductor materials such as 2D transition metal dichalcogenide materials and quantum dot. Several challenges should be overcome, however, to apply such new materials as backplane TFT materials for the commercial OLED and next-generation displays.

Flexible displays are considered the next-generation displays due to their high form freedom. The backplane TFTs of the true form freedom display should be made of flexible semiconducting materials. In this sense, organic semiconductors are referred to as candidate materials due to their high mechanical flexibility (Figure 1). Although rapid progress has been made of late, however, in the development of such materials, the mobility of the materials must be further improved for driving the OLED display. The representative TFT results of various materials are summarized in Table 9.

### 4. Outlook

The current active research on NEDs is expected to continue in the coming years as well with the growth of the AR and VR industry, enhancing their key system performance factors, such as the FOV, eye box size, form
Figure 5. Charge carrier mobility vs. mechanical flexibility of various semiconducting materials for TFTs for a flat panel display application. This figure is inspired and redrawn from the seminar presentation by Dr. Gerwin Gelinck (Holst Center).

Table 9. Recent representative results of various emerging semiconducting materials for TFTs.

| Semiconducting materials | Channel   | Processing temperature (°C) | Dielectric | $\mu_{FE}$ (cm²/Vs) | $L_{on}/L_{off}$ | Year | Ref. |
|--------------------------|-----------|-----------------------------|------------|---------------------|----------------|------|------|
| Metal oxide              | IGZO      | 350                         | AlOₓ       | 84.4                | $\sim 10^3$    | 2014 | [51] |
| Metal oxide              | ZITO      | 600                         | AlOₓ       | $\sim 117$          | $\sim 10^6$    | 2016 | [52] |
| Metal oxide              | ZTO       | 450                         | AlOₓ       | 112                 | $3 \times 10^5$ | 2016 | [53] |
| Metal halide             | CuL       | 60                          | ZrO₂       | $\sim 2$            | $1 \times 10^5$ | 2017 | [54] |
| Quantum dot              | CdS       | 300                         | ZrO₂       | 48                  | $\sim 10^4$    | 2009 | [55] |
| Carbon nano-materials    | SWCNT     | 500                         | ZrO₂       | 30                  | $10^5$          | 2013 | [56] |
| Quantum dot              | CdSe      | 400                         | ZrO₂       | $\sim 450$          | $\sim 10^6$    | 2015 | [57] |
| 2D layered materials     | MoS₂      | 500                         | ZrO₂       | 50.1                | $\sim 10^3$    | 2016 | [58] |
| Organic                  | DPPT-TT   | 150                         | Solid electrolyte | 50 | $\sim 10^2$ | 2017 | [59] |
| Organic                  | BTBT      | 150                         | PVP-HDA    | 43                  | $\sim 10^6$    | 2014 | [60] |

Additionally, the keywords for the display technology will be ‘flexibility’ and ‘high resolution’ because the applications of the display are being diversified. Therefore, the backplane technology represented by TFT will be focused on TFT for flexible OLEDs and high-resolution displays. QLEDs will be intensively developed for the next several years as an alternative to OLEDs, and further improvement of their device performances are expected in 2019. OLEDs will remain as the key technology for the flexible display, and further exploration of high-efficiency blue OLEDs and soluble OLEDs will be actively carried out.

Disclosure statement
No potential conflict of interest was reported by the authors.

Notes on contributors
Ho Jin Jang received his B.S. degree (2013) from the School of Chemical Engineering of Sungkyunkwan University, South Korea, where he is now an M.S. degree candidate. His main research areas are OLED fabrication processes, particularly the solution process and thermal vacuum evaporation.
**Jun Yeob Lee** received his Ph.D. degree from Seoul National University, South Korea in 1998. After completing his postdoc studies at Rensselaer Polytechnic Institute (1998-1999), he joined Samsung SDI and developed active-matrix OLEDs (AMOLEDs) for 6 years. After that, he worked as a professor at the Department of Polymer Science and Engineering of Dankook University. Since 2015, he has been a professor at the School of Chemical Engineering of Sungkyunkwan University. His main research areas are synthesis of organic electronic materials and development of a novel device structure for organic electronic devices.

**Jeonghun Kwak** received his B.S. (2005) and Ph.D. (2010) Electrical Engineering degrees from Seoul National University, South Korea. After one year of postdoc studies at SNU, he worked as an assistant professor in Dong-A University, South Korea from 2011 to 2015. He has been in the School of Electrical and Computer Engineering of University of Seoul, South Korea since 2015. His current research interests are opto- and nano-electronic devices such as organic and colloidal QDLEDs, organic thermoelectric devices, and other energy storage and harvesting technologies based on organic molecules, polymers, and low-dimension materials.

**Dukho Lee** received his B.S. Electrical Engineering degree from Seoul National University in 2015, where he is currently pursuing a Ph.D. degree at the School of Electrical Engineering. His research interests include 3D displays, holographic displays, AR, and NEDs.

**Jae-Hyeung Park** received his B.S., M.S., and Ph.D. degrees from Seoul National University in 2000, 2002, and 2005, respectively. After graduating, he joined Samsung Electronics, where he worked on the development of motion blur reduction techniques for LCDs. From 2007 to 2012, he was a faculty member of Chungbuk National University, South Korea. In 2013, he joined the faculty of Inha University, South Korea, where he is now still a professor. He has been working on the acquisition, processing, and display of 3D information using the holography and light field techniques.

**Byoungho Lee** is currently a professor at and the head of the School of Electrical and Computer Engineering of Seoul National University, South Korea. He is a fellow of IEEE, SPIE, and the Optical Society of America (OSA). He is also a member of the Korean Academy of Science and Technology and a senior member of the National Academy of Engineering of Korea. He has served on the board of directors of OSA. He has received many awards, including the Jin-Bo-Jang Medal from the President of Korea in 2016. He has served as the vice president of the Korean Information Display Society. He is currently the president-elect of the Optical Society of Korea.

**Yong-Young Noh** is a professor at the Department of Chemical Engineering of POSTECH in Pohang, South Korea. He received his Ph.D. in 2005 from GIST, South Korea, and then worked at Cavendish Laboratory in Cambridge, UK as a postdoctoral associate. Afterwards, he worked as a senior researcher at ETRI, as an assistant professor at Hanbat National University, and as an associate professor at Dongguk University in Seoul. He has received the Merck Young Scientist Award (2013), Korea President Award (2014), and IEEE George E. Smith Award (2014), and KIDS-Gold Award (2017, Samsung Display), was named Scientist of the Month by the South Korean government (Sep. 2016). He has published over 270 papers in international journals in the field of organic electronics, particularly on OFETs, OLEDs, carbon nanotubes, and oxide TFTs.

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