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

Ho Jin Jang, Jun Yeob Lee, Jaeyun Kim, Jeonghun Kwak and Jae-Hyeung Park

School of Chemical Engineering, Sungkyunkwan University, Jangan-gu, Republic of Korea; School of Electrical and Computer Engineering, University of Seoul, Seoul, Republic of Korea; Department of Electrical and Computer Engineering, Inter-University Semiconductor Research Center, Seoul National University, Seoul, Republic of Korea; Department of Information and Communication Engineering, Inha University, Incheon, Republic of Korea

ABSTRACT

In 2019, the device performances of the display technologies were largely advanced by the development of new materials and of the device architecture and driving scheme. The recent progress in the areas of virtual reality (VR), augmented reality (AR), quantum dot light-emitting diode (QLED), and organic light-emitting diode (OLED) is comprehensively summarized and discussed in this paper.

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1. Recent progress of augmented reality and virtual reality

The emerging augmented reality (AR) and virtual reality (VR) applications continue to drive the development of the near-eye display (NED) or head-mounted display (HMD) techniques. Various research and development efforts are being made to enhance the traditional performance factors of the AR and VR NEDs, such as field of view (FOV) and angular resolution. The recent researches, however, also focused on various features enabling realistic and comfortable image presentation, including vergence-accommodation conflict (VAC) mitigation, hard-edge occlusion, and vision correction. Table 1 shows the features of the recently reported or commercialized NEDs.

1.1. FOV and angular resolution

The FOV of a NED is the angular size of the displayed virtual image. Generally, a large FOV is desirable to cover the FOV of the human visual system, which reaches 160 degrees when the eye rolling is considered [15]. Although the maximum FOV of the commercialized VR NED is about 170 degrees, which is achieved by using double display devices [11], the typical FOV of the commercialized VR NED is limited to 110 degrees [16]. The effort to enhance the FOV for the VR NEDs is usually focused on the development of new lens optics [17,18]. In the case of the AR NEDs, the FOV is further limited due to the requirement of the transparent image combiner. The typical FOV of the commercially available AR NEDs is about 50 degrees [10,14]. The recently reported work for enhancing the FOV of the AR NEDs included the use of polarization-dependent grating [19,20]. The use of the geometric-phase (GP) lens has also been reported to achieve over 80 degrees FOV by enabling transmission-type configuration [9,21].

The angular resolution of a NED is defined by the number of pixels in a unit degree. The direct approach to enhancing the angular resolution is to increase the pixel density of the display panel. The trade-off relationship between the FOV and the angular resolution, however, makes it difficult to achieve a wide FOV and a high angular resolution simultaneously at a given pixel density of the display panel [22]. A notable research work in 2019 reported the foveated displays. Motivated by the different angular resolution of the human visual system in the central vision (around 60 pixels per degree) and the peripheral vision (around 30 pixels per degree) [23], the foveated displays present high-angular-resolution images only within the eye gaze area while maintaining a low angular resolution in the peripheral area, reducing the total system resolution requirement. Several techniques have been reported in 2019 to achieve the foveated image presentation and dynamic change of the foveated area according to the tracked eye gaze direction [13,24–26], which are summarized in Table 2.
Table 1. Features of the recently reported or commercialized AR and VR NEDs.

| Name         | FOV       | Resolution (pixels) | Focus cue | Image combiner      | Year | Ref. |
|--------------|-----------|---------------------|-----------|---------------------|------|------|
| Hu et al.    | 33 × 25   | 1024 × 768          | Varifocal | Freeform half mirror| 2014 | [1]  |
| Googleglass  | 13 × 7.3  | 640 × 360           | X         | BS                  | 2014 | [2]  |
| Yeom et al.  |           |                     | Holography| DOE                 | 2015 | [3]  |
| Holoens      | 30 × 17.5 | 1366 × 768          | X         | DOE                 | 2016 | [4]  |
| Maimone et al. | 80 (diag.) | 1920 × 1080       | Holography| HOE               | 2017 | [5]  |
| Jang et al.  | 55 × 40   | 960 × 540           | Light field| HOE               | 2017 | [6]  |
| Aksit et al. | 55–63     | 1280 × 720          | Varifocal | Diffuser-type HOE   | 2017 | [7]  |
| Magic Leap  | 40 × 30   | 1280 × 960          | Two layers| DOE               | 2018 | [8]  |
| Lee et al.   | 90 (diag.)|                    | X         | BS + Metasurface lens| 2018 | [9]  |
| Nreal        | 52 (diag) | 1080p               | X         | BS                  | 2019 | [10] |
| Pimax8K      | 170 × 130 | 3840 × 2160         | X         | VR                  | 2019 | [11] |
| Lee et al.   | 30        |                     | Tomographic| VR               | 2019 | [12] |
| Kim et al.   | 75 × 78   | 60 cpd in fovea      | Varifocal | HOE               | 2019 | [13] |
| Hololens2    | 52 (diag) | 2048 × 1080         | X         | DOE                 | 2019 | [14] |

Table 2. Foveated AR NEDs reported in 2019.

| # of panels per eye | Foveation mechanism                                      | Dynamic foveation | Ref. |
|--------------------|----------------------------------------------------------|-------------------|------|
| 2                  | High-resolution varifocal image on top of a low-resolution peripheral Maxwellian image | Mechanical movement | [13] |
| 2                  | Combining two images using BS with different magnifications | Cascaded GP deflector | [24] |
| 1 or 2             | Polarization-dependent focal-length pancake lens          |                   |      |
| 1                  | Intentional pinchusion                                     | Mechanical movement | [26] |

1.2. Focal cue

The usual AR and VR NEDs optically form virtual images at a fixed distance while the distance perceived by the user is varied by the disparity in the stereoscopic image pair presented to the two eyes. The difference between the optical and perceived distances causes the VAC, which hinders natural and comfortable viewing in both AR and VR applications. In the AR case, the different focal blur between the real objects and the virtual images also deteriorates the AR experience. VAC mitigation has been an active research field in academia for a decade. Since recently, however, industry has also been making considerable efforts to develop practical solutions for VAC [13,27]. Various techniques, including the multi-plane display [28,29], varifocal display [13,30], extended-depth-of-focus display [27], light field display [31], and holographic displays [32–36], have been reported in 2019, and their features are summarized in Table 3.

1.3. Various functionalities

Along with the research on the fundamental performance factors, including the FOV, angular resolution, and VAC mitigation, various techniques enabling more realistic and comfortable viewing have also been reported in 2019. One example is the hard-edge occlusion of real objects by the displayed virtual images in the AR NEDs. The usual AR NEDs only add the light for the virtual images to the light coming from real objects without proper blocking, which makes the displayed virtual images translucent. The hard-edge occlusion techniques block the light from real objects at the virtual image position, enabling more realistic image presentation and enhancing the image contrast. Although the first high-edge occlusion technique has been demonstrated nearly two decades ago [37], the recent works in 2019 report a more compact form factor [38] and variable distance occlusion [39]. Another example is the AR NEDs with vision prescription lenses [40]. For the widespread use of the AR and VR NEDs, comfortable wearing is important. The compact AR NEDs with vision prescription lenses make it easy to wear the AR NEDs on top of the vision-correcting glasses, making the AR NED experience comfortable and more practical. A subtractive AR NED has also been reported in 2019 [41]. While most AR NEDs work in additive mode, the subtractive AR NED presents images by subtracting the virtual image portion from the incoming real object light, making the virtual images more apparent in bright ambient light conditions. Table 4 summarizes these works.

Table 3. Focus-cue-supporting AR and VR NEDs reported in 2019.

| Type                      | Feature                                      | Ref. |
|---------------------------|----------------------------------------------|------|
| Extended depth of focus   | Pin mirror (array) combiner                   | [27] |
| Multiple plane            | Polarization multiplexing using GP lenses     | [28,29] |
| Varifocal                 | Mechanical axial shift of the display panel   | [13] |
| Varifocal                 | Freeform Alvarez lens                         | [30] |
| Light field               | Hybrid presentation of 2D and 3D images using an LC lens array to enhance the perceived resolution | [31] |
| Holographic               | Full color using a single SLM and grating     | [32] |
| Holographic               | Foveated hologram synthesis for NEDs          | [33,34] |
| Holographic               | Hologram synthesis from light field data with enhanced resolution over a holographic stereogram | [35,36] |
Table 4. AR NEDs with various functionalities reported in 2019.

| Type               | Feature                                                                 | Ref. |
|-------------------|-------------------------------------------------------------------------|------|
| Occlusion-capable | Double-pass configuration using polarization BS                         | [38] |
| Occlusion-capable | Varifocal image + occlusion using tunable lenses                         | [39] |
| Prescription AR   | Prescription lens implemented in the NED; compact form factor           | [40] |
| Subtractive AR     | Spatial color filtering using phase SLM; passive image illumination by environmental light | [41] |

2. Progress of QLEDs

Research on the synthesis of colloidal nanocrystal quantum dots (QDs) and their application to quantum dot light-emitting diodes (QLEDs) has attracted great attention for a decade due to such QDs’ unique optical and electrical properties. The photoluminescence quantum yield (PLQY) of the QDs have been approaching unity owing to the advances in the QD synthesis methods. As a result, the performance of QLEDs has also been increasing, as plotted in Figure 1. It is noticeable that the number of papers reporting InP-based QLEDs is currently rapidly increasing.

2.1. Cd-based QLEDs

Cd-based QDs have the advantages of narrow emission (FWHM < 30 nm) and high stability. With these advantages, the external quantum efficiency (EQE) of Cd-based QLEDs is continuously increasing. Recently, > 30% EQE was reported through shell growth control and modification of the surface ligands of the red-emitting Cd-based QDs [45]. As shown in Figure 1 and Table 5, the maximum EQEs of red-, green-, and blue-emitting QLEDs reached 30.9, 25.04, and 19.5%, respectively [45,51,54].

From the viewpoint of brightness, a QLED exhibiting an extremely high value of > 1,600,000 cd/m² was achieved by improving the heat dissipation through the use of sapphire as a substrate as sapphire has higher thermal conductivity than the glass substrate [52].

2.2. InP-based QLEDs

Colloidal QDs without any Cd atom is of interest due to the toxicity of Cd. For the red and green emitters, InP is the most widely investigated. The performance of InP-based QLEDs has been rapidly improved of late. A > 20% EQE was reported for the red-emitting InP-based QLEDs in November 2019, by removing the defective oxide layer at the surface of the InP core and engineering the shell thickness and ligand length [61]. This work also reported the high brightness of ∼ 100,000 cd/m² as well as enhanced operational lifetime. Bright and efficient green-emitting InP QLEDs with narrow spectral bandwidths (FWHM < 40 nm) were also reported by introducing a hole-suppressing interlayer with a top emission structure [59], and by adopting the composition-tailored ZnMgO nanoparticles as the ETL [66]. These results are brightening the prospects of using Cd-free QDs for the practical QLEDs. The device performances of the selected InP-based QLEDs are summarized in Table 6.

2.3. Demonstration of active-matrix QLED displays

The implementation of active-matrix QLEDs (AMQLEDs) is highly meaningful for the realization of QLED displays. A few companies and research groups have demonstrated monochromatic or full-color AMQLEDs [67–73], as shown in Figure 2. For the monochromatic AMQLEDs, the QD layer can be formed...

![Image](Figure 1. EQEs of the Cd- and InP-based QLEDs [42–66].)
Table 5. 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     | 640                  | 28        | 42,000                 | 20.5         | –             | [42] |
| CdSe/CdZnSe/ZnSe | 631             | 21        | 30,000[^a]             | 15.1         | 15.9          | [45] |
| CdZnSe/ZnS   | 624                  | 25        | 54,669                 | 18.5         | 31.36         | [44] |
| ZnCdSe/ZnSe/ZnS | 602              | 27        | 334,000                | 30.9         | 72.0          |      |
| Green        |                      |           |                        |              |               |      |
| CdSe/ZnS     | 515                  | 38        | 218,800                | 5.8          | 19.2          | [46] |
| CdSe/ZnS     | 526[^a]              | 27        | 90,000[^a]             | 21           | 82.0          | [47] |
| ZnCdSe/ZnS   | 532                  | 20        | 78,000                 | 16.5         | 70.1          | [48] |
| CdSe/ZnS/ZnS | 515                  | 26        | 460,000                | 6.4          | –             | [49] |
| CdSe/ZnS/ZnS | 522                  | 19        | 106,400                | 24.8         | 98.2          | [50] |
| CdSe/ZnS/ZnS/ZnS | 524              | 21        | 70,650                 | 25.04        | 96.42         | [51] |
| ZnCdSe/ZnS/ZnS | 538[^a]             | 20[^a]    | 1,680,000              | 16.6         | 75.3          | [52] |
| Blue         |                      |           |                        |              |               |      |
| ZnCdS/ZnS    | 443                  | 21.5      | 7600                   | 10.3         | 1.9           | [53] |
| CdSe/ZnS     | 468                  | 20        | 4890                   | 19.8         | 14.1          | [54] |
| ZnCdSe/ZnS/ZnS | 479              | 34        | 14,100                 | 16.2         | 11.8          | [55] |
| CdZnS/ZnS    | 452                  | 24        | 7993                   | 17.4         | 2.0[^a]       | [56] |

[^a] Estimated from the graph.

Table 6. Device performances of InP-based 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           | [57] |
| InP/ZnSe/ZnS  | 607                  | 48        | 1600                   | 6.6          | 13.6          | [58] |
| InP/ZnSeS     | 623                  | 38        | 27,800                 | 4.4          | 8.5           | [59] |
| InP/ZnSe/ZnS  | 618                  | 42        | 10,000                 | 12.2         | 14.7          | [60] |
| InP/ZnSe/ZnS  | 630                  | 35        | 100,000                | 21.4         | –             | [61] |
| Yellow        |                      |           |                        |              |               |      |
| InP/ZnSeS/ZnS | 545                  | 56[^a]    | 10,490                 | 1.5[^a]      | 4.44          | [62] |
| InP/ZnSe/ZnS  | 565                  | 65        | 1900                   | 5.1          | 18.0          | [63] |
| Green         |                      |           |                        |              |               |      |
| InP/ZnSeS     | 518                  | 64        | 3900                   | 3.46         | 10.9          | [64] |
| InP/GaP/ZnS/ZnS | 527              | 58        | 2938                   | 6.3          | 13.7          | [65] |
| InP/ZnSeS     | 539                  | 37        | 17,400                 | 3.4          | 21.6          | [59] |
| –             | 531                  | 34        | 13,900                 | 13.6         | –             | [66] |

[^a] Estimated from the graph.

Figure 2. Demonstration of monochromatic and full-color AMQLEDs [67–73].

3. Progress of organic light-emitting diodes (OLEDs)

3.1. Fluorescent OLEDs

In the field of fluorescent OLEDs, most of the past development efforts were focused on the research on singlet exciton harvesting fluorescent OLEDs rather than on the traditional fluorescent OLEDs. The progress of the fluorescent blue OLEDs was marginal. In the red, green, and blue singlet harvesting fluorescent OLEDs, the EQE is close to or above 20%. Therefore, the potential of the
singlet exciton harvesting fluorescent OLEDs as high-efficiency OLEDs has been established. Moreover, the lifetime was also largely advanced by the material and device engineering. In 2019, remarkable advances in the blue thermally activated delayed fluorescence (TADF) performances have been made. The EQE of the blue TADF OLEDs exceeding 30% with a deep-blue color coordinate was first demonstrated, and it was even better than that of the blue phosphorescent OLEDs. The lifetime data of the TADF OLEDs, however, are still limited. The device performances of the fluorescent OLEDs achieved in 2019 are summarized in Table 7.

### 3.2. Phosphorescent OLEDs (PhOLEDs)

The device performances of PhOLEDs have not been largely improved, but significant advances in the blue-device lifetime have been reported. For the first time, an over 1000 h device lifetime was reported in the deep-blue PhOLEDs’ EQE. The lifetime data of PhOLEDs are summarized in Table 8.

### 3.3. Soluble OLEDs

The device performances of the soluble OLEDs have been steadily improved every year. In particular, progress in the blue device performances was noticed in 2019. The lifetime of the blue soluble OLEDs is approaching that of the vacuum-deposited blue OLEDs. The EQE and lifetime data of soluble OLEDs are summarized in Table 9.

### 4. Outlook

The progress of the quantum dot light-emitting diode (QLED) device performances was remarkable in 2019. In particular, the Cd-free quantum dot (QD) technology is catching up with the Cd-based QD technology. Although the QLED performances of the Cd-free green and blue QDs are inferior to those of the Cd-based QDs, they will be upgraded in the near future. In the field of organic light-emitting diodes (OLEDs), the lifetime of the blue devices is not long enough, but the development of the narrowband blue emitters opened a new way of

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**Table 7.** Device performances of the fluorescent and TADF OLEDs in 2019.

| Device Type   | Color  | EQE (%) [1000 cd/m²] | CE (cd/A) [1000 cd/m²] | Color coordinates | Lifetime (h) | Ref. |
|---------------|--------|----------------------|------------------------|-------------------|--------------|-----|
| Fluorescence  | Blue   | 10.7 (@10 mA/cm²) | 9.5 ( @10 mA/cm²) | 0.138 0.100 | – | [74] |
| TADF          | Red    | 7.5 (@100 cd/m²) | 20         | 28.9 0.59 0.41 | – | [75] |
|               | Blue   | 4.6                  | 27.4 | 5.0 30.0 0.65 0.35 | – | [76] |
|               | Blue   | 34.3                  | 38.15 | 57.0 64.38 0.15 | 0.28 | – | [77] |
|               | Blue   | 26.0                  | 34.4 | 23.2 31.0 | 0.12 0.11 | 31 (100 cd/m², LT50) | [78] |
| Hyper-fluorescence | Red | –                   | – | 28 | 0.64 0.36 | 10,000 (1000 cd/m², LT50) | [80] |
| Green         | 20.6   | –                   | – | – | 0.28 0.65 | 48,000 (1000 cd/m², LT50) | [82] |
| Blue          | 22     | 26                   | – | – | 0.17 0.36 | 102.9 (1000 cd/m², LT50) | [79] |

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**Table 8.** Device performances of PhOLEDs in 2019.

| Device Type | Color | EQE (%) [1000 cd/m²] | CE (cd/A) [1000 cd/m²] | Color coordinates | Lifetime (h) | Ref. |
|-------------|-------|----------------------|------------------------|-------------------|--------------|-----|
| Red         | –     | 25                   | – | – | 0.70 0.30 | 55,000 (1000 cd/m², LT95) | [84] |
| Green       | –     | 25                   | – | – | 0.42 0.56 | 300,000 (1000 cd/m², LT95) | [84] |
| Blue        | –     | –                    | 47 | – | 0.18 0.42 | 20,000 (1000 cd/m², LT50) | [84] |
| Green       | –     | 24.7                 | 31.9 | 40.9 52.9 | 0.14 0.18 | – | [85] |
| Blue        | –     | 25.6                 | 27.6 | – | 0.12 0.13 | 10,700 (1000 cd/m², LT50) | [86] |

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**Table 9.** Device performances of soluble OLEDs in 2019.

| Device Type | Color | EQE (%) [1000 cd/m²] | CE (cd/A) [1000 cd/m²] | Color coordinates | Lifetime (h) | Ref. |
|-------------|-------|----------------------|------------------------|-------------------|--------------|-----|
| Red         | –     | –                    | – | 28 | 0.68 0.32 | 6000 (1000 cd/m², LT95) | [87] |
| Green       | –     | –                    | – | 95 | 0.31 0.64 | 20,000 (1000 cd/m², LT95) | [87] |
| Blue        | –     | –                    | – | 10 | 0.12 0.12 | 1200 (1000 cd/m², LT95) | [87] |
| Green       | –     | –                    | – | 7 | 0.08 0.08 | 600 (1000 cd/m², LT95) | [87] |
upgrading the device performances of the blue OLEDs. The continuous exploration of the narrowband organic emitters in the red, green, and blue colors will further promote the efficiency and lifetime of the OLEDs. The augmented reality (AR) and virtual reality (VR) displays have also been significantly advanced. The active applications of liquid crystal (LC) or metahologram-based global positioning system (GPS) devices to achieve a wide field of view (FOV), a high compact form factor, and enhanced vergence-accommodation conflict (VAC) mitigation were notable in 2019. Foveated displays are also being studied actively, and their implementations in various system configurations have been reported. Research on the new image combining devices and optical systems is expected to continue to enhance not only the key performance factors like the FOV, angular resolution, and form factor but also new features like VAC mitigation and hard-edge occlusion.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Notes on contributors

Ho Jin Jang received his B.S. degree from the Department of Chemical Engineering of Sungkyunkwan University, South Korea in 2013. He is now on Ph.D. course continuing M.S. degree at the School of Chemical Engineering of the same university. His main research areas are organic light-emitting diode (OLED) fabrication processes through solution processes and thermal vacuum evaporation.

Jun Yeob Lee received his Ph.D. from Seoul National University, South Korea in 1998. After serving as a postdoc at Rensselaer Polytechnic Institute (1998–1999), he joined Samsung SDI and developed active-matrix organic light-emitting diodes (AMOLEDs) for 6 years. He then worked as a professor at the Department of Polymer Science and Engineering of Dankook University and has been a professor at the School of Chemical Engineering of Sungkyunkwan University since 2015. His main research areas are the synthesis of organic electronic materials and the development of a novel device structure for such devices.

Jaeyun Kim received his B.S. (2014) and M.S. (2016) degrees from the Department of Electronic Engineering of Dong-A University, South Korea. He is currently pursuing a Ph.D. at the School of Electrical and Computer Engineering of University of Seoul, South Korea. His research topic is multifunctional sensor devices using organic thermoelectric devices and quantum dot light-emitting diodes (QDLEDs).

Jeonghun Kwak received his B.S. (2005) and Ph.D. (2010) Electrical Engineering degrees from Seoul National University (SNU), South Korea. After holding a one-year postdoctoral position in SNU, he worked as an assistant professor at the Department of Electronic Engineering of Dong-A University, South Korea, from 2011 to 2015, and at the School of Electrical and Computer Engineering of University of Seoul, South Korea from 2015 to 2019. From March 2019, he has been with the Department of Electrical and Computer Engineering of SNU. His current research interests are opto- and nano-electronic devices like organic and colloidal QDLEDs, organic thermoelectric devices, and other energy storage and harvesting technologies...
based on organic molecules, polymers, and low-dimensional materials.

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

References

[1] X. Hu, and H. Hua, High-Resolution Optical See-Through Multi-Focal-Plane Head-Mounted Display Using Freeform Optics, Opt. Express 22, 13896–13903 (2014).
[2] A.D. Hwang, and E. Peli, An Augmented-Reality Edge Enhancement Application for Google Glass, Optom. Vis. Sci. 91, 1021–1030 (2014).
[3] H.-J. Yeom, H.-J. Kim, S.-B. Kim, H. Zhang, B. Li, Y.-M. Ji, S.-H. Kim, and J.-H. Park, Opt. Express 23, 32025–32034 (2015).
[4] B.C. Kress, and W.J. Cummings, 3D Holographic Head Mounted Display Using Holographic Optical Elements with Astigmatism Aberration Compensation, Digital Opt. Technol. 2017, 103350K (2017).
[5] A.Mainmone, A. Georgiou, and J.S. Kollin, Optical Architecture of Hololens Mixed Reality Headset, ACM Trans. Graph. 36, article 85 (2017).
[6] C. Jang, K. Bang, S. Moon, J. Kim, S. Lee, and B. Lee, Retinal 3D: Augmented Reality Near-Eye Display via Pupil-Tracking Light Field Projection on Retina, ACM Trans. Graph. 36, article 190 (2017).
[7] K. Aksit, W. Lopes, J. Kim, P. Shirley, and D. Luebke, Near-Eye Varifocal Augmented Reality Display Using See-Through Screens, ACM Trans. Graph. 36, article 1 (2017).

https://magic-learn.realtny/news/magic-learn-one-field-view-specs-finally-uncovered-0186278/.
[9] G.-Y. Lee, J.-Y. Hong, S. Hwang, S. Moon, H. Kang, S. Jeon, H. Kim, J.-H. Jeong, and B. Lee, Metasurface Eyepiece for Augmented Reality, Nat. Commun. 9, article 4562 (2018).
[10] https://www.nreal.ai/old-press/nreal-light-announcement/.
[11] https://www.pimax.com/pages/pimax-8k-series.
[12] S. Lee, Y. Jo, D. Yoo, J. Cho, D. Lee, and B. Lee, Tomographic Near-Eye Displays, Nat. Commun. 10, article 2497 (2019).
[13] J. Kim, Y. Jeong, M. Stengel, K. Aksit, R. Albert, B. Boudaoud, T. Greer, J. Kim, W. Lopes, Z. Majercik, P. Shirley, J. Spjut, M. McGuire, and D. Luebke, Foveated AR: Dynamically-Foveated Augmented Reality Display, ACM Trans. Graph. 38, article 99 (2019).
[14] https://www.microsoft.com/en-us/hololens.
[15] M. Hillenbrand, W. Singer, H. Munz, and N. Kewen, See-Through Near to Eye Displays: Challenges and Solution Paths, 59th Ilmenau Scientific Colloquium, (11–15 Sep. 2017).
[16] https://en.wikipedia.org/wiki/Comparison_of_virtual-reality_headsets.
[17] B. A. Narasimhan, Ultra-Compact Pancake Optics Based on ThinEyes’ Super-Resolution Technology for Virtual Reality Headsets, Proc. SPIE 10676, Digital Optics for Immersive Displays, 106761G (21 May 2018).
[18] B. Wheelwright, J. Gollier, and M. Geng, Hybrid Fresnel Lens with Reduced Artifacts, U.S. patent 10,133,076 (Nov. 20, 2018).
[19] S.J. Robbins, E. Glik, S. He, and X. Lou, MEMS Laser Scanner Having Enlarged Fov, U.S. Patent Application Publication US 2018/0172994 (Jun. 21, 2018).
[20] J.D. Waldern, A.J. Grant, and M.M. Popovich, DigiLens Switchable Bragg Grating Waveguide Optics for Augmented Reality Applications, Proc. SPIE 10676, Digital Optics for Immersive Displays, 106760G (21 May 2018).
[21] S. Moon, C.-K. Lee, S.-W. Nam, C. Jang, G.-Y. Lee, W. Seo, G. Sung, H.-S. Lee, and B. Lee, Augmented Reality Near-Eye Display Using Pancharatnam-Berry Phase Lenses, Sci. Rep. 9, article 6616 (2019).
[22] H.J. Jang, J.Y. Lee, J. Kwak, D. Lee, J.-H. Park, B. Lee, and Y. Y. Noh: Progress of Display Performances: AR, VR, QLED, OLED, and TFT, J. Inf. Display 20, 1–8 (2019).
[23] R.R. Hainich, O. Birnich, Displays Fundamentals & Applications (CRC Press, Boca Raton, Florida, United states, 2011).
[24] T. Zhan, Y.-H. Lee, G. Tan, J. Xiong, K. Yin, F. Gou, J. Zou, N. Zhang, D. Zhao, J. Yang, S. Liu, and S.-T. Wu, Panchratnam-Berry Optical Elements for Head-Up and Near-Eye Displays, J. Opt. Soc. Am. B 36, D52–D65 (2019).
[25] B. Wheelwright, Tradeoffs in VR Optics, OSA Frontiers in Optics 2019 (FiO 2019), Washington, DC, USA, paper FW5A.1, 2019.
[26] K. Aksit, P. Chakravarthula, K. Rathinavel, Y. Jeong, R. Albert, H. Fuchs, and D. Luebke, Manufacturing Application-Driven Foveated Near-Eye Displays, IEEE Trans. Vis. Comput. Graph. 25, 1928–1939 (2019).
[27] https://letinar.com/technology/.
[28] C.Yoo, K. Bang, C. Jang, D. Kim, C.-K. Lee, G. Sung, H.-S. Lee, and B. Lee, Dual-Focal Waveguide See-Through Near-Eye Display with Polarization-Dependent Lenses, Opt. Lett. 44, 1920–1923 (2019).
[29] J. Xiong, G. Tan, T. Zhan, Y.-H. Lee, and S.-T. Wu, Four-Plane Near-Eye Display without Sacrificing the Frame Rate, SID Symp. Dig. Tech. Pap. 50, 620–623 (2019).
[30] A. Wilson, and H. Hua, Design and Demonstration of a Vari-Focal Optical See-Through Head-Mounted Display Using Freeform Alvarez Lenses, Opt. Express 27, 15627–15637 (2019).
[31] P.-Y. Chou, J.-Y. Wu, S.-H. Huang, C.-P. Wang, Z. Qin, C.-T. Huang, P.-Y. Hsieh, H.-L. Lee, T.-H. Lin, and Y.-P. Huang, Hybrid Light Field Head-Mounted Display Using Time-Multiplexed Liquid Crystal Lens Array for Resolution Enhancement, Opt. Express 27, 1164–1177 (2019).
[32] Z. Zhang, J. Liu, Q. Gao, X. Duan, and X. Shi, A Full-Color Compact 3D See-Through Near-Eye Display System Based on Complex Amplitude Modulation, Opt. Express 27, 7023–7035 (2019).
[33] L. Wei, and Y. Sakamoto, Fast Calculation Method with Foveated Rendering for Computer-Generated Holograms Using an Angle Changeable Ray-Tracing Method, Appl. Opt. 58, A258–A266 (2019).

[34] Y.-G. Ju, and J.-H. Park, Foveated Computer-Generated Hologram and Its Progressive Update Using Triangular Mesh Scene Model for Near-Eye Displays, Opt. Express 27, 23725–23738 (2019).

[35] J.-H. Park, and M. Askari, Non-Hogel-Based Computer Generated Hologram from Light Field Using Complex Field Recovery Technique from Wigner Distribution Function, Opt. Express 27, 2562–2574 (2019).

[36] N. Padmanaban, Y. Peng, and G. Wetzstein, Holographic Near-Eye Displays Based on Overlap-Add Stereograms, ACM Trans. Graph. 38, article 214 (2019).

[37] K. Kiyokawa, Y. Kurata, and H. Ohno, An Optical See-Through Display for Mutual Occlusion of Real and Virtual environments, in Proc. ISAR, 60–67 (2000).

[38] A. Wilson, Mutual Occlusion in Augmented Reality displays, OSA Frontiers in Optics 2019 (FiO 2019) (Washington, DC, USA, paper FTh3A.2, 2019).

[39] K. Rathinavel, G. Wetzstein, and H. Fuchs, Varifocal Occlusion-Capable Optical See-Through Augmented Reality Display Based on Focus-Tunable Optics, IEEE Trans. Vis. Comput. Graph. 25, 3125–3134 (2019).

[40] J. Kim, M. Stengel, J.-Y. Wu, B. Boudaoud, J. Spjut, K. Aksit, R. Albert, T. Greer, Y. Jeong, W. Lopes, Z. Majercik, P. Shirley, M. McGuire, and D. Luebke, Matching Prescription & Visual Acuity: Towards AR for Humans, ACM Siggraph 2019 Emerging Technologies, article 18 (2019).

[41] Y. Itoh, T. Langlotz, D. Iwai, K. Kiyokawa, and T. Amano, Light Attenuation Display: Subtractive See-Through Near-Eye Display via Spatial Color Filtering, IEEE Trans. Vis. Comput. Graph. 25, 1951–1960 (2019).

[42] X. Dai, Z. Zhang, Y. Jin, Y. Niu, H. Cao, X. Liang, J. Chen, J. Wang, and X. Peng, Solution-Processed, High-Performance Light-Emitting Diodes Based on Quantum Dots, Nature 515, 96–99 (2014).

[43] W. Cao, C. Xiang, Y. Yang, Q. Chen, L. Chen, X. Yan, and L. Qian, Highly Stable QLEDs with Improved Hole Injection via Quantum Dot Structure Tailoring, Nat. Commun. 9, 2608 (2018).

[44] Q. Su, T. Sun, H. Zhang, and S. Chen, Origin of Positive Aging in Quantum-Dot Light-Emitting Diodes, Adv. Sci. 5, 1800549 (2018).

[45] J. Song, O. Wang, H. Shen, Q. Lin, Z. Li, L. Wang, X. Zhang, and L.S. Li, Over 30% External Quantum Efficiency Light-Emitting Diodes by Engineering Quantum Dot-Assisted Energy Level Match for Hole Transport Layer, Adv. Funct. Mater. 29, 1808377 (2019).

[46] J. Kwak, W.K. Bae, D. Lee, I. Park, J. Lim, M. Park, H. Cho, H. Woo, D.Y. Yoon, K. Char, S. Lee, and C. Lee, Bright and Efficient Full-Color Colloidal Quantum Dot Light-Emitting Diodes Using an Inverted Device Structure, Nano Lett. 12, 2362–2366 (2012).

[47] J.R. Manders, L. Qian, A. Titov, J. Hyvonen, J.T. Scott, K.P. Acharya, Y. Yang, W. Cao, Y. Zheng, J. Xue, and P.H. Holloway, High Efficiency and Ultra-Wide Color Gamut Quantum Dot LEDs for Next Generation Displays, J. Soc. Inf. Disp. 23, 523–528 (2015).

[48] Z. Li, Y. Hu, H. Shen, Q. Lin, L. Wang, H. Wang, W. Zhao, and L.S. Li, Efficient and Long-Life Green Light-Emitting Diodes Comprising Tridentate Thiol Capped Quantum Dots, Laser Photon. Rev 11, 1600227 (2017).

[49] X. Li, Y.B. Zhao, F. Fan, L. Levina, M. Liu, R.Q. Bermudez, X. Gong, L.N. Quan, J.Z. Fan, Z. Yang, S. Hoogland, O. Voznyy, Z.H. Lu, and E.H. Sargent, Bright Colloidal Quantum Dot Light-Emitting Diodes Enabled by Efficient Chlorination, Nat. Photonics 12, 159–164 (2018).

[50] H. Moon, and H. Chae, Efficiency Enhancement of All-Solution-Processed Inverted-Structure Green Quantum Dot Light-Emitting Diodes via Partial Ligand Exchange with Thiophenol Derivatives Having Negative Dipole Moment, Adv. Optical Mater. 8, 1901314 (2020).

[51] Z. Yang, Q. Wu, G. Lin, X. Zhou, W. Wu, X. Yang, J. Zhang, and W. Li, All-Solution Processed Inverted Quantum Dot Light-Emitting Diodes with Concurrent High Efficiency and Long Lifetime, Mater. Horiz. 6, 2009–2015 (2019).

[52] Y. Sun, Q. Su, H. Zhang, F. Wang, S. Zhang, and S. Chen, Investigation on Thermally Induced Efficiency Roll-Off: Toward Efficient and Ultrabright Quantum-Dot Light-Emitting Diodes, ACS Nano 13, 11433–11442 (2019).

[53] H. Shen, W. Cao, N.T. Sherwmon, C. Yang, L.S. Li, and J. Xue, High-Efficiency, Low Turn-on Voltage Blue-Violet Quantum-Dot-Based Light-Emitting Diodes, Nano Lett. 15, 1211–1216 (2015).

[54] L. Wang, J. Lin, Y. Hu, X. Guo, Y. Lv, Z. Tang, J. Zhao, Y. Fan, N. Zhang, Y. Wang, and X. Liu, Blue Quantum Dot Light-Emitting Diodes with High Electroluminescent Efficiency, ACS Appl. Mater. Interfaces 9, 38755–38760 (2017).

[55] Q. Lin, L. Wang, Z. Li, H. Shen, L. Guo, Y. Kuang, H. Wang, and L.S. Li, Nonblinking Quantum-Dot-Based Blue Light-Emitting Diodes with High Efficiency and a Balanced Charge-Injection Process, ACS Photonics 5, 939–946 (2018).

[56] D. Li, J. Bai, T. Zhang, C. Chang, X. Jin, Z. Huang, B. Xu, and Q. Li, Blue Quantum Dot Light-Emitting Diodes with High Luminance by Improving the Charge Transfer Balance, Chem. Commun. 55, 3501–3504 (2019).

[57] J.H. Jo, J.H. Kim, K.H. Lee, C.Y. Han, E.P. Jang, Y.R. Do, and H. Yang, High-Efficiency Red Electroluminescent Device Based on Multishelled InP Quantum Dots, Opt. Lett. 41, 3984–3987 (2016).

[58] F. Cao, S. Wang, F. Wang, Q. Wu, D. Zhao, and X. Yang, A Layer-by-Layer Growth Strategy for Large-Size InP/ZnSe/ZnS Core–Shell Quantum Dots Enabling High-Efficiency Light-Emitting Diodes, Chem. Mater. 30, 8002–8007 (2018).

[59] T. Lee, D. Hahn, K. Kim, W.K. Bae, C. Lee, and J. Kwak, Highly Efficient and Bright Inverted Top-Emitting InP Quantum Dot Light-Emitting Diodes Introducing a Hole-Suppressing Interlayer, Small 15, 1905162 (2019).

[60] Y. Li, X. Hou, X. Dai, Z. Yao, L. Lv, Y. Jin, and X. Peng, Stoichiometry-Controlled InP-Based Quantum Dots: Synthesis, Photoluminescence, and Electroluminescence, J. Am. Chem. Soc. 141, 6448–6452 (2019).

[61] Y.H. Won, O. Cho, T. Kim, D.Y. Chung, T. Kim, H. Chung, H. Jang, J. Lee, D. Kim, and E. Jang, Highly Efficient and Stable InP/ZnSe/ZnS Quantum Dot Light-Emitting Diodes, Nature 575, 634–638 (2019).
[62] H.C. Wang, H. Zhang, H.Y. Chen, H.C. Yeh, M.R. Tseng, R.J. Chung, S. Chen, and R.S. Liu, Cadmium-Free InP/ZnSe/ZnS Heterostructure-Based Quantum Dot Light-Emitting Diodes with a ZnMgO Electron Transport Layer and a Brightness of Over 10 000 cd m$^{-2}$, Small 13, 1603962 (2017).

[63] Y. Kim, B. Heyne, A. Geßner, Y. Park, M. Kang, S. Ahn, B. Lee, and A. Wedel, P-110: Efficient InP-based Quantum Dot Light Emitting Diodes utilizing a Crosslinkable Hole Transport Layer, SID Digest 49, 1625–1628 (2018).

[64] J. Lim, M. Park, W.K. Bae, D. Lee, S. Lee, C. Lee, and K. Char, Highly Efficient Cadmium-Free Quantum Dot Light-Emitting Diodes Enabled by the Direct Formation of Excitons within InP@ZnSe Quantum Dots, ACS Nano 7, 9019–9026 (2013).

[65] H. Zhang, N. Hu, Z. Zeng, Q. Lin, F. Zhang, A. Tang, Y. Jia, L.S. Li, H. Shen, F. Teng, and Z. Du, High-Efficiency Green InP Quantum Dot-Based Electroluminescent Device Comprising Thick-Shell Quantum Dots, Adv. Opt. Mater. 7, 1801602 (2019).

[66] H. Moon, W. Lee, J. Kim, D. Lee, S. Cha, S. Shin, and H. Chae, Composition-Tailored ZnMgO Nanoparticles for Electron Transport Layers of Highly Efficient and Bright InP-Based Quantum Dot Light Emitting Diodes, Chem. Commun. 55, 13299–13302 (2019).

[67] K.S. Cho, E.K. Lee, W.J. Joo, E. Jang, T.H. Kim, S.J. Lee, S.J. Kwon, J.Y. Han, B.K. Kim, B.L. Choi, and J.M. Kim, High-Performance Crosslinked Colloidal Quantum-Dot Light-Emitting Diodes, Nat. Photonics 3, 341–345 (2009).

[68] S. Coe-Sullivan, Z. Zhou, Y. Niu, J. Perkins, M. Stevenson, C. Breen, P.T. Kazlas, and J.S. Steckel, 12.2: Invited Paper: Quantum Dot Light Emitting Diodes for Near-to-Eye and Direct View Display Applications, SID Int. Symp. Dig. Tech. Pap. 42, 135–138 (2011).

[69] T.H. Kim, K.S. Cho, E.K. Lee, S.J. Lee, J. Chae, J.W. Kim, D.H. Kim, J.Y. Kwon, G. Amaratunga, S.Y. Lee, B.L. Choi, Y. Kuk, J.M. Kim, and B.L. Choi, Full-Colour Quantum Dot Displays Fabricated by Transfer Printing, Nat. Photonics 5, 176–182 (2011).

[70] Y. Yang, Y. Zheng, W. Cao, A. Titov, J. Hyvonen, J.R. Manders, J. Xue, P.H. Holloway, and L. Qian, High-Efficiency Light-Emitting Devices Based on Quantum Dots with Tailored Nanostructures, Nat. Photonics 9, 259–266 (2015).

[71] C. Jiang, L. Mu, J. Zou, Z. He, Z. Zhong, L. Wang, M. Xu, J. Wang, J. Peng, and Y. Cao, Full-Color Quantum Dots Active Matrix Display Fabricated by Ink-Jet Printing, Sci. China Chem. 60, 1349–1355 (2017).

[72] J. Kim, J. Lee, and J. Jang, 80-2: AMQLED Display with Solution-Processed Oxide TFT Backplane, SID Int. Symp. Dig. Tech. Pap. 49, 1080–1083 (2018).

[73] Y. Li, Z. Chen, B. Krystal, Y. Zhang, D. Li, G. Yu, X. Wang, L. Wang, Y. Shi, Z. Wang, Y. Chen, J. Yu, and Y. He, 80-1: Invited Paper: Developing AMQLED Technology for Display Applications, SID Int. Symp. Dig. Tech. Pap. 49, 1076–1079 (2018).

[74] T. Masuda, Y. Nakano, Y. Takahashi, H. Ito, K. Okinaka, E. Kambe, Y. Kawamura, and H. Kuma, 6-3: Distinguished Paper: Highly Efficient Fluorescent Blue Materials and Their Applications for Top Emission OLEDs, SID Int. Symp. Dig. Tech. Pap. 49, 52–55 (2018).

[75] R. Furue, K. Matsuo, Y. Ashikari, H. Ooka, N. Amanokura, and T. Yasuda, Highly Efficient Red–Orange Delayed Fluorescence Emitters Based on Strong π-Acceptor Dibenzo[cd]phenazine and Dibenzo[18]annulene Cores: toward a Rational Pure-Red OLED Design, Adv. Opt. Mater. 6, 1701147 (2018).

[76] Y.L. Zhang, Q. Ran, Q. Wang, Y. Liu, C. Hanisch, S. Reineke, J. Fan, and L.S. Liao, High-Efficiency Red Organic Light-Emitting Diodes with External Quantum Efficiency Close to 30% Based on a Novel Thermally Activated Delayed Fluorescence Emitter, Adv. Mater. 31, 1902368 (2019).

[77] T. Baumann, M. Budzynski, and C. Kasperek, 33-3: TADF Emitter Selection for Deep-Blue Hyper-Fluorescent OLEDs, SID Int. Symp. Dig. Tech. Pap. 50, 466–469 (2019).

[78] D.H. Ahn, S.W. Kim, H. Lee, I.J. Ko, D. Karthik, J.Y. Lee, and J.H. Kwon, Highly Efficient Blue Thermally Activated Delayed Fluorescence Emitters Based on Symmetrical and Rigid Oxygen-Bridged Boron Acceptors, Nat. Photonics 13, 540–546 (2019).

[79] Y. Kondo, K. Yoshiura, S. Kitera, H. Nishi, S. Oda, H. Gotob, Y. Sasada, M. Yanai, and T. Hatakeyama, Narrowband Deep-Blue Organic Light-Emitting Diode Featuring an Organoboron-Based Emitter, Nat. Photonics 13, 678–682 (2019).

[80] Kyulux, 2018 OLED KOREA CONFERENCE

[81] S. Y. Yeo, A. Endo, J. Adachi, Invited Towards Commercialization of Hyperfluorescence, The 19th International Meeting on Information Display, (2019).

[82] J. Adachi, H. Okada, HyperfluorescenceTM, A Disruptive Technology, Changes the OLED Displays, The 18th International Meeting on Information Display, 104 (2018).

[83] D. Zhang, X. Song, M. Cai, and L. Duan, Blocking Energy-Loss Pathways for Ideal Fluorescent Organic Light-Emitting Diodes with Thermally Activated Delayed Fluorescent Sensitizers, Adv. Mater. 30, 1705250 (2018).

[84] www.oled.com

[85] H. Shin, Y.H. Ha, H.G. Kim, R. Kim, S.K. Kwon, Y.H. Kim, and J.J. Kim, Controlling Horizontal Dipole Orientation and Emission Spectrum of IR Complexes by Chemical Design of Ancillary Ligands for Efficient Deep-Blue Organic Light-Emitting Diodes, Adv. Mater. 31, 1808102 (2019).

[86] M. Jung, K.H. Lee, J.Y. Lee, and T. Kim, A Bipolar Host Based High Triplet Energy Electroplex for an over 10 000 h Lifetime in Pure Blue Phosphorescent Organic Light-Emitting Diodes, Mater. Horiz. (2020). doi:10.1039/C9MH01268K.

[87] T. Yamada, Latest Development of Soluble-OLED Material and its Application to Mid- to Large-Sized Panel Production, IEEE (2019). doi:10.23919/AM-FPD.2019.8830610