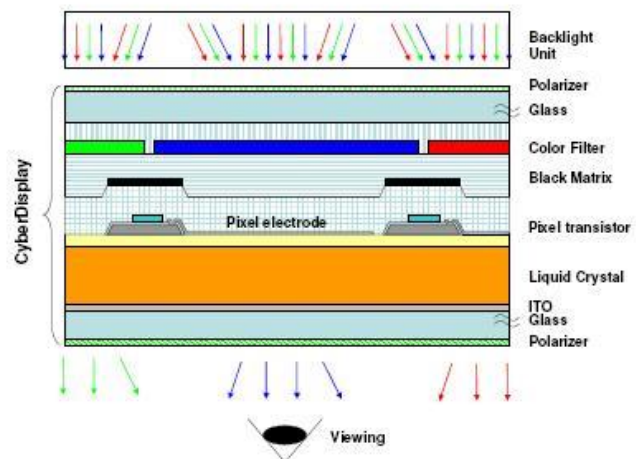


# Choosing the Right Microdisplay for Near-to-Eye Applications

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## Introduction

There are often multiple display technologies to consider for any display-based application. While the choice involves many factors beyond the display alone, this paper will focus on microdisplay technologies aimed for “near to eye” display applications such as electronic viewfinders, AR/VR headsets, head-mounted displays, and sights.

Microdisplays are different from direct-view displays like those found in TVs, monitors, or phones. First, the size of microdisplays is smaller than 1.3 inches in diagonal. Second, microdisplays have a much higher pixel density ranging from 1700 to 4000 pixels per inch (ppi), with a pixel size less than 15 microns. Third, microdisplays need magnifying optics between the microdisplay and the eye. The high pixel density together with magnifying optics is important for creating more lifelike, large images to the eye.

Even the best direct-view liquid crystal displays (LCDs) can’t match the pixel density of microdisplays. For example, the new Meta Quest Pro VR headset uses dual 2.48” LCDs with miniLEDs and quantum dots to offer 1800 x 1920 resolution per eye and 1050 ppi. The Pico 4 and Pico 4 Pro VR headsets can reach 1200 ppi with dual 2.5” LCDs.

The fabrication of microdisplays is also fundamentally different from direct-view displays. Microdisplays are fabricated on a silicon substrate (the backplane) with different display technologies possible on top (the frontplane). The backplane of a direct-view display is fabricated on glass – often very large glass substrates – with lower performing electronics on the backplane, and the LCD or organic light emitting diode (OLED) materials available for the frontplane.

## Overview of Microdisplay Technologies

Table 1 below summarizes some of the strengths and weaknesses of four different microdisplay technologies: LCD, Liquid Crystal on Silicon (LCOS), OLED and Micro Light Emitting Diode (microLED). These technologies represent four microdisplay options available from Kopin – perhaps the only supplier to offer such a broad range.

In the sections below, we will examine each of these technologies to discuss these display attributes and point out the applications where they have gained the most traction.

It should be noted that there are additional technologies such as DLP and laser beam scanning that can be used to create near-to-eye displays. DLP solutions seem more suited for larger-sized applications like HUDs and projectors while laser beam scanning (LBS) often suffers from image quality issues (check out Microsoft’s HoloLens 2).

	LCD	LCOS	OLED	MicroLED
Contrast	–	–	+	+
Brightness	+	+	–	++
Image Burn-in	+	+	–	+
Optics Coupling	+	–	+	+
Need for Separate Illumination Source	–	–	+	+
Compact System	+	–	+	+
Color Breakup	+	–	+	+
One Frame Delay	+	–	+	+
Integration with Other Functions	–	+	+	+
Resolution (Angular and Total Resolution)	+	++	++	++
Manufacturing Maturity	++	++	+	–

*Table 1: Assessment of Various Microdisplay Technologies for Near-to-Eye Applications*

## LCD Microdisplays

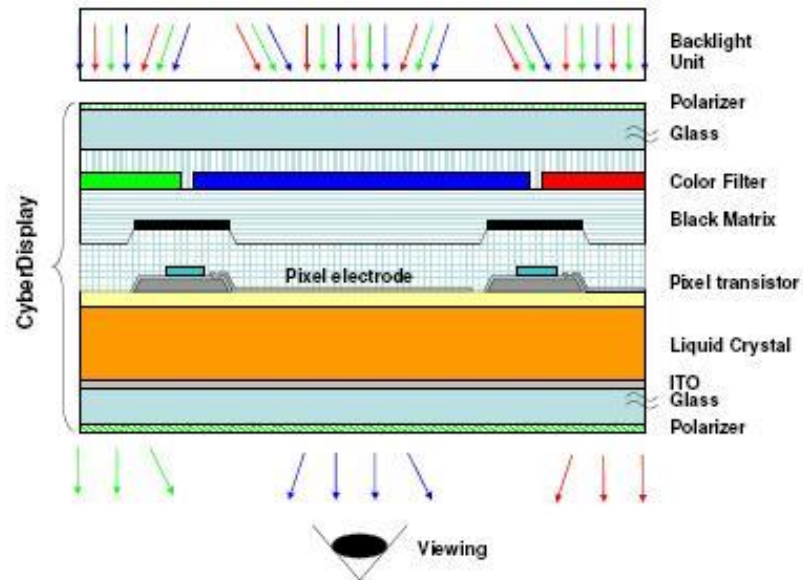
LCDs are transmissive displays that use a light source (backlight) to illuminate the LCD panel from behind. Each pixel in an LCD is like a valve that regulates how much light passes based on a voltage applied to pixel electrodes. Most LCDs use a white-light backlight with color filters in front of the LCD panel to create a color display (see Figure 1).

As noted above, the Meta Quest Pro represents the best-in-class capability of a direct-view LCD, but this approach cannot obtain the higher pixel densities of a microdisplay. To achieve this, Kopin pioneered a process to create transmissive LCDs where the backplane circuits are first fabricated in higher-performing single-crystal silicon and then the thin circuit layer, which is semi-transparent, is lifted-off and transferred to a glass substrate for more conventional LCD fabrication. Kopin calls this a CyberDisplay, which is the LCD technology summarized in Table 1.

The biggest positives of the CyberDisplay are the manufacturing maturity and extreme brightness, while the modest negatives include relatively low contrast.

The CyberDisplay has enjoyed great success since the 1990s. For example, CyberDisplays were very popular in camcorder and camera electronic viewfinders from multiple brands in the 1990s and early 2000's with more than 30 million displays delivered. CyberDisplays have also been highly successful in sights for weapons, hunting and other applications, having sold over 300K displays and display modules

for such applications to date.



*Figure 1: Structure of a Transmissive LCD Panel*

One of the key advantages of the CyberDisplay is its ability to reach very high brightness levels. This has been aided by the silicon backplane and black matrix light-blocking layer. One continuing success story is Kopin's sole-source supply of monochrome green CyberDisplays for the F-35 Helmet-Mounted Display (HMD) (Figure 2). This display has a resolution of SXGA (1280x1024) and can reach over 17,000 nits of brightness for use in bright outdoors. This display provides an augmented reality (AR) capability for the pilot with critical flight, tactical, and sensor information for advanced situational awareness, precision, and safety.

Full-color microdisplays with very high brightness and good contrast performance are highly desired by the military, so Kopin developed a new transmissive LCD named Brilliant. By enhancing the backplane design and processing, the Brilliant display delivers higher voltage to each pixel to increase contrast to around 500:1 compared to the CyberDisplay's < 200:1 contrast. With a high-power backlight, this Brilliant display can now reach > 34,000 nits of brightness – a very high level indeed.

One of the platforms that uses this Brilliant display is the Common Helmet Mounted Display (CHMD) (Figure 2). It is an advanced, see-through, high-definition, digital helmet-mounted display that supports the U.S. Army's CH-47F Chinook and the UH-60L/M/V Black Hawk fleets to provide both day and night enhanced situational awareness and survivability in all flight conditions.

A third application for high-brightness monochrome and color LCD displays is weapon sights. The display projects critical information, such as distance, temperature, wind speed, compass and GPS, onto a direct view optical sight. Some applications only need monochrome red symbology overlay on a narrow field of view optics but requires high brightness over 17,000 nits. Unlike OLED displays, LCD displays don't exhibit any image burn-in when displaying static symbology for long periods of time.



F-35 HMD



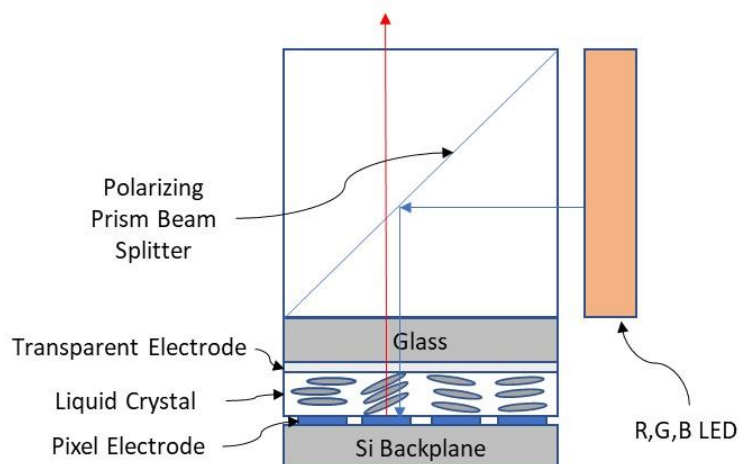
CHMD

*Figure 2: Military Helmet-Mounted Displays using the CyberDisplay*

So, when is a CyberDisplay or Brillian display the right choice? One consideration is compactness of the solution as the display and optics can be quite thin. Certain applications where the display needs to be very bright, such as in day light applications, is another good fit because of their high luminance levels. If environmental ruggedness is a key need, these displays have been proven in the most demanding environments.

## LCOS Microdisplays

While Kopin's CyberDisplay and Brillian displays are transmissive LCDs, LCOS displays are reflective. They still require external illumination but now a frontlight vs. a backlight is needed (Figure 3).



*Figure 3: Configuration of a Liquid Crystal on Silicon (LCOS) Display*

Like other microdisplays, the backplane is patterned in silicon, but no lift-off process is needed – the LCD frontplane is fabricated on top of the silicon. Light from the frontlight is reflected by a polarizing beam splitter toward the LCOS display, where it is reflected by the pixel electrodes of the backplane and passes out through the beam splitter. A full-color image is created by sequentially flashing red, green and blue light from the LED frontlight (color sequential operation). As a result, one pixel is needed to get a color image, instead of three red, green, and blue subpixels for the transmissive LCD.

The color sequential technique works well without color break-up artifacts (different colors land on different places on the retina for a moving object) only if the LCOS display can be operated at a very fast refresh rate (more than 120 Hz for each color or 360 Hz for all RGB colors). Most LCOS displays use twisted nematic liquid crystal which has slow response time (milliseconds), and special care is needed to make the LCOS display run at fast frame rates to avoid color break-up. Kopin uses a special material called ferroelectric liquid crystal, which has a very fast switching characteristic (microseconds) and binary on-off operation with pulse width modulation for grayscale control.

LCOS displays can have higher light efficiency than transmissive LCDs and therefore have an advantage in applications where high brightness with lower power consumption is needed such as battery-operated wearable AR systems.

One area where Kopin's LCOS displays have a strong value proposition is the display of phase or structured light patterns. Phase patterns are used with laser sources to create holographic images while structured light patterns are used in 3D automatic optical inspection (AOI) (see Figure 4).

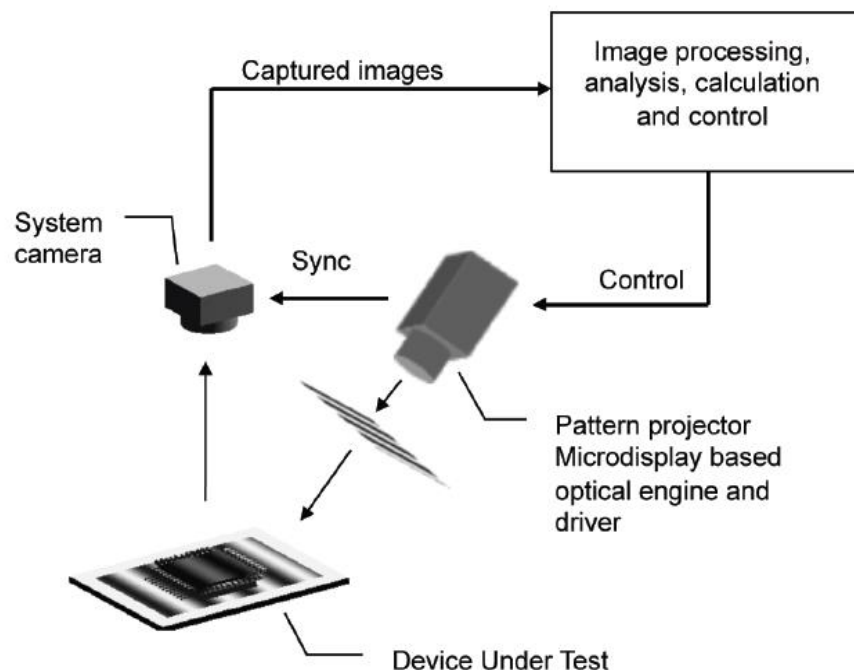


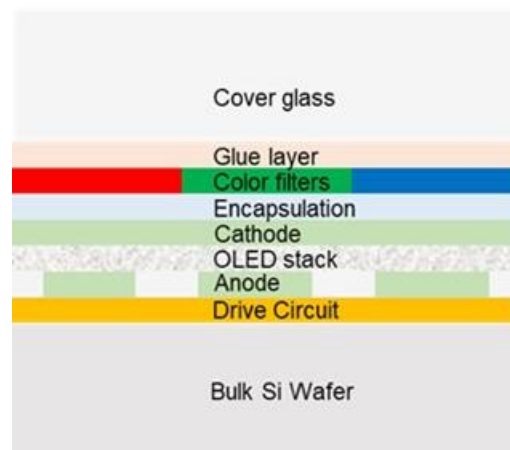
Figure 4: Configuration of 3D Automatic Optical Inspection

Kopin's SXGA (1280x1024) ferroelectric LCOS microdisplay has been a very popular choice to power the optical engine for 3D automated optical inspection (3D AOI). Patterns are projected by the FLCOS microdisplay onto a part moving down a production line, with a high-speed camera capturing the pattern as it interacts with the device under test. Algorithms can interpret the captured pattern to identify if the part is mechanically within specifications. Applications include precision printed circuit board assembly, solder paste inspection and small mechanical inspection in automatic assembly processes, where surface height distribution is calculated and compared with the reference in seconds.

## OLED Microdisplays

Like LCDs, OLED displays can be fabricated on glass (direct-view) or on silicon (microdisplay). The backplane for microdisplays contains the driving electronics and is fabricated in a semiconductor foundry. The frontplane consists of metallization layers, OLED layers and an encapsulation layer to prevent moisture and oxygen from reaching the OLED materials.

Color OLED microdisplays can be produced two ways. The first is to construct the OLED layers to create white light that is then filtered with red, green, or blue filters over each sub-pixel as shown in in Figure 5. The alternative approach is to directly pattern red, green, and blue sub-pixels with dedicated OLED stacks for each sub-pixel. Direct patterning has been used for direct-view OLED displays but it has not yet been proven for manufacturing of OLED microdisplays with tiny subpixels. Kopin and other leading OLED microdisplay suppliers have chosen the color filter approach.



*Figure 5: OLED Microdisplay with Color Filter Structure*

OLED displays are self-emitting, which means they are completely dark when not driven (backlight and frontlight systems cannot reach very low black levels). This means they achieve much higher contrast ratios (> 10,000: 1) than LCD or LCOS displays. Like LCDs and LCOS microdisplays, OLED microdisplays offer high resolution, a wide color gamut and good compatibility with magnification optics.

Because OLED microdisplays cannot deliver the high brightness levels that LCD or LCOS display can, they are better suited for immersive applications where high brightness is not needed. Such applications



include virtual reality, mixed reality with video see-through, electronic viewfinders, night vision devices and more.

One of the biggest markets for OLED microdisplays is electronic viewfinders for still and video cameras. Sony has a dominant position in this area, selling millions of devices each year. However, OLED microdisplay-based AR and VR headsets (designated as SiOLED in Figure 6, referring to OLED on Silicon) are expected to become the dominant technology over the next few years (see Figure 6 from Display Supply Chain Consultants (DSCC)). High-resolution, compact OLED microdisplays will allow compact, stylish VR glasses with lifelike image quality.

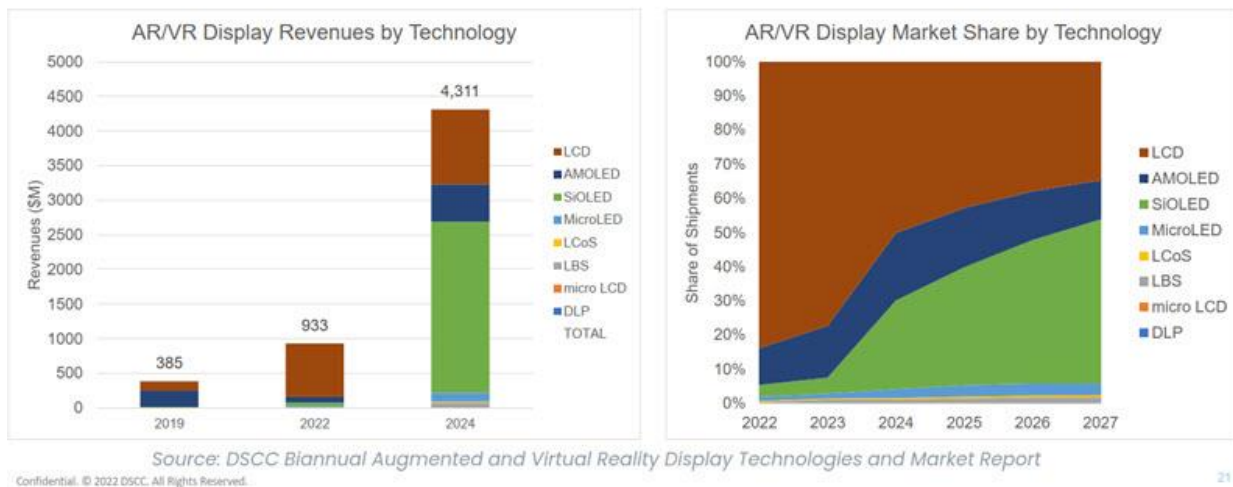


Figure 6: By 2027, OLED on Silicon (SiOLED) will represent 48% of all AR/VR Shipments

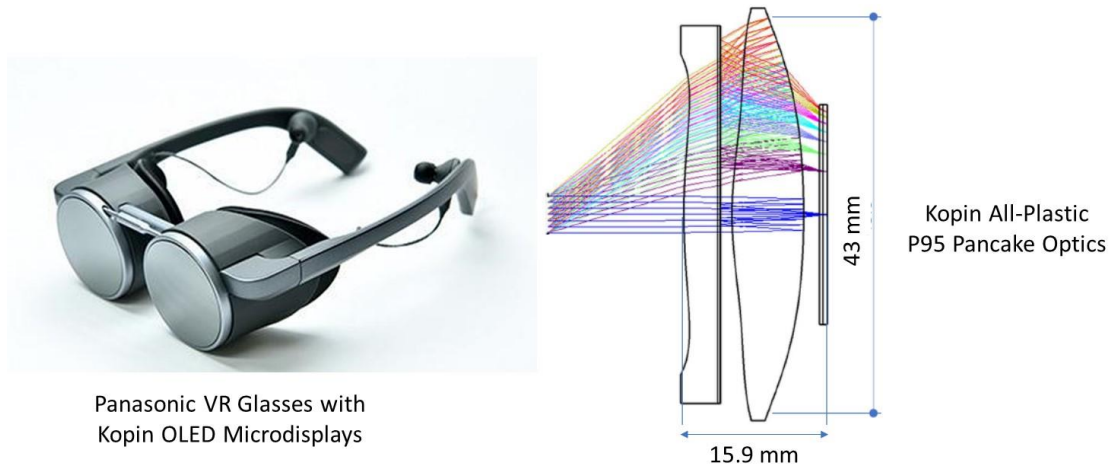
For VR and MR applications, Kopin has developed a 1.3"-diagonal 2.6K x 2.6K OLED microdisplay, with higher resolution devices in development. Performance of this device is state-of-the-art (120 Hz refresh, 30 color bits and contrast of >10,000:1, which are good for HDR imaging, >100% of sRGB color gamut, and >1000 nits of luminance). Kopin's patented backplane design allows lower power consumption and higher frame rates to avoid motion artifacts. The backplane also integrates MIPI receiver and DSC (Display Stream Compression) circuits.

To be suitable for brighter environments including augmented reality applications, Kopin is offering displays with dual-stack OLED structures and developing triple-stack OLED architectures. As the name implies, this means multiple OLED emitting layers on top of each other to increase brightness. This requires higher voltage but less current for the same brightness, which improves the reliability. Special backplane designs and processes are needed to reach both higher luminance levels and wider color gamut.

Kopin has also pioneered development of all-plastic Pancake optics to enable thin, lightweight, and high-performance VR headset designs. Pancake optics, compared to other optics designs, can provide far superior magnified image quality in a much thinner form factor, especially for VR headset products with FOV ranging from 50° to 100°. However, previous Pancake optics needed at least one spherical glass lens to avoid image artifacts caused by birefringence of plastic materials, but this spherical glass lens added



both weight and cost to the lens system as well as reduced optical design flexibilities compared to aspherical plastic lens. Kopin's patent-pending Pancake optics design, together with processes to make aspherical plastic lenses with virtually no birefringence, has provided much better image quality, much smaller size, lighter weight, and lower cost than anything previously available. Kopin's P95 Pancake optics design offers a wide 95-degree field of view with superb image quality.



*Figure 7: Pancake Optics are Being Adopted by Many VR Headset Developers*

## microLED Microdisplays

The most immature but potentially most impactful microdisplay technology is based on inorganic LEDs. Various classes of LED-based displays are characterized by the size of the LED device (micro, mini or standard) and the pixel pitch or space between each full-color LED pixel.

MiniLEDs and standard-sized LEDs are commercially available from many suppliers and are used for backlights for tablets, laptops, and TVs as well as direct-view LED screens for home entertainment, digital signage, virtual production, advertising and much more.

MicroLED microdisplays can be fabricated only with the smallest LEDs which are typically less than 5 microns. Like other microdisplay technologies, the backplane is fabricated in silicon with the frontplane composed of microLEDs.

The fabrication of microLED microdisplays poses several challenges. The first issue is the size of the microLED itself. As the LED gets smaller and smaller, it can lose efficiency. Defects at the edges of the LED are where most efficiency losses occur. For larger-sized LED, the emitting area is much larger than the edge area, so the losses are easily overcome. But as the LED gets smaller, the edge area is a much larger proportionally to the emitting area, so these losses become more significant. For many AR and VR applications, the microLED needs to be in the 2- to 5-micron range. As a result, development of

passivation technologies to address these losses are a key area of research and development. While it is true that smaller LEDs are less efficient, it is also true that they can be driven to very high luminance levels (sometimes millions of nits). This makes them ideal for applications in bright ambient lighting like augmented reality.

The second issue is microLED pitch. With direct-view LED displays, the pixel pitch is much larger than the device wafer pitch. Pick and place mass transfer technologies are commonly used to make such displays. But for AR/VR microLED displays, the wafer pixel pitch (single to 10 microns) is also the display-level pixel pitch. As a result, monolithic wafer-to-wafer bonding technologies need to be developed.

The third key issue is the creation of color microLED displays. In direct-view LED displays, the red, green and blue LEDs come from separate LED wafers that have been fabricated and tested to fit in certain quality bins. Mass transfer techniques (pick and place, stamp transfer or laser transfer) move the LED to the display substrate with the larger pixel pitch.

For monolithic microLEDs, many companies are focused on fabricating a blue microLED wafer and then using a color conversion technology to achieve red and green pixels. Such color conversion can be achieved by patterning (lithographically or ink jet deposited) quantum dots or even very fine grain phosphors. Color filters are added on top of quantum dots to absorb unconverted blue light.

There are other approaches such as nano-wire microLED structures that can be grown to create red, green, or blue light (Glo/Nanosys), stacked RGB epi wafers (OKI, Ostendo) or multi-color pixels (Porotech).

Finally, there are also multiple ways to fabricate a monolithic microLED display. For example, the microLED epi layer can be fabricated on sapphire or silicon substrates. These are then flipped over and wafer-bonded to the silicon backplane wafer, with the epi substrate then removed to create a hybrid wafer. Alternatively, some seek to fabricate the silicon backplane electronics on top of the finished epi wafer.

Kopin has chosen to fabricate blue LEDs on a silicon substrate and wafer bond it to the silicon backplane. Once the epi carrier substrate is removed, quantum dots are fabricated to create red and green sub-pixels (Figure 8).

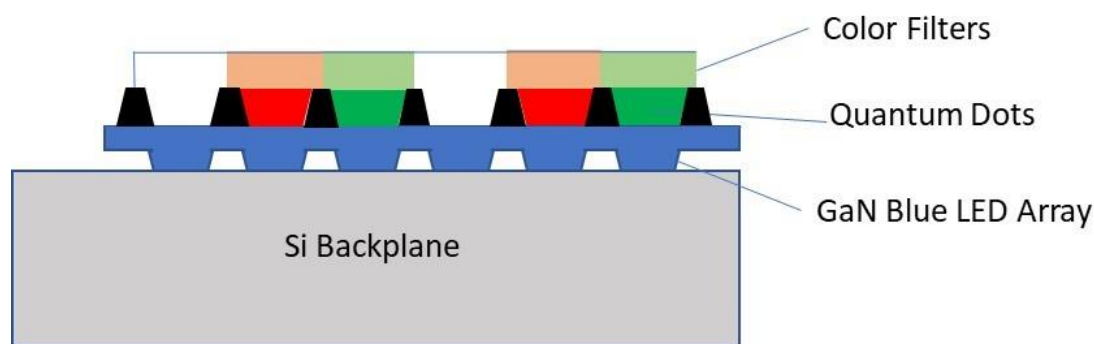


Figure 8: microLED microdisplay Structure



So far, only monochrome microLED microdisplays are commercially available, but full-color commercialization is thought to be not too far off. However, as Figure 6 suggests, it will be some time for microLEDs to develop the performance and cost to supplant other options in AR/VR.

## Summary

AR, VR, electronic viewfinders, sights and many more applications offer a large market opportunity for microdisplays. It is a very busy field with multiple microdisplay technologies and lots of companies, especially in the microLED area. What is nice about Kopin is that they already offer or are developing four different microdisplay technologies and multiple manufacturing strategies to offer high performance and value pricing, allowing customers to choose the right display for their applications.