

Technology Overview

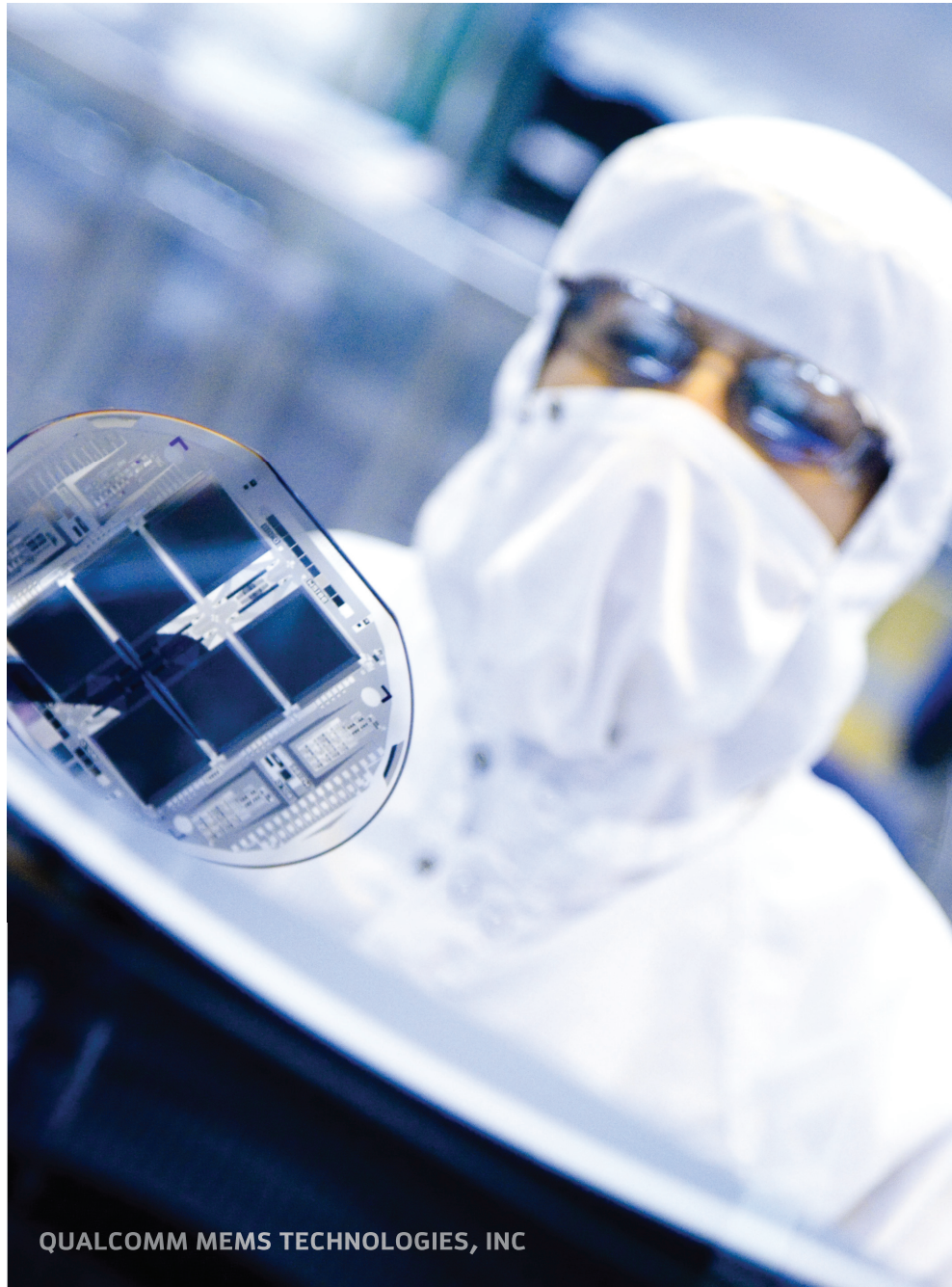


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Executive Summary

Today's mobile devices are a far cry from the devices of 20—or even 5—years ago. Gone are the days of carrying a separate camera, phone, music player and PDA—today's mobile devices range from cell phones to smartphones to PC tablets and each incorporates these functions into one multipurpose device for its respective market segment. As computer technology and multimedia converge, the industry has witnessed a dramatic change in how consumers view their mobile devices. Today's indispensable tools bring users information and entertainment. But as functionality increases and consumers use their devices for more than just making and receiving calls or sending and receiving email, consumers demand more — including extended battery life and superior viewability in all environmental conditions—in short, a convergent device. The key to such improvements is the display. Today's liquid-crystal displays (LCDs) consume significant power, suffer from poor viewability in direct sunlight and do not offer convergent capabilities. Electrophoretic display, found primarily in e-readers, offer low power, for reading at least, and outdoor viewability, but struggle with color and refresh rates. A revolutionary display technology, however, makes all of this possible. Qualcomm's mirasol® displays, based on Interferometric Modulation (IMOD) technology, offer users a convergent display experience, with paper-like readability in almost any ambient condition, significantly less power consumption, brilliant reflective color, and video-rate response times. In addition, mirasol displays offer features such as industry-standard interface compatibility, manufacturability in existing Flat-Panel Display (FPD) fabs and compatibility with industry standard and emerging touch technologies—making mirasol displays the best display solution for today's convergent mobile devices.

Overview of Mobile Display Technologies

Ink and paper are arguably the de facto standard for information display. Developed over 5,000 years ago, today's inks and dyes provide lifelike color imagery. Display technologies, on the other hand, are relatively new. The CRT was developed less than 100 years ago and the increasingly popular flat-panel display less than 40 years ago. For some time now, engineers have been working to create a display technology capable of providing a paper-like reading experience, not only with regards to superior viewability, but also with respect to cost, power and ease of manufacture. Display technologies such as backlit LCDs, reflective LCDs, electroluminescent (EL) displays, organic light-emitting diodes (OLED) and electrophoretic displays (EPD) were all steps in this direction. Qualcomm's mirasol displays, based on industry-proven MEMS technology, promise to take the quest for paper-like displays to a new level.

A wide variety of display technologies are aiming to capture the key characteristics of ink and paper. In this section we will compare them, with particular emphasis on energy consumption and readability.

Emissive/Transmissive Displays

Displays are classified as one of three types: emissive/transmissive, reflective or transreflective. A transmissive LCD consists of two transmissive substrates between which the liquid-crystal material resides. By placing a backlight underneath one of the substrates and by applying a voltage to the liquid-crystal material the light reaching the observer can be modulated so as to make the display pixel appear bright or dark. A display can also directly emit light, as in the case of an OLED display, whose active display material emits light. In the case of an LCD, a constant source of power is required to both modulate the liquid-crystal material and to power the backlight. An LCD requires constant refreshing—at least sixty times per second—in order to prevent the liquid-crystal material from transitioning to a different modulation state, resulting in image degradation or flicker. Such is also the case with OLED and EPD—constant power must be provided to the light-emitting materials in order to prevent screen flicker.

Reflective Displays (Continuous refresh type)

In a reflective display, one of the substrates found in a transmissive display is replaced with a reflective substrate. Reflective displays usually employ liquid-crystal material on top of the reflective substrate so as to modulate the ambient light reflecting off the reflective substrate. Since there is no backlight in reflective displays, they consume substantially less power than emissive displays. However, since the material providing modulation is liquid-crystal, the majority of these types of displays must constantly be refreshed or the displayed image will be lost. So far, most portable devices employing reflective displays are the continuous refresh type.

Reflective Displays (Bistable type)

A bistable display is capable of maintaining one of two states (on or off) without any external influence such as an electric field. A bistable reflective display employing liquid-crystal material for light modulation is in many ways identical to the continuous-refresh reflective display. The key difference is the type of liquid-crystal material that is used. Through proper choice of chemistry, manufacturing and drive schemes, the liquid-crystal material can be locked into one of two states. Once the material has been locked into a certain configuration, it is not necessary for the display to be refreshed. In fact, power can be completely removed from the system and the display will maintain the last image shown.

EPD and mirasol displays are also bistable. EPDs typically consist of charged microcapsules containing dye suspended between two substrates. The microcapsule, generally a sphere, is black on one half and white on the other. Depending on the electric field applied between the two substrates, the microcapsule will flip orientation to position either the black or the white half toward the observer. Depending on the capsule orientation, the ambient light will either be reflected toward the observer or be absorbed.

In a mirasol display, a flexible thin-film mirror is fabricated on a transparent substrate, leaving an air gap of a few hundred nanometers between the thin film and the substrate such that when ambient light enters this cavity and reflects off the thin-film mirror, it interferes with itself, producing a resonant color determined by the height of the cavity. A mirasol display produces iridescent color, similar to what you would observe in a butterfly's wings. Depending on the electric field applied between the substrate and the thin film, the film can be positioned in one of two states. Because mirasol displays are bistable, they don't require a refresh until the image is changed. As a result, they consume very little power, providing extended battery life for the user.

Transflective Displays

Transflective displays are a hybrid of emissive and reflective display technologies. Transflective displays were engineered to overcome the shortcomings of emissive displays, namely the backlight's high power consumption, and the shortcomings of reflective displays, such as poor image quality at low ambient light levels. Transflective displays employ a partially transmissive mirror as the secondary substrate, as well as a traditional backlight. In low light situations, the device operates as a transmissive display, employing the backlight. In high ambient light conditions, the backlight turns off and the display functions as a reflective display. A transflective display is a compromise and its image quality is generally subpar. In sunlight they are not as bright as purely reflective displays, while indoors they are not as bright as emissive displays. Regardless, they offer a compromise for applications where a wide variety of lighting conditions are seen and transflective displays are widely used in the portable device market.

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Overview of IMOD Technology in mirasol Displays

Micro-Electro-Mechanical-Systems (MEMS)-based display technologies have been under development for some time, but have recently started to gain traction. Display systems based on arrays of movable mirrors are now widely available in the consumer marketplace. Deformable mirrors and mechanical shutters are also making use of MEMS-based displays. Their digital nature and fast response make them ideal for display applications. However, their role has been limited to applications with fixed-angle light sources rather than portable direct-view displays, as they are not effective when removed from a fixed-angle light source.

Developed to address these shortcomings, mirasol displays are based on the principle of interference, which is used to determine the color of the reflected light. IMOD pixels are capable of switching speeds on the order of 10 microseconds. Additionally, mirasol displays fabricated to use IMOD technology have shown reflectivity of greater than 40 percent, contrast ratios greater than 10:1 and drive voltages of as low as 5 volts. Though simple in structure, IMOD elements provide the functions of modulation, color selection and memory while eliminating active matrices, color filters and polarizers. The result is a high-performance display capable of active-matrix type functionality at passive-matrix cost. Qualcomm's mirasol displays are a strong contender in the display industry, with the potential to offer many of the benefits of ink and paper with video.

How It Works

Color Generation

At the most basic level, a mirasol display is an optically resonant cavity similar to a Fabry-Perot etalon. The device consists of a self-supporting deformable reflective membrane and a thin-film stack (each of which acts as one mirror of an optically resonant cavity), both residing on a transparent substrate.

When ambient light hits the structure, it is reflected both off the top of the thin-film stack and off the reflective membrane. Depending on the height of the optical cavity, light of certain wavelengths reflecting off the membrane will be slightly out of phase with the light reflecting off the thin-film structure. Based on the phase difference, some wavelengths will constructively interfere, while others will destructively interfere as shown in Figure 1. As illustrated, the red wavelengths have a phase difference which leads to constructive interference, while the green and blue wavelengths have a phase difference which leads to destructive interference. As a result, the human eye will perceive a red color, as certain wavelengths will be amplified with respect to others. Color generation via interference is much more efficient in its use of light compared to traditional color filters and polarizers, which work on the principle of absorption and waste much of the light entering the display.

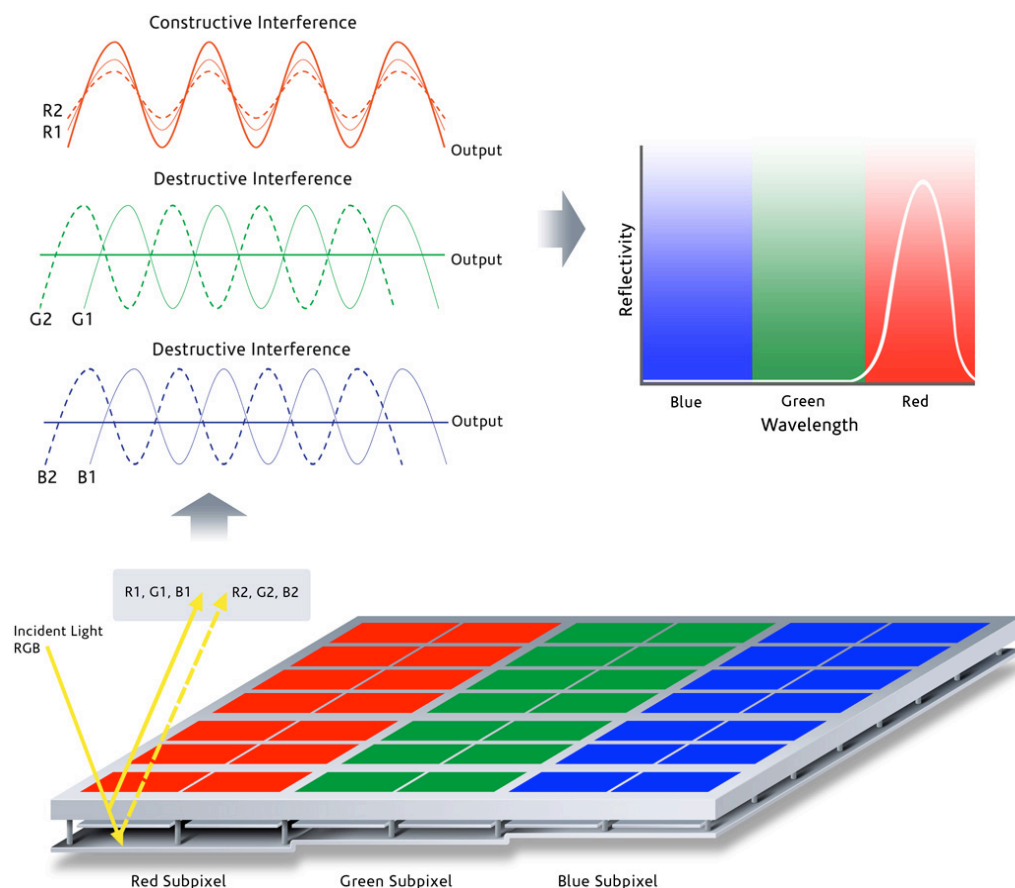


Figure 1. IMOD Structure Showing Light Reflecting off the Thin-film Stack and Mirror Interfering to Produce Color

The image on a mirasol display can switch between color and black by changing the membrane state. This is accomplished by applying a voltage to the thin-film stack, which is electrically conducting and is protected by an insulating layer. When a voltage is applied, electrostatic forces cause the membrane to collapse. The change in the optical cavity now results in constructive interference at ultraviolet wavelengths, which are not visible to the human eye. Hence, the image on the screen appears black.

A full-color display is assembled by spatially ordering IMOD elements reflecting in the red, green and blue wavelengths as shown in Figure 1.

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Grayscale Generation

At the most basic level, the IMOD element is a 1 bit device, that is, it can be driven to either a dark (black) or bright (color) state. In order to be able to show grayscale images, spatial or temporal dithering can be used.

Spatial dithering divides a given subpixel into many smaller addressable elements, and drives the individual elements separately in order to obtain the gray levels. Such a scheme requires an additional row driver per element. In Figure 2 a binary weighted spatial dithering scheme is shown which produces 8 gray shades per color, for a total of 512 colors.

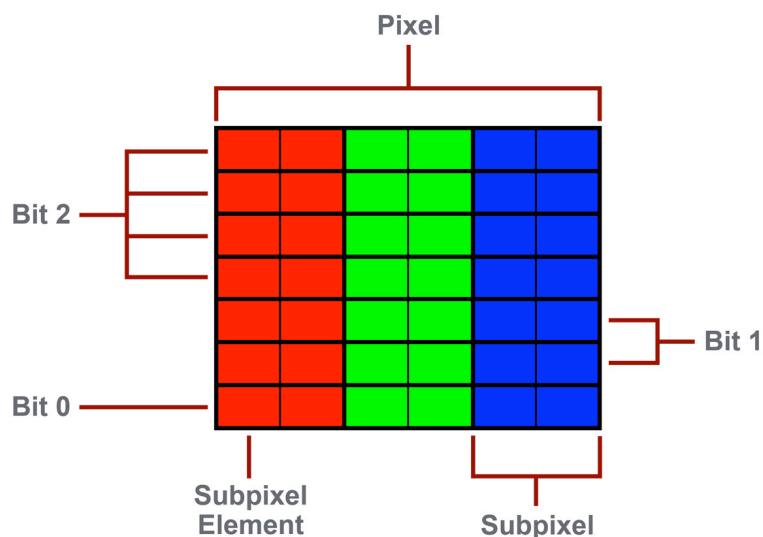


Figure 2. Grayscale Generation in a Pixel

Alternatively, temporal dithering can be used to obtain additional gray shades. Temporal dithering works by splitting each field of data into, for example, two fields, where one subfield lasts 8 times longer than the other. As shown in Figure 3, the subpixel elements are area weighted in ratios of 1:2:4. In order to achieve 64 gray levels per color for a total of 256K colors, this area ratio is combined with the subfield timing (area of subpixel elements x temporal subfield) to give a ratio of 1:2:4:8:16:32. Cycling the frames at >50Hz allows the eye to time integrate the subfields and perceive the large number of gray shades.

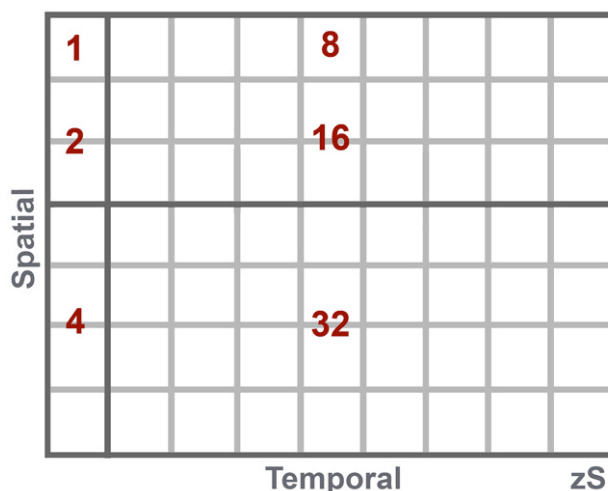


Figure 3. Grayscale Generation Via Temporal Dithering

Both spatial and temporal dithering have their pros and cons. Spatial dithering offers lower power consumption as the display does not need to be refreshed as often as when temporal dithering is used. Since power consumption is proportional to the display refresh frequency, temporal dithering is best used in cases where power is of less concern. Temporal dithering, however, offers a lower cost display since fewer IMOD elements are addressed and provides a higher fill factor. Finally, a combination of both temporal and spatial dithering can also be used to increase the number of gray levels; such a scheme could balance the optical efficiency/power tradeoff.

Bistability

One of the key advantages of the mirasol display's design is its bistable nature, which allows for near-zero power usage in situations where the display image is unchanged. This means that mirasol displays benefit from considerable power savings, especially compared to displays that continually refresh, such as LCDs. The bistability of mirasol displays comes from the inherent hysteresis derived from the technology's electro-mechanical properties. More specifically, it derives from an inherent imbalance between the linear restorative forces of the mechanical membrane and the non-linear forces of the applied electric field. As shown in Figure 4, the resulting electro-opto-mechanical behavior is hysteretic in nature and provides a built-in "memory" effect similar to the thin-film transistor (TFT) element in an active-matrix display.

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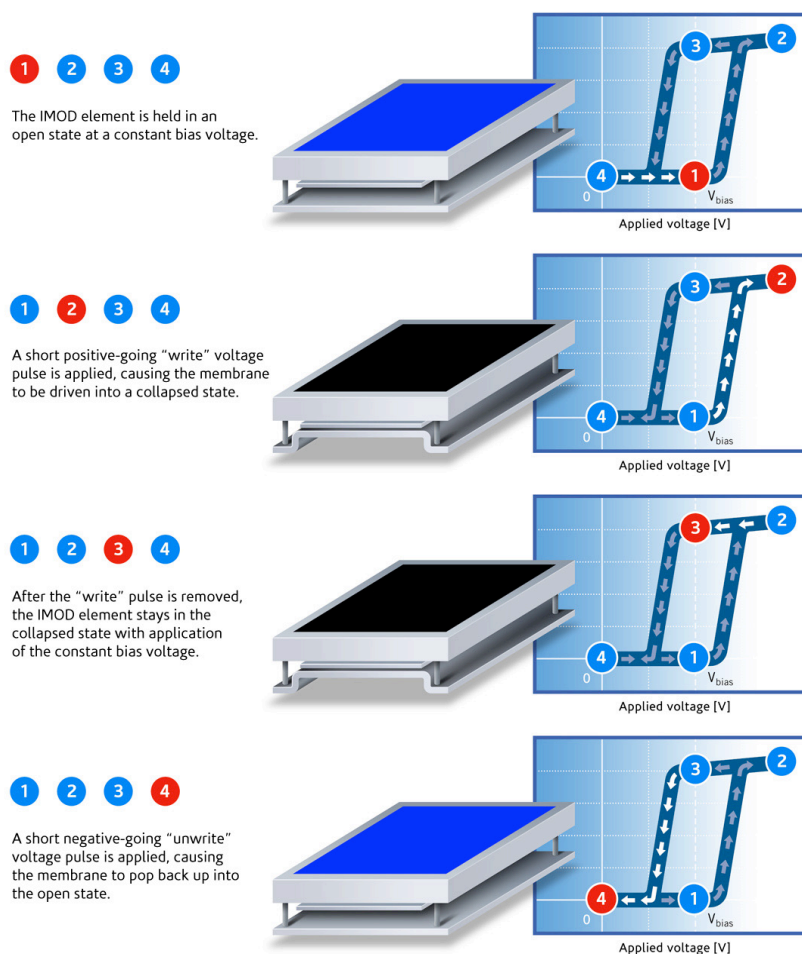


Figure 4. Hysteresis Effect in an IMOD Pixel

The membrane is held in the open state by applying a voltage V_{bias} . By applying a short write voltage pulse, the membrane will collapse and stay in that state as the voltage returns to V_{bias} levels. In order to return to the open state, a short negative unwrite pulse ($V_{unwrite}$) is applied, causing the membrane to snap back into the open state.

Additional Key Attributes

Speed

Since visible light wavelengths operate on the nanometer scale (i.e., 380nm to 780nm), the deformable IMOD membrane only has to move a short distance—a few hundred nanometers—in order to switch between two colors. This switching happens extremely fast, on the order of tens of microseconds. This switching speed directly translates to a video rate-capable display with no motion-blur effects. Traditional STN- or cholesteric-based passive matrix displays have switching speeds as slow as tens or hundreds of milliseconds. An IMOD element's switching time is 1000 times faster than traditional displays. In addition, mirasol displays switching speed is maintained across a wide temperature range, unlike organic liquid-crystal-based displays, whose switching speeds decrease as temperatures go into low environmental ranges.

Readability

Humans view the world by sensing the light reflecting from various surfaces. As a result, a reflected image from a newspaper is more appealing and easier to view for the human eye, compared to a backlit image. Based on human perception, there are two critical factors which determine readability: luminance and contrast.

Luminance is the amount of light that reaches the human eye. In the case of a reflective display, it is the amount of ambient light that is reflected from the display, rather than absorbed. The key metric is the reflectivity of the display's white state, which is measured by comparing it to the reflectivity of a standard white source. A white sheet of paper measures between 70 and 90 percent reflectivity, and a newspaper measures on the order of 60 percent reflectivity.

Contrast is the ratio of the display's white state reflectivity to its dark state. This metric dictates whether or not the human eye will be able to perceive transitions between the dark and light areas on the display, which translates to spatial detail. If the contrast is too low, the display will appear washed out and the user will have difficulty perceiving image details. A high contrast ratio makes the image look sharper and improves readability. For reference, a newspaper has a contrast ratio of approximately 4:1.

Comparing the readability of reflective displays to that of emissive displays, it is clear that emissive displays work well at low ambient light levels. The problem with these displays, however, is when ambient light levels increase from room lighting to levels found outdoors on a sunny day, making it difficult for the user to discern spatial detail as shown in Figure 5. This is illustrated by the fact that a user must typically shield their portable-device screen when they are outdoors in bright sunlight. Two factors account for this: first, the increase in light that is reflected from the device pixel in the black state and second, the ambient light exceeding the light levels being emitted from the display. Both of these factors reduce the display's contrast.

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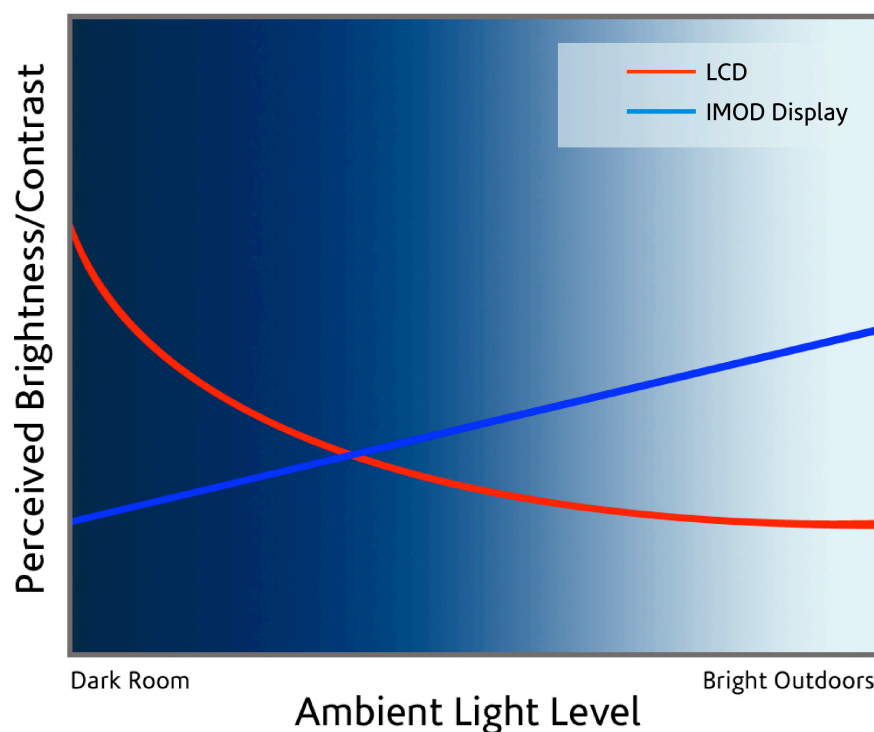


Figure 5. Brightness/Contrast Versus Ambient Light Levels

In the case of reflective displays, the black state suffers from the same problem as emissive displays—the black-level luminance increases as ambient light levels increase. However, the display's white state offers superior viewability. As ambient light levels increase, so does the mirasol display's white-state reflectivity. As a result, a mirasol display offers a superior contrast ratio in brightly lit environments. In darker environments, supplemental illumination is provided by a low-power frontlight.

An additional benefit of mirasol displays is their wide viewing angle. Unlike an LCD display, which exhibits grayscale inversion when viewed at angles varying in elevation from normal (looking directly at the display, head-on), the mirasol display shows a non-grayscale-inverted image. Images shown on mirasol displays are also impervious to rotations around the normal, once again unlike LCD-based displays. In this sense, the IMOD element provides the benefit of an emissive—a wide symmetrical viewing angle.

Qualcomm's mirasol displays offer reflectivity on the order of 60 percent and contrast ratios greater than 10:1. By comparison, the *Wall Street Journal* newspaper offers a reflectivity of 60 percent and a contrast ratio of around 4:1.

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