



## Mobile Display Technologies

The Primary Interface Between Man and Machine – Now in Your Pocket

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## Introduction

Display is the most important interface between humans and machines, with the ability to present information in terms of text, graphics, animation, and video.

Historically, the display industry was stuck in neutral compared to the rest of the high tech sector, which has evolved at warp speed. By contrast, CRT (Cathode Ray Tube) was the king of display for more than eight decades.

But that has quickly changed. Today, many new display devices, such as LCD, Plasma, DLP (digital light processing), LCoS (liquid crystal on silicon), and SED (surface-conduction electron-emitter display) have suddenly emerged. Driven by computers, high-definition TV (HDTV), and mobile devices (including cell phones), the display industry is evolving at a much faster rate than ever before. With so many options, choosing the best display solution for your mobile device has become a real challenge.

This whitepaper describes modern mobile display devices and technologies and compares their pros and cons for use in various mobile applications. Marvell® is a strong SoC provider in the cell phone and mobile device market and has many unique solutions for mobile displays. By choosing the right combination of display device and SoC, you can achieve greater system performance for your mobile device.

## Display Performance and Mobile Requirements

The number of display devices can be overwhelming. So, how do you know which one works best for your particular device or application?

First, let's start by asking which display features and parameters are favorable to the application. Next, let's define some important general display performance attributes, as shown in the following table. This table also describes some important mobile display performance attributes.

Display Attribute	Description
Resolution	Number of pixels in X by Y dimensions For example, 1024 x 768
Screen size	Size of image area, as measured diagonally in inches For example, 16" or 42"
Contrast ratio	Brightest color (white) over darkest color (black) of display luminance
Brightness	Luminance
Response time	Display update transition time
Uniformity	Evenness in brightness and color
Pixel or color depth	Number of bits per pixel
Color gamut	Subset of colors that can be accurately represented
Refresh rate	Number of vertical scans per second (This is different from the Frame rate, which usually refers to the number of frames the host renders to the display device per second.)
Viewing angle	Maximum angle at which the display is properly visible, in horizontal and vertical directions.

## Becoming Mobile

As mobile and handheld devices grow exponentially, so do mobile displays. In general mobile displays are smaller than general displays, but size is not the only thing that matters.

The previous section defined performance attributes of general displays. But mobile displays have additional requirements and attributes as outlined in the following table:

Mobile Display Attribute	Description
Low power	Critical to save battery power
Thin	Low profile mobile form factor
Lightweight	Easy to carry around
Outdoor reading	Readable even in sunlight
Durable	Robust
Bi-stability	Retains image without refreshing and even without power. This can conserve significant power for still image display.
Pixel density	High ppi (pixel per inch) is needed for short-distance viewing

The following sections describe several mobile display devices and technologies, their performance attributes, and the pros and cons of their use in mobile applications. These displays include:

- 1) Liquid-Crystal Display (LCD):
  - a. Active matrix LCD
  - b. Reflective & Transflective LCD
  - c. Cholesteric Liquid Crystal Display (Ch-LCD)
  - d. Memory-LCD
- 2) ElectroPhoretic Display (EPD)
- 3) Organic Light Emitting Diode (OLED)
- 4) Mirasol (IMOD)
- 5) Electrowetting Display (EWD)
- 6) Quick-Response Liquid Powder Display (QR-LPD)

## Mobile Display Device Technologies

### 1) Liquid-Crystal Display (LCD)

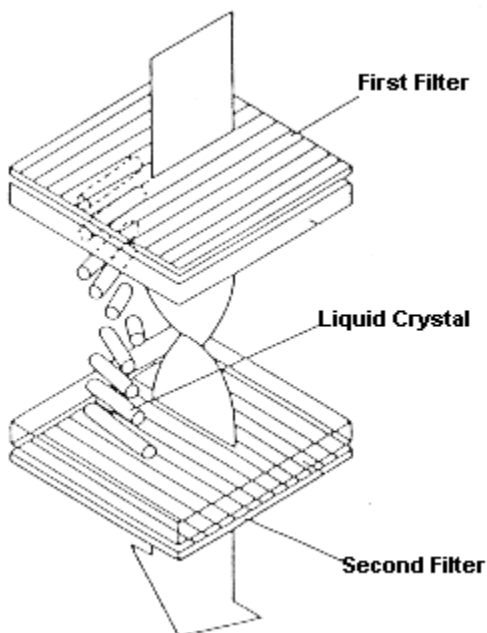
#### a. Active-matrix LCD

Active-matrix LCD is a mature technology that has been around for more than 30 years, but it has become very popular lately. LCD surpassed CRT in worldwide TV sales in 2007 and became the most common display device for both desktop and mobile applications.

Liquid crystal has two useful properties.

- It can polarize light. A typical LCD consists of two polarizing filters with liquid crystal sandwiched in between, as shown in Fig.1. The two polarizing filter's axes of transmission are perpendicular to each other.
- Its polarization can be modulated (twisted or rotated) electrically. The electric field can modulate liquid crystal molecules twisting or rotating. If the liquid crystal twists 90 degrees, all the light passing through the first filter can pass through the second filter. This is the bright state. If the liquid crystal twists less than 90 degrees, less light will pass through and gray levels are produced. If the liquid crystal is not twisted at all, the rotation is zero degree and no light will pass through. This is known as the dark state.

Figure 1: Light passing through when liquid crystal twists 90 degrees.



To build an LCD display, a backlight is placed behind an LCD panel. Each pixel has a transparent electrode to modulate the electric field and, in effect, its brightness, with a common transparent electrode (ITO) on the other side. Pixel brightness is controlled by the voltage of the electrode. When the pixel count is large, a capacitor is needed to hold the electrode voltage level in each pixel. Thin-film-transistors (TFT) are used to drive the electrodes. This is the so-called active matrix array.

To produce color, each pixel is divided into three sub-pixels with red, green, and blue filters.

The liquid crystal transition doesn't happen instantly. Typical response time is between 8ms and 16ms, resulting in a refresh rate of 60Hz to 120Hz.

Even though LCD is the most commonly used display for mobile devices, it is not very power efficient. It has several other disadvantages. To begin with, LCD's backlight burns significant power (>70%). Even for a completely dark image, the backlight must still remain on. To avoid flicker artifacts caused by charge leakage, LCD displays must be refreshed at a certain minimum rate, such as ~ 40 Hz. Therefore, even for a still image, LCD needs to be refreshed. That means it is burning the same amount of power as if it were playing a video. LCD uses polarized light resulting in wastage of at least 50% of light. When LCD is in the dark state, 100% of light is wasted. Therefore LCD's light efficiency is sub-optimal. As a result, LCD devices waste a lot of power.

LCD has several other disadvantages when used for mobile applications. The backlight requirement means that LCD-based devices are neither thin nor lightweight. Since LCD is a backlight-based transmissive display, its readability drops significantly in outdoor usage. And, in direct sunlight, LCD is virtually unreadable.

Even though LCD isn't ideal for mobile applications, it is still a very popular display. That's why significant effort has been made to reduce its power consumption in mobile devices. One such improvement is the introduction of MIPI DSI (Mobile Industry Processor Interface, Display Serial Interface), a display standard for mobile and handheld devices. With a scalable data-lanes configuration, the interface is able to transfer data up to 3 Gbits/s with low differential swing voltage. The interface is very low power and has very low emission levels. MIPI DSI supports DSI video mode and DCS command mode.

Another way to lower LCD power is to reduce its refresh rate. Conventional LCD needs to refresh at  $\geq 40\text{Hz}$ , otherwise the pixel charge would leak so much that flicker becomes noticeable. Some progress has been made to reduce the LCD refresh rate to below 1Hz, and thus save significant power for still image display.

As a major SoC supplier, Marvell's SoCs offer many enhancements for mobile displays. For example, the ARMADA™ 610 device contains an EPD controller and two MIPI DSI ports. The first MIPI DSI port supports four DSI lanes, while the second MIPI DSI port supports three DSI lanes. Each DSI lane can transfer data at up to 1 Gbits/s.

## **b. Reflective & Transflective LCD**

Another way to save LCD power is to remove the backlight. In this case a reflective layer is placed behind the LCD screen, which can reflect ambient light and make LCD readable. Reflective mode LCD has some advantages:

- It saves approximately 70% power over conventional LCD by removing the backlight. This also helps reduce overall weight.
- It is more suitable for outdoor reading.

There are several disadvantages of reflective LCD:

- Color is not an option due to lack of a strong light source.
- It has a low contrast ratio (typically ~ 12:1).
- It has low brightness, especially in dim areas (polarization cuts 50% of the light).

To address these issues, some companies, such as Pixel Qi, have developed Transflective LCD that can switch between backlit mode and reflective mode. For outdoor or low power readings, it can operate in the reflective mode; for color indoor displays, it can operate in the backlit mode. This is a hybrid solution. In reflective mode, it behaves like a reflective LCD; in backlit mode, it behaves like a conventional LCD.

## **c. Cholesteric Liquid Crystal or Ch-LCD**

Ch-LCD is similar to LCD, but with a different type of liquid crystal material that has the physical property to organize its molecules into a cholesteric phase. Ch-LCD has two stable states. It is stable when the spiral axis is vertical or horizontal, so the direction of liquid crystal molecules can be maintained semi-permanently without power. So far, Fujitsu has demonstrated Ch-LCD prototypes, with Cinflex running the production.

Ch-LCD has two main advantages: it is bi-stable, which means it only requires power during image updating. And it produces color (although the color quality is not as good as conventional LCD). Moreover, Ch-LCD doesn't require backlight, so it is low power and lightweight. However, Ch-LCD also has several disadvantages: its response time is slow and its contrast ratio is low. Also, the cost is very high.

#### d. Memory-LCD

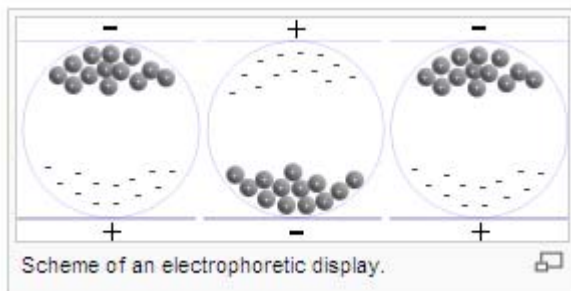
Sharp® announced memory-LCD in June 2009. It is a new type of LCD with built-in memory in each pixel, thus reducing the energy consumption significantly compared to conventional LCD. In the memory-LCD, each pixel is equipped with memory circuitry to save the image information uploaded to the display. Therefore the image information has to be rewritten only in the pixels where content has changed in comparison to the previous picture frame.

Memory-LCD has two main advantages. It can hold an image without power and it has good response time. However, memory-LCD also has several disadvantages: it is currently only available in monochrome (color is not available at this time), it has a low contrast ratio of 10:1, and it is only available for use in small sized applications of approximately 1.5 inch.

## 2) ElectroPhoretic Display or EPD

ElectroPhoretic display (EPD) is sometimes also referred to as electronic paper, e-paper, or electronic ink. EPD is built with millions of microcapsules. Each microcapsule contains positively charged white pigments and negatively charged black pigments that are suspended in a clear fluid, as shown is Fig.2. EPD forms an image by rearranging charged pigment particles with an electric field. Each pixel has an electrode on one side, and a common transparent electrode on the other side. By applying different voltages in different pixels, a gray scale image is formed.

Figure 2: Gray scale EPD scheme.

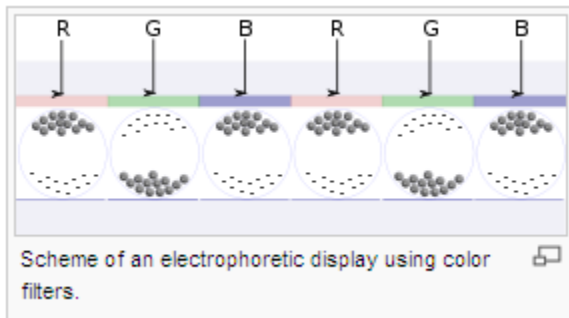


EPD is a reflective mode display and as such, it doesn't require any backlight. The white pigments are reflective, while the black pigments are not. Therefore, the image can be viewed clearly in ambient light or in direct sunlight, very much like real paper.

EPD doesn't require the screen to be constantly refreshed if the image doesn't change. The clear fluid inside the microcapsule has high viscosity. When the electric field is removed, the black and white pigments do not move around. Therefore, EPD is bi-stable, meaning that the image can remain visible without any electric power.

To produce a color image, color filters are placed on top of the EPD, as shown in Fig.3.

Figure 3: Color ElectroPhoretic display by using color filters.



Based on the above description, we can see that EPD has some very attractive features for mobile applications:

- No backlight – This is a significant power savings over LCD, and also makes EPD-based devices thin and light.
- Bi-stable – No refresh is needed for still images. This saves significant power for book reading and other non-motion applications.
- Reflective display – EPD is ideal for outdoor reading.
- Light efficiency is high – EPD doesn't use polarized light.

However, EPD has many weaknesses compared to LCD:

- Slow image update – LCD screen updates in one step of 8~16ms. An EPD image update takes 12 steps for a black-white image, and approximately 39 steps for a gray-scale image. Each step takes 20ms. In other words, EPD takes 240ms for a black-white update; and approximately 780ms for a gray-scale update. This makes EPD unsuitable for video applications.
- Low Contrast Ratio (CR) – First generation EPD CR is approximately 8:1, second generation CR is approximately 15:1. These CRs are very low compared to conventional LCD. Lack of backlight is one of the main reasons for this.
- Low pixel depth – Only 4 bit per pixel, or 16 gray levels at this time.
- Poor color performance – With very low CR and no backlight, EPD doesn't have enough light to start with. Adding color filters further reduces approximately two-thirds of the light, so that EPD lacks suitable color saturation and brightness. Today commercial EPDs are mostly gray-scale only.
- Image ghosting – After image updating, the old image is still partially visible, resulting in image ghosting artifacts. To eliminate image ghosting, full-flash update is usually required. But full-flashing itself is an annoying artifact.

Due to EPD's paper-like appearance and bi-stability, the eBook market has been growing rapidly. Many EPD drive electronics have emerged using discrete components.

Marvell's ARMADA 166E is the industry's first SoC with integrated EDP controller. This integrated solution has significantly reduced device count, cost, and power consumption. Marvell's EPD also has parallel updating capability, which allows each pixel to start updating without waiting for other pixels. This feature makes motion animation flicker free in EPD devices, overcoming one of the major drawbacks of EPD.

Marvell's second generation EPD controller is integrated in ARMADA 610. Some of the new features in the second generation EPD controller are:

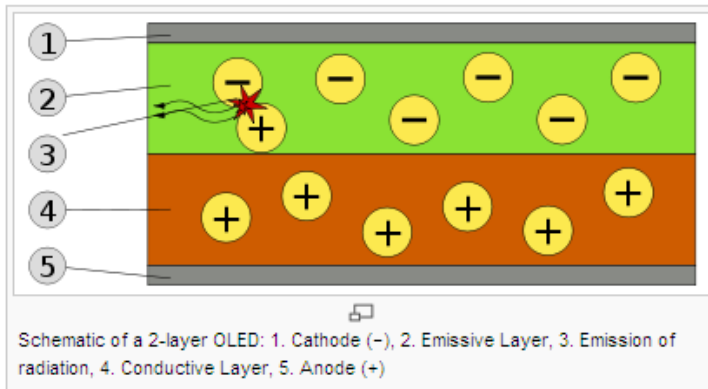
- Support for multiple windows with a different waveform in each window.
- The ability to take a RGB16 color image and directly map it to a color EPD panel.
- Frame-buffer caching so that only changed pixel data is updated, and unchanged pixel data is skipped (saving DRAM bandwidth as well as power).
- Support for WinCE® pixel data format (in addition to Linux and Android, which was supported in the first generation).

### 3) Organic Light Emitting Diode or OLED

OLED display technology is based on light-emitting diodes (LED). It is an LED in which the emissive electroluminescent layer is composed of a film of organic compounds that emit light when an electric current passes through it.

As shown in Fig.4, a typical OLED consists of an anode and a cathode, an emissive layer, a conductive layer, and a substrate. When a voltage is applied between the anode and cathode, electron current flows from cathode to anode. This causes the emissive layer to become negatively charged, and the conductive layer to become positively charged. When the positive and negative charges recombine in the emissive layer, light is emitted. Since OLED emits light by itself, it doesn't require a backlight.

Figure 4: When a voltage is applied, OLED emits light.



OLED has several advantages over conventional LCD. Since it emits light, OLED has a higher contrast ratio than LCD. And because it has no backlight, OLED is thinner and lighter and has better light efficiency than LCD. Each pixel emits light only when needed. No light is blocked or wasted. It doesn't use polarized light, which saves another 50% of the light. OLED's transition time can be less than 1ms, offering a refresh rate of up to 1000 Hz.

OLED also has several disadvantages. OLED's main problem is a shorter lifespan due to its use of organic materials. In particular, the blue OLED's lifespan is approximately 14 thousand hours to half brightness. OLED also has color balancing issues. The blue light degrades significantly faster than other colors, leading to color imbalance over time. OLED is not ideal for eReader applications because it burns more power than LCD when displaying mostly white content (such as books) and its outdoor readability is poor. OLED is also more sensitive to water than other display technologies.

#### 4) Mirasol (IMOD)

Mirasol display uses MEMS (micro-electro-mechanical system) technology to build an array of Interferometric Modulator (IMOD) elements. Each IMOD element has two conductive plates with a thin gap. Depending on the cell gap dimension, the IMOD element reflects red, green, or blue light without any voltage being applied. When a voltage is applied, the two plates are pulled together; the light is absorbed, and the IMOD element turns to black.

Figure 5: IMOD elements for red, green, and blue.



The IMOD elements have some hysteresis so that once the two plates are pulled together, it requires less energy to hold it than was exerted in pulling them together. This makes Mirasol display somewhat bi-stable.

In general, Mirasol display has the following advantages:

- Mirasol uses reflective mode so it doesn't need backlight. The IMOD element reflects ambient light, so it is low power and can be used outdoors.
- Mirasol is bi-stable. If the image doesn't change, it only needs a very small amount of power to hold the image (if not running pulse width modulation or PWM). No constant refresh is needed.
- Mirasol can update very fast. The IMOD element transition time is less than 1ms. Mirasol can also display video at a high frame rate, while EPD cannot.
- Mirasol can display color, while EPD mostly cannot.

Mirasol has some disadvantages:

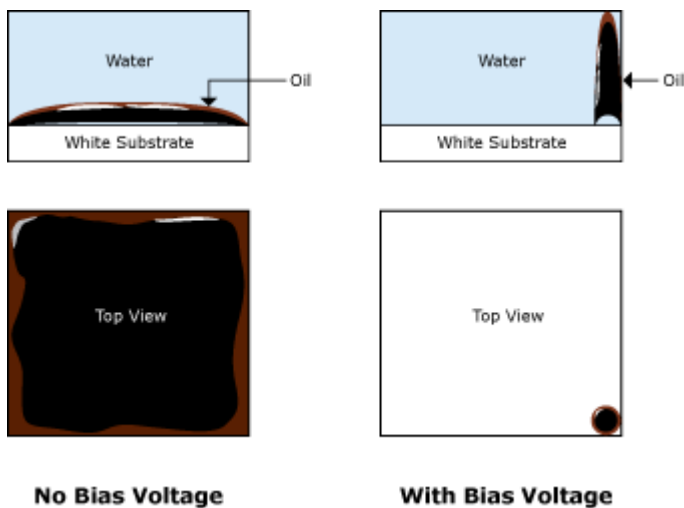
- It is difficult to scale up MEMS devices in size. As the screen size increases, cost goes up and yield goes down exponentially. Today, the largest Mirasol display is 5.7", barely enough for an eBook.
- Each IMOD element or subpixel has two states – color or black. So the color depth or pixel depth is very low, at 1 bit per subpixel. By default, Mirasol can produce very few colors or gray levels. To increase the colors or gray levels, either spatial or temporal modulations are needed.
  - In the time domain, PWM can be used to produce more gray levels or more colors. But this will burn more power, even for still images.
  - In the spatial domain, spatial dithering can be used to produce more gray levels or more colors. But this will trade off image quality or resolution. Also processing the image for dithering burns some power.

## 5) Electrowetting Display or EWD

Electrowetting Display (EWD) is based on the phenomenon that the shape of a confined (in a pixel) oil and water interface can be modulated by an electric voltage. With no voltage applied, the oil surface is flat and covers the whole pixel area; when a voltage is applied, the oil is pushed aside, exposing the substrate layer.

If the oil is black and the substrate layer is white, a gray scale modulation can be achieved by changing the voltage level.

Figure 6: Electrowetting display mechanism.



LiquaVista® is a leading developer of EWD technology. They have successfully demonstrated working samples in 6".

EWD has more advantages than most other displays:

- It can work in reflective mode with no backlight. It conserves power and is excellent for outdoor reading. (It can also work in transmissive and transmissive modes).
- Response time is <10ms. It can easily play video content.
- There are many solutions for color EWD, such as color filters, colored oil, colored substrate, 2-layered color oil, and more.
- Its contrast ratio is approximately 18:1, which is better than that of EPD.
- EWD can use PWM or analog modulation to produce gray scale. In analog modulation mode, the refresh rate can be down to 1Hz, resulting in significant power saving.

The main disadvantage of EWD is that there has not been any volume production of EWD panels yet. LiquaVista is trying to get into production by late 2011.

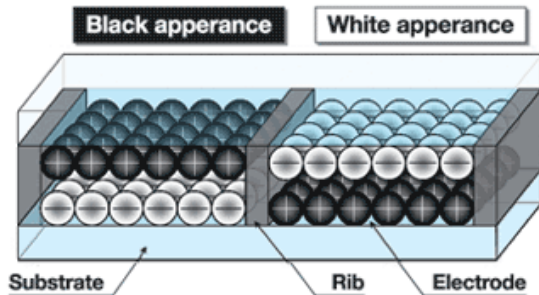
EWD's interface is very similar to LCD. But it needs variable refresh rate down to 1Hz. Marvell is in a good position to build a SoC with EWD driving capability.



## 6) Quick-Response Liquid Powder Display or QR-LPD

Bridgestone® (yes, the tire company) has developed Quick Response Liquid Powder Display (QR-LPD). Positive-charged black and negative-charged white Electronic Liquid Power are enclosed in each pixel between front and back electrodes. The gray level can be modulated by the electric field.

Figure 7: Liquid Powder display mechanism.



QR-LPD's appearance is similar to EPD, but it has many advantages over EPD. It has better color and image update time is faster. It doesn't require a backlight and it is excellent for outdoor reading. It is bi-stable, so no power is needed for still images. QR-LPD panels are thin and flexible.

QR-LPD's main disadvantage is that it has a limited number of updates. Currently QR-LPD update time is limited to between 200,000 and 1 million times. Bridgestone plans to increase this number.

Bridgestone forecasts QR-LPD will do 8 bits per pixel for 256 gray level and 16.7 million colors in late 2010 and will reach video speed in 2011.

### Market and Applications

Some of the mobile displays have been used in real products. Others are in prototyping stage. The table below provides a brief summary.

MARKET & APPS					
Mobile Display	eBook	Smart phone	Tablet	PDA	Netbook
LCD	For 2 <sup>nd</sup> screen	Product	Product	Product	Product
Reflective LCD	Low volume				Product
Ch-LCD	Low volume				
Memory-LCD		Low volume			
EPD	Product				
OLED		Product		Low volume	
IMOD	Future	Product			
EWD	Future				
QR-LPD	Future				

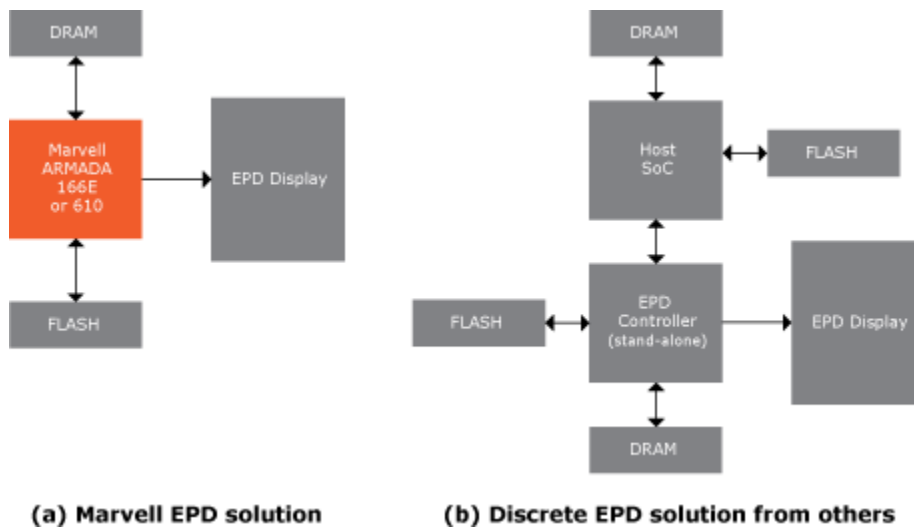
## Conclusion

As we can see, many new display technologies are emerging for the mobile market. Each one has its pros and cons. They are summarized in the table below.

Mobile Display	Pros	Cons
LCD (active-matrix)	Most mature. Excellent color. Video speed	High power. Low light efficiency. Thick. Poor outdoor readability
Reflective LCD	Good outdoor readability. Lower power than LCD	No color. Low contrast ratio (CR). Low brightness
Ch-LCD	Low power. Has color	Slow response. Low CR
Memory-LCD	Low power. Fast response	No color. Low CR. Size limitation
EPD	Low power. Paper-like. Excellent for outdoor use. Very thin and light	No (or poor) color. Slow update. Low CR. Low brightness
OLED	High CR. Excellent color. Video speed. Thin and light	Shorter lifespan. Color balance change over time. Poor outdoor readability
IMOD	Low power. Video speed. Good for outdoor reading. Good color.	Size limitation. Low color depth.
EWD	Lower power. Video speed. Outdoor reading. Color. Thin and light	Not in production. CR is not very high
QR-LPD	Low power. Paper-like. Excellent for outdoors. Thin and light	Limited updates. Poor color. Slow update. Low CR. Low brightness

Although Marvell is not a display company, we can certainly provide value-added SoCs with enhanced mobile display features. For example, both ARMADA 166E and ARMADA 610 have integrated EPD controllers that can be used for eReader applications. Since Marvell EPD is an integrated solution, we can significantly lower the device count, as shown in figure 8.

Figure 8: EPD display system architectures.



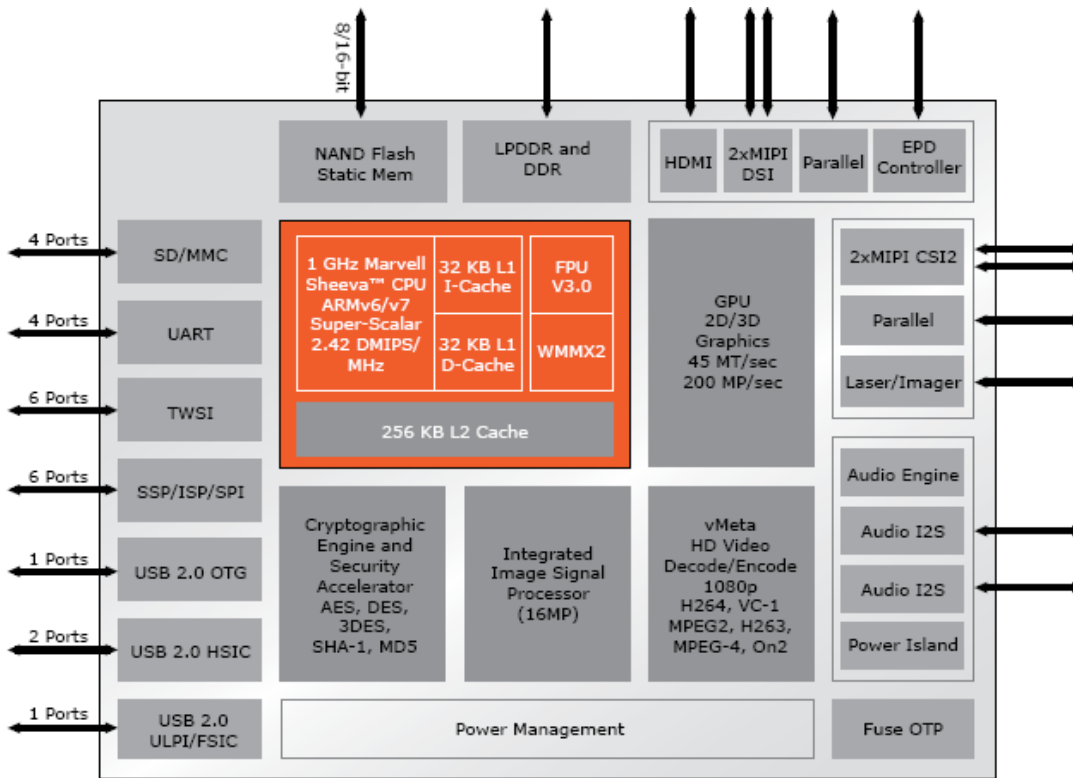
In addition, Marvell EPD controllers have the best motion animation and hand-writing performance. Each pixel can start update without waiting for others to finish. In this way, our animation and hand-writing can run continuously (framelessly) without any jitter or flicker artifacts.

Marvell's second generation EPD controller in ARMADA 610 has more features and enhancements, such as multiple windows with different waveforms and modes in each window, direct map of RGB16 color images to EPD color panel, frame-buffer caching to save power and bandwidth, and WinCE support.

For mobile LCD display, ARMADA 610 supports two MIPI DSI ports. The first port supports four DSI lanes; the second port supports three DSI lanes. Each lane supports up to 1 Gbps data transfer rate.

Figure 9 shows Marvell ARMADA 610 block diagram, which includes EPD controller, MIPI DSI, as well as many key modules such as 2D/3D graphics, HD video codec, ISP, Security, SD/MMC, USB, Wi-Fi, and camera interface, etc.

Figure 9: ARMADA 610 application processor.



Marvell will further explore the mobile display market opportunities. We shall first identify the mobile displays issues in both the interface and display control functions. Then we'll provide solutions with Marvell value-added SoCs.

With success in ARMADA 166E, followed by ARMADA 610, Marvell is perceived as a SoC vendor with innovative mobile display expertise. We shall keep this momentum and continue to provide value and solutions to the mobile market.

### Samson Huang

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Samson Huang is currently staff manager in the Consumer and Computing Business Unit (CCBU), responsible for EPD controller design. He joined Marvell in January, 2010 from eReader company Skiff, LLC. For three years, Samson has been developing EPD controllers, and has achieved the best motion animation performance in the industry. In early 2009, Skiff and Marvell jointly developed the industry's first integrated EPD in SoC, which has significantly reduced device count and power consumption. Prior to Skiff, Samson worked at Intel on LCoS (liquid-crystal on silicon) HDTV, digital video & image processing, and digital TV on PC, as well as Pentium II chip design. He also worked on CMOS sensor SoC design while at Micron Technology. He currently holds 15 US patents.

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